2012

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Repository Citation

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Digital Object Identifier (DOI)
http://dx.doi.org/10.2495/UT120271

Notes/Citation Information

Estimation of gap acceptance parameters for HCM 2010 roundabout capacity model applications

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Abstract

This paper deals with the field data observation and successive application of estimation procedures in order to estimate follow-up headway and critical headway at roundabouts. Average follow-up and average critical headway are two critical parameters in the new roundabout capacity model presented in the 2010 edition of the Highway Capacity Manual (HCM). The HCM 2010 capacity model was developed as an exponential regression model with parameter estimates based on gap acceptance theory. Gap acceptance models are strongly affected by driver behaviour and local habits. Follow-up headways can be field measured, while critical headway cannot be obtained directly. The paper mainly aims to check if general suggested values are well-suited also for Italy or not. There have been numerous techniques developed for estimating critical headway. In order to perform a better check of a sample of experimentally observed values, three different procedures are chosen and applied. The first is a quite popular mathematical method based on maximum likelihood technique. The second is a statistical method based on the median of the observed sample distribution. The third is a graphical method known as Raff's method. All these three methods require information about the accepted headway and the largest rejected headway for each driver. Therefore a sample of field data was recorded by digital camera and processed following the instructions suggested by NCHRP. The sample data of critical headway and follow-up headway are gathered in seven selected roundabouts located in Northern Tuscany (Italy). Our first obtained results indicate that the average critical headway is significantly lower than the values recommended by some international references. However, the average follow-up headway is only higher than that recommended for the State of

California and it is lower than that recommended by all other international references. Finally, conclusions drawn along with insights for further research developments are suggested.

1 Introduction

The roundabout capacity model presented in the 2010 edition of the Highway Capacity Manual (HCM 2010) [1] was developed as an exponential regression model with parameter estimates based on gap acceptance theory. Gap acceptance models are strongly affected by driver behaviour and local habits. Therefore, the HCM 2010 capacity model should be calibrated to local conditions. Two parameters that may be changed to reflect local driving behaviour are the critical headway and follow-up headway (referred to as critical gap and follow-up time in earlier studies [2]). The accuracy of capacity calculations at roundabouts is dependent largely on the accurate estimation of critical headway and follow up headway. The NCHRP Report 572 presents a set of critical headway and follow–up headway values based on a comprehensive evaluation of roundabouts throughout the United States [3]. Its recommended operational models were incorporated into the 2010 HCM. Measurements of critical headway and follow-up headway were provided by Xu and Tian [2] for ten roundabouts in California. In that study, the capacity model was calibrated using these measurements. The purpose of this research project is to test the adaptability of the HCM2010 capacity model in Tuscany (Italy) and in Kentucky (USA). To achieve this goal, two alternative calibration approaches can be used: one is local gap acceptance data collection and the other is entry lane simulation. The first step of this research project was related to local data collection. Therefore, the pilot study was conducted at seven roundabouts located in Northern Tuscany collecting a field data sample and then applying three different critical headway estimation procedures. There have been numerous techniques developed for estimating the critical headway. Among these methods, there is the popular maximum likelihood technique [5]. Then, a statistical method based on the median of the observed sample distribution [10] and a graphical technique known as Raff's method [11] were applied in order to compare the previous obtained values through the maximum likelihood technique. This paper shows the results of such pilot study, which can be considered as our research project first step.

