# ESTIMATING AND UPDATING GAP ACCEPTANCE PARAMETERS FOR HCM6TH ROUNDABOUT CAPACITY MODEL APPLICATIONS

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ABSTRACT
This paper treats on-field observing data and then applying estimation procedures to estimate follow-up headway and critical headway at roundabouts. The theory of gap acceptance constitutes the attempt to faithfully represent the behavior of users at non-traffic light intersections. The follow-up headway and critical headway are two critical parameters of the roundabout capacity model illustrated in the 6th edition of Highway Capacity Manual (HCM6th). The capacity model was developed as an exponential regression model and is strongly influenced by driver behavior and local habits. This paper, therefore, aims at verifying whether the suggested general values are also suitable for Italy. The follow-up headway can be measured on-field, while the critical headway cannot be obtained directly, in fact numerous studies and techniques have been developed for its estimation. The most popular ones are the Maximum Likelihood method, the Raff method and the Median method. The latter has been chosen as the calculation method, since it is the one that is more frequently used and is considered both the simplest and characterized by an acceptable approximation threshold. This method requires information on the accepted headway and the major rejected headway for each driver, therefore, a sample of data was recorded on-field with a digital camera and then processed. Sample data of the critical headway and of the subsequent headway were collected for three carefully selected roundabouts in the province of Lucca, Tuscany (Italy). As a check, it was verified that the values of the critical headway and of the follow-up headway calculated were comparable to those obtained from the analysis carried out in Tuscany in 2012. Finally, a comparison has made between the default values of HCM6th and our firstly obtained results indicated that the average critical headway was significantly lower than the recommended values. Insights for further research developments are suggested in the conclusions.
*Keywords: gap acceptance theory, critical headway, follow-up headway, HCM6th, roundabout capacity model, median method.*

## 1 INTRODUCTION

The Highway Capacity Manual 2010 roundabout capacity model (HCM 2010) [1] was developed as an exponential regression model with parameter estimates based on gap acceptance theory. Later this model was updated and further illustrated in the 6th edition of the Highway Capacity Manual (HCM6th) [2].

Gap acceptance models are strongly affected by driver behavior and local habits. Therefore, the HCM6th capacity model should be calibrated to local conditions. Two parameters that may be changed to reflect local driving behavior are the critical headway and follow-up headway (referred to as critical gap and follow-up time in earlier studies [3]). 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 [4].

Its recommended operational models were incorporated into the 6th edition of HCM. The purpose of this research project is to test the adaptability of the HCM6th capacity model in Tuscany (Italy). To achieve this goal, we collected local gap acceptance data.

 
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The first step of this research project was related to the local data collection. Therefore, the study was conducted at three selected roundabouts located in the province of Lucca in Tuscany (Italy), collecting and analysing a field data sample. The follow-up headway can be measured on-field, while the critical headway cannot be obtained directly, in fact, numerous studies and techniques have been developed for its estimation. The most popular ones are the Maximum Likelihood method, the Raff method and the Median method [5].

The latter has been chosen as the calculation method, since it is the one that is most frequently used and is considered both the simplest and characterized by an acceptable approximation threshold [6]. This paper shows the results of such study, which can be considered as the continuation of the previous research, in fact, we also verified that the values of the critical headway and of the follow-up headway calculated are comparable to those obtained from the analysis carried out in Tuscany in 2012 [7].

## 2 DATA COLLECTION AND EXTRACTION

Data collection was carried out on three existing roundabouts using digital video cameras SONY DCR-SX34 placed at specific points of the roundabout intersections during weekday peak periods (Fig. 1) Flows of vehicles circulating in the ring and entering in the roundabout were recorded when high traffic volumes were actually observed.

Figure 1: Measurement station with Sony DCR-SX34 video camera.

A continuous queue at 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 the position of the roundabouts respect to the city of Lucca in order to measure headways related to different areas. As can be seen in Fig. 2 the selected roundabouts are located at:

- Porta Santa Maria;
- Porta Elisa;
- Piazzale Boccherini.


Figure 2: The three selected roundabouts in Lucca. *(Source: http://www.pacinifazzi.it.)*

As we can find in other studies [3], [4], [7], we made the following assumption: the conflicting flow was assumed unique and was not considered separately for each lane in the ring; in fact, experimental observations at multi-lane roundabout have shown that drivers are conditioned by the conflicting flow of both lanes in the ring. Headway data were extracted later from the recorded videos. For each entry, we first defined the finish lines:

- "s" as conflict section;
- "i" as entrance section;
- "u" as exit section.