2 Data collection and extraction

Data collection was carried out on seven existing roundabouts using digital video cameras placed at the center of the central island during weekday peak periods. Flows of vehicles circulating on the ring and entering in the roundabout were recorded when high traffic volumes were actually observed. A continuous queue on the entrance of each branch was required in order to have a considerable number of follow-up headways, while intense heavy flow on the ring was needed

to obtain a significant number of drivers who rejected at least one headway before entering the roundabout. Sites were selected on the basis of several geometric combinations (single-lane, multi-lane) and land use (residential, commercial, industrial) in order to measure headways related to several types of drivers. Experimental observations at multi-lane roundabout have shown that drivers are conditioned by the conflicting flow of both lanes in the ring: therefore, this flow was assumed unique and was not considered separately for each lane in the ring. This assumption was made also in other studies [2, 3]. The studied roundabouts are located in some cities of the Northern part of Tuscany: Pisa, Viareggio, Camaiore, Massa, Pietrasanta, Carrara and Lucca. Data collection sites are summarized in Table 1. Headway data were extracted later from the recorded videos. Three time events were recorded: the time at which an entering vehicle stopped at the stop line, the passage times of circulating vehicles that directly conflicted with the entering vehicle, and the time when the entering vehicle left the stop line. The passage times of circulating vehicles define the start and end of major stream headways that were either accepted or rejected by the entering vehicles. The definition of headways from NCHRP 572 was used in this paper [3]. The procedure for extracting video data required the following steps: display the movie using the Quick Time Player™ software in order to record the frame number in which happens the event of interest; record the frame number on Excel worksheet; review the movie once for each event of interest.

Table 1:   Summary of roundabout data collection locations.

City	Location	Inscribed Circle Diam.	Entry Lanes	Branch	Date and Time
Pisa	V. Paparelli V. Pratale	180 ft (55 m)	1	South	18/11/2011Tues. 06:20 - 07:20 pm
Viareggio	V. Aurelia V. Polo	92 ft (28 m)	1	West	19/11/2011Sat. 12:15 - 12:50 am
Viareggio	V. Aurelia V. Polo	92 ft (28 m)	1	North	19/11/2011Sat 12:15 - 12:50 am
Camaiore	V. Sarzanese V. Italica	122 ft (37 m)	1	East	06/12/2011Tues. 07:30 - 08:05am
Massa	V. Avenza V. Mattei	122 ft (37 m)	2	East	08/12/2011Thur. 05:50 - 06:45 pm
Pietrasanta	V. Maggio V. Aurelia	161 ft (49 m)	2	West	21/12/2011Wed. 05:50 - 06:45 pm
Carrara	V. Settembre V. Covetta	111 ft (34 m)	2	North	10/01/2012Tues. 06:40 - 07:40 pm
Lucca	V. Carducci V. Europa	144 ft (44 m)	2	North	23/01/2012Mon. 04:10 - 05:00 pm
Lucca	V. Carducci V. Europa	144 ft (44 m)	2	East	23/01/2012Mon. 04:10 - 05:00 pm

3 Data analysis

Accepted headways, maximum rejected headways and follow-up headways were calculated in the worksheet. Headways were determined by counting frames between successive vehicles (25 frames per second per EU standards). Next,

three different procedures were applied in order to estimate critical headways and a comparison was carried out between the resulting values. Finally, the follow-up headways were computed directly.

3.1 Critical headway

Critical headway represents the minimum time interval in the circulating flow when an entering vehicle can safely enter a roundabout [2]. In general, critical headway is a parameter that depends on local conditions such as geometric layout, driver behaviour, vehicle characteristics, and traffic conditions [4].

However, critical headway cannot be measured directly in the field or from recorded events. Numerous studies and techniques have been developed for estimating critical headway. In this study, three different critical headway procedures are chosen and applied in order to compare the obtained values. These methods require information about the accepted headway and the largest rejected headway for each driver. The rejected and the accepted headways were enumerated within the Excel worksheet.

3.1.1 Maximum likelihood method

The maximum likelihood method [5] was used to estimate critical headway. This technique provides an estimate of the average critical headway of all the drivers by assuming that a single driver's critical headway ranges between his or her largest rejected headway and the accepted headway.

A probabilistic distribution for critical headways must be assumed. Troutbeck [6] used a Log-normal distribution, Brilon [7] used a hyper-Erlang distribution. Weinert [8] compared the results obtained from different assumptions about the type of probabilistic distribution: Log-normal, Weibull and Erlang.