Then three times events were recorded: the time at which an entering vehicle stopped at the stop line, the passage times of circulating vehicles that going directly conflicted with the entering vehicle, and the time when the entering vehicle left the stop line [8]. 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 Report 572, has used in this paper [4].

The procedure for extracting video data required the following steps: display the movie using the VLC media 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.

## 3 DATA ANALYSIS

Accepted headways, maximum rejected headways and follow-up headways were calculated in the worksheet. The headways were determined through VLC Media Player™ software, by counting frames between successive vehicles (25 frames per second, for EU standards). Next, the Median method has been used as the calculation method to estimate critical headways. Finally, the follow-up headways have computed directly from the observed values.

### 3.1 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 gap under a condition of the queue [3].

Follow-up headways were computed from the recorded time events. Once all the individual follow-up headways were obtained, the average and the standard deviation were calculated. Table 1 summarizes the follow-up headway averages for the seven entrance branches of the three roundabouts. Instead, Table 2 summarizes the follow-up headway standard deviations for the seven entrance branches of the three roundabouts.

Table 1: The follow-up headway averages.

| Roundabout site | The follow-up headway averages (s) | | | | | |
|---|---|---|---|---|---|---|
| | Entrance 1 | | Entrance 2 | | Entrance 3 | |
| | Left | Right | Left | Right | Left | Right |
| Porta Santa Maria | 2.55 | 2.49 | / | / | / | / |
| Porta Elisa | 2.53 | 2.44 | 2.51 | 2.39 | 2.40 | 2.60 |
| Piazzale Boccherini | 2.47 | 2.60 | 2.52 | 2.61 | 2.54 | 2.47 |

Table 2: The follow-up headway standard deviations.

| Roundabout site | The follow-up headway standard deviations (s) | | | | | |
|---|---|---|---|---|---|---|
| | Entrance 1 | | Entrance 2 | | Entrance 3 | |
| | Left | Right | Left | Right | Left | Right |
| Porta Santa Maria | 0.58 | 0.61 | / | / | / | / |
| Porta Elisa | 0.54 | 0.56 | 0.59 | 0.55 | 0.53 | 0.58 |
| Piazzale Boccherini | 0.58 | 0.61 | 0.53 | 0.63 | 0.52 | 0.61 |

As we can see from the tables, as regards Porta Santa Maria roundabout only one entrance was considered, while for those of Porta Elisa and Piazzale Boccherini three entrances were considered. Furthermore, since each entry, of all the seven branches under study, was a two-lane entry, the distinction was made between the right lane and the left lane.

### 3.2 Critical headway

Critical headway represents the minimum time interval in the circulating flow when an entering vehicle can safely enter a roundabout [3]. In general, the critical headway is a parameter that depends on local conditions such as geometric layout, driver behavior, vehicle characteristics, and traffic conditions [9]. However, the critical headway unlike follow-up headway cannot be measured directly in the field or from recorded events. Hence, numerous studies and techniques have been developed for estimating critical headway.

The most popular ones are the Maximum Likelihood method, the Raff method and the Median method [5]. The latter has been chosen as the calculation method, since it is the one that is most frequently used and is considered both the simplest and characterized by an acceptable approximation threshold [6].

This method, like the others, require information about the accepted headway and the largest rejected headway for each driver. The rejected and the accepted headways were being enumerated within the Excel worksheet.

The Median method is a statistical method, based on the median of the observed distribution, that was used to estimate critical headway. This method assumes that the best estimate of critical headway for each driver is the average between 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 s. This way, a histogram has depicted, where the $x$-axis contains the classes of critical headways and the $y$-axis reports the frequencies (in percentage).

Therefore, the class containing the median of the distribution was determined and at the end, the critical headway of the sample was estimated within this class, assuming a linear trend. An amount of 979 drivers was analyzed to calculate the critical headway of left and right lanes of the seven entrance branches of the three roundabouts. The obtained results of the critical headway measurements of all the sampled sites are summarized in Table 3.