As differences in the results between various distribution assumptions were only a few thousandths of a second [8], the Log-normal distribution was assumed.

Table 2:   Critical headway results at single lane roundabout locations.

Maximum likelihood methodology			
Location	Critical headway		Sample size
	Mean (s)	Standard deviation (s)	
Pisa	3.80	0.89	71
Viareggio-West	3.99	0.79	98
Viareggio-North	4.10	0.95	47
Camaiore	3.54	0.67	61
Average	3.86	0.82	Total =277

The parameters of a Log-normal function, the mean μ and variance σ^2, are obtained by maximizing the likelihood function. The likelihood function is defined as the probability that the critical headway distribution lies between the observed distribution of the largest rejected headways and the accepted headways. The parameters μ and σ^2 are obtained by maximizing this likelihood function. In this way, the distribution of critical headways, as well as their mean and variance, can be derived. Solution was found using Scilab [9] to solve the

two equations. This way, the mean critical headway and its variance were computed. Table 2 summarizes the maximum likelihood results for critical headways for all single-lane sites. As can be seen, critical headway varies between 3.54 and 4.10 seconds (s) with a mean value of 3.86 seconds (s).

Maximum likelihood results for critical headways for all multilane sites are summarized in Table 3. It can be seen that critical headway for the left lane varies between 3.59 and 4.42 s with a mean value of 3.90 s and critical headway for the right lane varies between 3.19 s and 4.33 with a mean value of 3.69 s.

Table 3:   Critical headway results at multi lane roundabout locations.

Maximum likelihood methodology				
Location	Lane	Critical headway		Sample size
		Mean (s)	Standard deviation (s)	
Massa	Left	4.05	0.81	62
	Right	4.33	1.08	59
Pietrasanta	Left	3.59	0.64	53
	Right	3.50	0.80	36
Carrara	Left	4.42	1.14	51
	Right	3.85	0.88	56
Lucca - North	Left	3.71	0.75	54
	Right	3.56	0.61	43
Lucca - East	Left	3.71	0.99	82
	Right	3.19	0.80	69
Average	Left	3.90	0.87	Total L. = 302
	Right	3.69	0.83	Total R. = 263

3.1.2 Median method

A statistical method, based on the median of the observed distribution, known as the median method [10], was used to estimate critical headway. This method assumes that the best estimate of critical headway for each driver is the average of the largest rejected headway and the accepted headway.

The value of critical headway thus obtained for each driver was recorded in size classes of 0.5 seconds. In this way, a histogram was constructed: the x-axis contains the classes of critical headways and the y-axis reports the frequencies. Therefore, the class containing the median of the distribution was determined; finally, the critical headway of the sample was estimated within this class, assuming a linear trend. Results of the critical headway measurements of all the sites are summarized in Tables 8 and 9.

The critical headways for the four single-lane sites obtained by this method varies between 3.58 and 3.97 s with a mean value of 3.86 s, while the critical headways of all the multilane sites for the left lane varies between 3.64 and 4.18 s with a mean value of 3.84 s and the critical headway for the right lane varies between 3.23 s and 4.35 s with a mean value of 3.74 s.

3.1.3 Raff's method

A graphical method, based on the Raff's definition [11], or Raff's method, was used to estimate critical headway. The concept of critical gap was used by Raff, who defined it as the gap that has the number of accepted shorter gaps equal to

the number of longer rejected gaps. Using this graphical method, two cumulative distribution curves are drawn: one of them relates gap lengths t with the number of accepted gaps less than t and the other relates t with the number of rejected gaps greater than t. The intersection of these two curves gives the value of t for the critical gap [12]. For each observed approach, the two cumulative distribution curves are constructed. At the intersection point, each curve is a linear segment the curve is comprised of discrete points. Next, the equations of the segments that intersect are determined and the system of the equations is solved. Therefore, the value of critical headway represented by the intersection point may be determined. Results of critical headway measurements of all the sites are summarized in Table 4 and Table 5.