Table 3: Observed critical headway values.

| Roundabout site | Critical headway (s) | | | | | |
|---|---|---|---|---|---|---|
| | Entrance 1 | | Entrance 2 | | Entrance 3 | |
| | Left | Right | Left | Right | Left | Right |
| Porta Santa Maria | 3.70 | 3.79 | / | / | / | / |
| Porta Elisa | 3.72 | 3.69 | 3.71 | 3.36 | 3.78 | 3.72 |
| Piazzale Boccherini | 3.77 | 3.60 | 3.76 | 3.58 | 3.82 | 3.63 |

As an example, the calculation of the critical headway of the left lane of branch n. 1 of Porta Elisa roundabout is shown. The following is reported: an extract of first 10 rows of the excel table containing 72 rows, one row for each one of the observed vehicles traversing the studied entrance, its largest rejected interval, its accepted interval and the average between them (Table 4); the histogram containing the classes of the critical headway and the frequencies in percentage (Fig. 3).

To estimate the critical headway, first of all the sum of the percentages of classes 2.5, 3.0 and 3.5 was calculated (34.72%) to find the remaining percentage to reach 50% (15.28%). Hence, we evenly distributed the 0.5 s in the 4.0 class by dividing 0.5 by the percentage frequency 34.72 and obtaining 0.0144. Finally, we have multiplied the percentage 15.28% by 0.0144 and we have obtained 0.22 s, which is the period to add to the previous class 3.5 s to obtain the critical headway in this specific case (3.72 s).

## 4 RESULTS OF THE EXPERIMENTS

The experimental results for follow-up headway are summarized as follows. Follow-up headways averages range between 2.39 s and 2.61 s with a mean of 2.50 s. If we made the

Table 4: Extract (first 10 rows) of the 72 rows critical headway worksheet.

| Vehicles | Largest rejected headway | Accepted headway | Average |
|---|---|---|---|
| 1 | 2.9 | 6.2 | 4.55 |
| 2 | 2.4 | 6.4 | 4.40 |
| 3 | 3.0 | 6.0 | 4.50 |
| 4 | 3.9 | 3.2 | 3.55 |
| 5 | 2.2 | 3.5 | 2.85 |
| 6 | 1.5 | 3.6 | 2.55 |
| 7 | 1.3 | 6.7 | 4.00 |
| 8 | 2.4 | 5.4 | 3.90 |
| 9 | 1.6 | 3.0 | 2.30 |
| 10 | 1.8 | 3.9 | 2.85 |

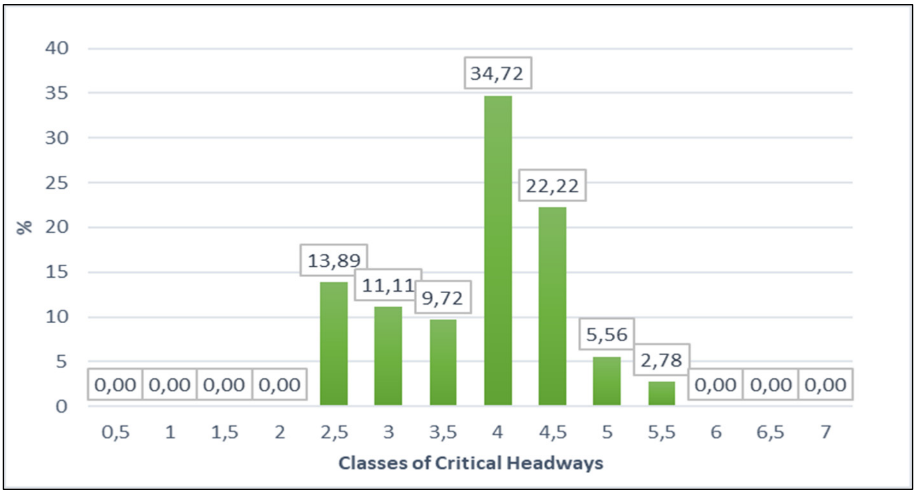


Figure 3: One of the experimental histograms.

distinction between the right lane and the left lane, the values are closer. In fact, for the left lane only, the follow-up headway averages vary between 2.40 s and 2.55 s with an average of 2.48 s; while for the right lane only, the follow-up headway varies between 2.39 s and 2.61 s with an average of 2.50 s.

The values of the average follow-up headway for each type of lane for the three roundabouts are summarized in Table 1. Regarding follow-up headways standard deviations ranges between 0.52 s and 0.63 s with a mean of 0.58 s. Also in this case, if we made the distinction between the right lane and the left lane, the values are closer. In fact, for the left lane only, the follow-up headway standard deviations varies between 0.52 s and 0.59 s with an average of 0.56 s; while for the right lane only, the follow-up headway varies between 0.55 s and 0.61 s with an average of 0.58 s.