Critical headways for the four single-lane sites obtained by this method vary between 3.28 and 3.72 s with a mean value of 3.50 s, while critical headways of all the multilane sites for the left lane vary between 3.29 and 3.86 s with a mean value of 3.55 s and critical headway for the right lane varies between 2.82 s and 4.12 with a mean value of 3.38 s.

3.1.4 Comparison with three methods

The results obtained by the three methods for all sites show little variation. Critical headway determined by the maximum likelihood methodology and the median method are most similar, while the values produced by the Raff's method are systematically lower (as seen for example in Figure 1, relative to single-lane roundabouts).
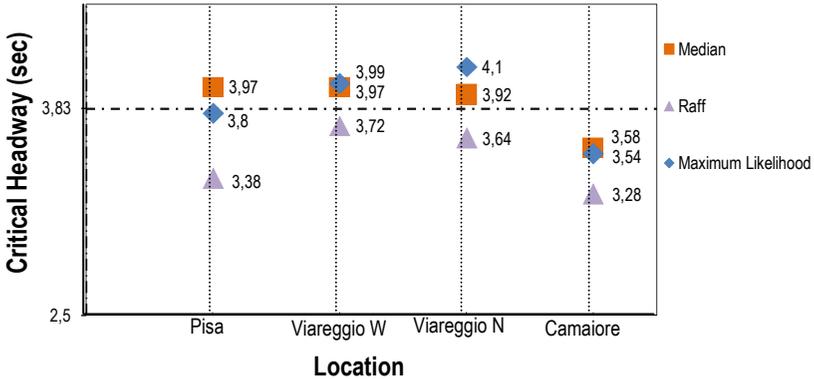
Figure 1:   Results for each estimation method: comparison.

The development of the median method was easier and faster than the maximum likelihood methodology, while producing quite similar results. Such trend of the median method shall be also checked in the further steps of this research project.

Tables 4 and 5 show the comparison between the results respectively obtained for each observed location in respect to the three estimation methods.

For single-lane roundabouts, critical headways estimated by the median method differ from corresponding values obtained by maximum likelihood by

−4.39% to +4.47%, while the values obtained by Raff's method are lower and differ by −6.67% to −11.22% (see Table 4). In the case of multilane roundabouts, critical headways estimated by the median method differ from corresponding values obtained by maximum likelihood by a percentage of −5.43% to +1.95% for the left lane, and by −3.38% to +5.90% for right lane. The values obtained by Raff's method are lower and differ by −5.68% to −12.67% for the left lane, and by −4.85% to +11.60% for the right lane (see Table 5).

Table 4:   Critical headway results at single lane roundabout: comparison.

Critical headway (s) – Single lane						
Location	Median	Likelihood	%	Raff	Likelihood	%
Pisa	3.97	3.80	+4.47	3.38	3.80	−11.05
Viareggio W	3.97	3.99	−0.50	3.72	3.99	−6.77
Viareggio N	3.92	4.10	−4.39	3.64	4.10	−11.22
Camaiore	3.58	3.54	+1.13	3.68	3.54	−7.34

Table 5:   Critical headway results at multi lane roundabout: comparison.

Critical headway (s) – Left lane						
Location	Median	Likelihood	%	Raff	Likelihood	%
Massa	4.00	4.05	−1.23	3.82	4.05	−5.68
Pietrasanta	3.66	3.59	+1.95	3.29	3.59	−8.36
Carrara	4.18	4.42	−5.43	3.86	4.42	−12.67
Lucca N	3.64	3.71	−1.89	3.41	3.71	−8.09
Lucca W	3.73	3.71	+0.54	3.36	3.71	−9.43
Critical headway (s) – Right lane						
Location	Median	Likelihood	%	Raff	Likelihood	%
Massa	4.35	4.33	+0.46	4.12	4.33	−4.85
Pietrasanta	3.64	3.50	+4.00	3.15	3.50	−10.00
Carrara	3.72	3.85	−3.38	3.50	3.85	−9.09
Lucca N	3.77	3.56	+5.90	3.29	3.56	−7.58
Lucca W	3.23	3.19	+1.25	2.82	3.19	−11.60