The values of the standard deviation follow-up headway for each type of lane for the three roundabouts are summarized in Table 2. The experimental results obtained through the Median method for critical headway are summarized as follows. Critical headway ranges between 3.36 s and 3.82 s with a mean of 3.59 s. If we made the distinction between the right lane and the left lane, the values are closer. In fact, for the left lane only, the critical headway varies between 3.70 s and 3.82 s with an average of 3.76 s; while for the right lane only, the critical headway varies between 3.36 s and 3.79 s with an average of 3.58 s. The values of the average critical headway for each type of are summarized in Table 3.

### 4.1 Comparison with previous studies

In the following, the average critical headway and the average follow-up headway obtained in 2020 in Tuscany were compared with the values from previous studies. Initially, a direct comparison was carried out between this study and the similar work conducted in 2012, always for Tuscany, by Gazzarri et al. [7]. In that research it had already been done a comparison between their headway results and those from some international references, such as HCM2010 [1] default capacity model, NCHRP Report 572 [4] and Xu and Tian [3] (work conducted in 2008 for the State of California). Then, comparisons were made between the headway results from this research and the default data of HCM6th that is the international reference [2].

Table 5 shows the comparison between the critical headway of HCM6th, Tuscany 2012 and Lucca 2020. Table 6 shows the comparison between the follow-up headway of HCM6th, Tuscany 2012 and Lucca 2020. Finally, a comparison of the capacity model calibration by these different studies was carried out to evaluate the differences in capacity calculations at roundabouts.

Table 5: Critical headway comparison.

| Average critical headway (s) | |
|---|---|
| HCM6th (2016) | 4.29 |
| Tuscany 2012 | 3.69 |
| Lucca 2020 | 3.59 |

Table 6: Follow-up headway comparison.

| Average follow-up headway (s) | |
|---|---|
| HCM6th (2016) | 3.19 |
| Tuscany 2012 | 2.59 |
| Lucca 2020 | 2.50 |

### 4.2 HCM6th capacity model calibration

Local calibration of the capacity models is recommended to best reflect local driver behavior. [2] The HCM6th capacity model was calibrated by using specific data for critical headway and follow up headway. The estimates parameters *A* and *B* are shown in Table 7.

Table 7: Parameters *A* and *B* estimates.

| | $t_c$ (s) | $t_f$ (s) | $A = 3{,}600/t_f$ | $B = (t_c - 0.5\ t_f)/3{,}600$ |
|---|---|---|---|---|
| HCM6th (2016) | 4.29 | 3.19 | 1,128 | 0.00075 |
| Tuscany 2012 | 3.69 | 2.59 | 1,390 | 0.00067 |
| Lucca 2020 | 3.59 | 2.50 | 1,440 | 0.00065 |

The HCM6th capacity formula is a function of the parameters *A* and *B* and of the circulating flow *Qc*. A table was built with its relative graph (Fig. 4), where, as *Qc* varies, it is possible to obtain the capacity *Ce* of the entrance, using the parameters *A* and *B* of the HCM6th [2], of Tuscany 2012 [7] and of Lucca 2020. The circulating flow *Qc* was made to vary between 0 pc/h and 1,200 pc/h (Table 8).