3.2 Follow-up headway

Follow-up headway is the minimum headway between two entering vehicles, which can be calculated by the average difference between the passage times of two entering vehicles accepting the same mainstream gap under a queued condition [2]. Follow-up headways were computed from recorded time events. Once the individual follow up headway was obtained, the mean and standard deviation were calculated. Table 6 summarizes critical headway results for the four single-lane locations. As can be seen, the follow-up headway varies between 2.52 and 2.76 s with a mean value of 2.63 s. Results of the follow-up headway measurements of all the multilane sites are summarized in Table 7. It can be seen that the follow-up headway for the left lane varies between 2.16 and 3.10 s with a mean value of 2.65 s and the follow-up headway for the right lane ranges between 2.44 s and 2.91 with a mean value of 2.64 s. The mean value obtained for the follow-up headways in both lanes is almost the same.

Table 6:   Follow-up headway results at single lane roundabout locations.

Follow-up Headway (s)			
Location	*Mean (s)*	*Standard Deviation (s)*	*Sample Size*
Pisa	2.59	0.90	500
Viareggio - West	2.65	0.69	155
Viareggio - North	2.76	0.68	190
Camaiore	2.52	0.80	226
Average	2.63	0.77	Total = 1071

Table 7:   Follow-up headway results at multi lane roundabout locations.

Follow-up Headway (s)				
Location	*Lane*	*Mean (s)*	*Standard Deviation (s)*	*Sample Size*
Massa	Left	3.10	0.95	145
	Right	2.70	0.71	205
Pietrasanta	Left	2.16	0.49	57
	Right	2.44	0.58	29
Carrara	Left	2.77	0.72	59
	Right	2.91	0.76	143
Lucca - North	Left	2.66	0.61	82
	Right	2.58	0.61	87
Lucca - East	Left	2.56	0.66	124
	Right	2.59	0.69	92
Average	Left	2.65	0.69	Total L. = 467
	Right	2.64	0.67	Total R. = 556

4   First experimental results

The results obtained through the three estimation methods for all sites show little differences. The maximum likelihood method has been also previously applied by several authors, and these values are herewith considered for later comparisons. Therefore, our average critical headway obtained by the maximum likelihood method was compared to such international referenced values.

The first experimental results for critical headway are summarized as follows. For single-lane roundabout, critical headway ranges between 3.54 and 4.10 s with a mean of 3.86 s and with an average weighted on the inverse of the standard deviation of 3.83 s. In the case of multilane roundabout, the critical headway obtained for left lane varies between 3.59 and 4.42 s with a mean of 3.90 s and with an average weighted on the inverse of the standard deviation of 3.85 s; while, critical headway obtained for right lane varies between 3.19 and 4.33 s with a mean of 3.69 s and with an average weighted on the inverse of the standard deviation of 3.64 s. The weighted average was calculated in function of the inverse of the standard deviation so that the smaller values of the standard deviation carry the same weight as larger values. Moreover, as the average critical headway and weighted average critical headway are quite similar.