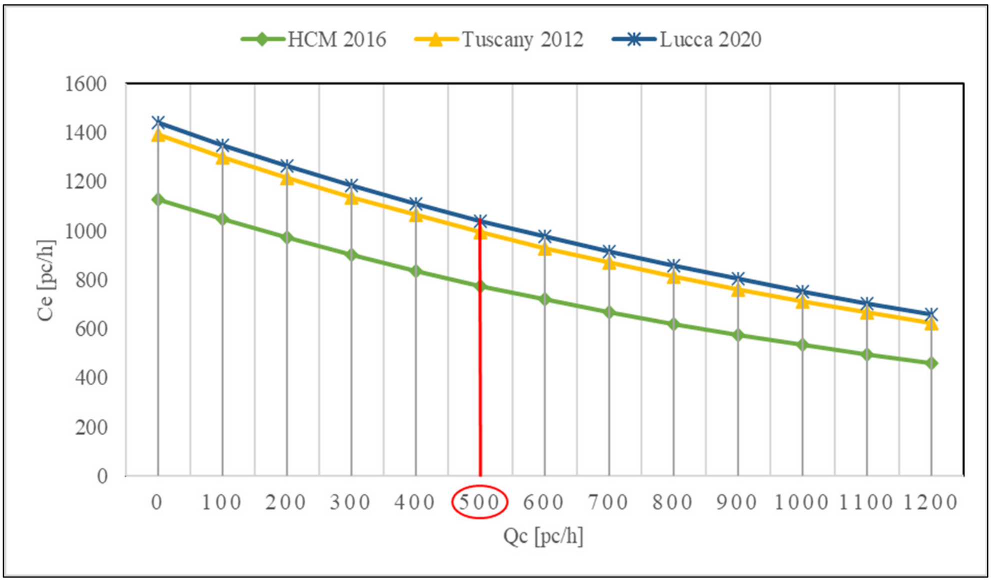


Figure 4: HCM6th roundabout capacity model calibration.

Table 8: Calculation *Ce* as *Qc* varies.

| *Ce = A^(-B·Qc)* | HCM6th (2016) | | Tuscany 2012 | | Lucca 2020 | |
|---|---|---|---|---|---|---|
| *Qc* (pc/h) | *A* | 1,128 | *A* | 1,390 | *A* | 1,440 |
| | *B* | 0.00075 | *B* | 0.00067 | *B* | 0.00065 |
| 0 | 1,128 | | 1,390 | | 1,440 | |
| 100 | 1,046 | | 1,300 | | 1,349 | |
| 200 | 971 | | 1,216 | | 1,264 | |
| 300 | 901 | | 1,137 | | 1,185 | |
| 400 | 836 | | 1,063 | | 1,110 | |
| 500 | 775 | | 994 | | 1,040 | |
| 600 | 719 | | 930 | | 975 | |
| 700 | 667 | | 870 | | 914 | |
| 800 | 619 | | 813 | | 856 | |
| 900 | 574 | | 761 | | 802 | |
| 1,000 | 533 | | 711 | | 752 | |
| 1,100 | 494 | | 665 | | 704 | |
| 1,200 | 459 | | 622 | | 660 | |

One can observe that models resulting from the use of Lucca specific data and Tuscany specific data for critical headway and follow-up headway have a higher intercept, and thus a higher capacity, over their whole range when compared with HCM6th model. Fig. 4 shows the trend of several capacity models. The "Lucca model" provides values of roundabout capacity significantly greater than those provides by HCM6th capacity model [2]: for example, considering a conflicting flow amounting to 500 pc/h, the capacity is +34.20% greater (Table 9).

Table 9: Percentage difference.

| Capacity *Ce* (pc/h) | |
|---|---|
| Conflicting flow *Qc* = 500 pc/h | |
| HCM6th (2016) | 775 |
| Tuscany 2012 | 994 (+28.26%) |
| Lucca 2020 | 1,040 (+34.20%) |

## 5 FURTHER RESEARCH

An observation that is easily understood is that the critical headway is not only variable from driver to driver, but the same individual may behave differently according of several factors. Furthermore, apparently irrational behavior by several drivers must be considered: some of their after refusing intervals of a given width, they accepted one of width inferior [10]. This attitude is called "inconsistency" and is probably realized when the user has been stationary at the intersection for a long time. This phenomenon is observable in the obtained data.

The continuous research and eventual updates of the critical headway and the follow-up headway are of fundamental importance, since the accuracy of capacity calculations for roundabout branches largely depends on the estimate of these two parameters that reflect the local driving behavior.

This research can be considered the natural continuation of the studies done in Tuscany in 2012 [7]. As with the previous study, these experimental results confirm that critical headway and follow-up headway are heavily influenced by driver behavior and local habits. The differences highlighted in the previous research between Tuscany (Italy) and the United States required further observations on the ground; then this research can be used as further confirmation of the results obtained. Anyway, the highlighted differences between Lucca and in general Tuscany (Italy) and the United States requires further field observations, to account for a wider range of local site conditions to improve the capacity model calibration. The median method is easier and faster than the other methods and it produces quite similar results, therefore it is the best to use also in future research.

Finally, as actual behavior of entering drivers may be influenced by the presence of heavy vehicles, this issue should be studied. Further next research steps will concern with both extensions of sample data, and application of simulation approach.

The experimental findings of this research work addressed to experimentally derive the roundabout model parameter values can be viewed as a practical design reference, which is useful both for the City of Lucca Technical Bureau, and for any other location in Tuscany.

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