Therefore, the average critical headway was assumed equal to the weighted average critical headway. The average critical headway for each type of lane is summarized in Table 8. The first experimental results for follow-up headway are summarized as follows. For single-lane roundabouts, the follow-up headway obtained ranges between 2.52 and 2.76 s with a mean of 2.63 s and with an average weighted on the inverse of the standard deviation of 2.64 s. In the case of multilane roundabout, critical headway obtained for left lane varies between 2.16 and 3.10 s with a mean of 2.65 s and with an average weighted on the inverse of the standard deviation of 2.59 s. While, critical headway obtained for right lane varies between 2.44 and 2.91 s with a mean of 2.64 s and with an average weighted on the inverse of the standard deviation of 2.63 s. Also in this case, the weighted average was calculated in function of the inverse of the standard deviation for the same reason as explained above. Moreover, the average follow-up headway and weighted average follow-up headway are much similar. Therefore, the average follow-up headway for this study was assumed equal to the weighted average follow-up headway. The average follow-up headway for each type of lane is summarized in Table 8.

Table 8:   Average critical headway and average follow-up headway.

Average critical headway (s)					
Roundabout		North Tuscany		California	
		Mean (s)	Standard deviation (s)	Mean (s)	Standard deviation (s)
Single-lane	single	3.83	0.40	4.85	0.40
Multilane	Left	3.85	0.36	4.74	0.59
	Right	3.64	0.35	4.46	0.57
Average follow-up headway (s)					
Roundabout		North Tuscany		California	
		Mean (s)	Standard deviation (s)	Mean (s)	Standard deviation (s)
Single-lane	single	2.64	0.38	2.45	0.21
Multilane	Left	2.59	0.29	2.20	0.41
	Right	2.63	0.30	2.16	0.48

4.1 Comparison with previous studies

In the following, the average critical headway and the average follow-up headway obtained in Tuscany were compared with the values from previous international studies. Initially, a direct comparison was carried out between this study and the similar work conducted for State of California, by Xu and Tian [2]. Then, comparisons were made between the headway results from this research and those from some international references, such as HCM2010 [1] default capacity model, NCHRP 572 [3], and Xu and Tian [2]. Finally, a comparison of the capacity model calibration by these different studies was carried out in order to evaluate the differences in capacity calculations at roundabouts.

4.1.1 Comparison with the study in California

The experimental results of this study were been analyzed and compared to the California values [2].

Table 8 summarizes the final results for these different sources. The following observations can therefore be made:

-   the average critical headway of North Tuscany's sites is always smaller than the average critical headway obtained in California, for each lane;
-   the average follow up headway of North Tuscany's sites, instead, is always larger than the average follow up headway obtained in California, for each lane.

4.1.2 Comparison with previous studies

The results of this study have been analysed and compared with data from previous international references. Table 9 summarizes the values drawn from these different references. Based on the results, the following observations may be made:

-   the average critical headway of North Tuscany's locations is always smaller than the average critical headway values drawn from international references;
-   the average follow-up headway of North Tuscany's locations, also, is always smaller than the average follow-up headway suggested by HCM2010 and NCHRP 572, for each lane, but it is larger than the average follow-up headway referred to California, for each lane.

Table 9:   International references comparison.

Average critical headway (s)			
Lane	single	left	right
HCM 2010	5.19	4.29	4.11
NCHRP 572	5.10	4.50	4.20
California	4.90	4.80	4.40
North Tuscany	3.83	3.85	3.64
Average follow-up headway (s)			
Lane	single	left	right
HCM 2010	3.20	3.20	3.20
NCHRP 572	3.20	3.40	3.10
California	2.50	2.30	2.20
North Tuscany	2.63	2.65	2.64

4.2 HCM 2010 capacity model calibration

Local calibration of the capacity models is recommended to best reflect local driver behaviour [13]. The HCM2010 capacity model was calibrated by using specific data for critical headway and follow up headway. Mathematical forms of the capacity model and their related parameters estimates, for each lane, are shown in Table 10.

One can observe that models resulting from the use of California-specific data and Northern Tuscany-specific data for critical headway and follow-up headway

Table 10:   HCM 2010 capacity model.

	t_f (s)	t_c (s)	A	B	C_e (pc/h)
HCM 2010 capacity model					
Single lane roundabout					
HCM 2010	3.19	5.19	1130	0.001	$1130*exp((-1*10^{-3})*V_c)$
NCHRP 572	3.20	5.10	1125	0.000972	$1125*exp((-0.972*10^{-3})*V_c)$
California	2.50	4.90	1440	0.00101	$1440*exp((-1.01*10^{-3})*V_c)$
North Tuscany	2.64	3.83	1364	0.00070	$1364*exp((-0.70*10^{-3})*V_c)$
Left lane roundabout					
HCM 2010	3.19	4.29	1130	0.00075	$1130*exp((-0.75*10^{-3})*V_c)$
NCHRP 572	3.40	4.50	1059	0.000778	$1059*exp((-0.778*10^{-3})*V_c)$
California	2.30	4.80	1565	0.001014	$1565*exp((-1.014*10^{-3})*V_c)$
North Tuscany	2.59	3.85	1390	0.000710	$1390*exp((-0.70*10^{-3})*V_c)$
Right lane roundabout					
HCM 2010	3.19	4.11	1130	0.0007	$1130*exp((-0.7*10^{-3})*V_c)$
NCHRP 572	3.10	4.20	1161	0.000736	$1161*exp((-0.736*10^{-3})*V_c)$
California	2.20	4.40	1636	0.000917	$1636*exp((-0.917*10^{-3})*V_c)$
North Tuscany	2.63	3.64	1369	0.000646	$1369*exp((-0.646*10^{-3})*V_c)$

have a higher intercept, and thus a higher capacity, over their whole range when compared with any of the models based on international references.

Figure 2 shows the trend of several capacity models in the case of single lane-roundabout.
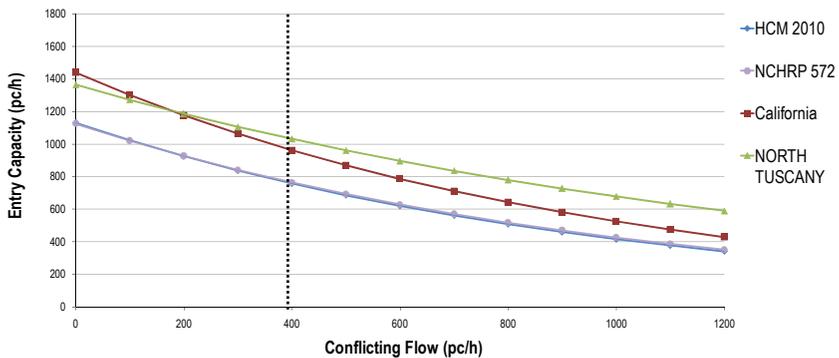

Figure 2:   HCM2010 roundabout capacity model calibration: single lane.

The Northern Tuscany model provides values of roundabout capacity greater than those provides by HCM2010 capacity model: for example, considering a conflicting flow amounting to 400 pc/h, the capacity is between +23.80% and +36.10% greater (see Table 11).

5   Further research

These first experimental results confirm that critical headway and follow-up headway are heavily influenced by driver behaviour and local habits. Moreover,

Table 11:   HCM2010 vs. other studies: capacity.

Capacity(pc/h)			
Conflicting flow = 400 pc/h			
Lane	single	left	right
HCM 2010	757	837	854
NCHRP 572	763 (+0.68%)	776 (−7.33%)	865 (+1.27%)
California	961 (+26.92%)	1043 (+24.62%)	1134 (+32.74%)
North Tuscany	1031 (+36.10%)	1046 (+24.99%)	1057 (+23.80%)

the highlighted differences between Tuscany (Italy) and the United States requires further field observations, to account for a wider range of local site conditions in order to improve the capacity model calibration, as recommended to by HCM2010. The median method is easier and faster than the maximum likelihood method while producing quite similar results. Such trend shall be checked in further research developments. Finally, as actual behaviour of entering drivers may be influenced by the presence of heavy/longer vehicles, this issue should be studied in depth. Next research steps will concern with both extension of sample data, and application of simulation approach.

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