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A method for estimating pedestrian critical gap using microsimulation

Método para estimação da brecha crítica de pedestres usando microssimulação

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ABSTRACT
Estimating critical gap is crucial for modelling pedestrian level of service at crossings. Critical gap modelling becomes more challenging in signalized crossings because the proportion of pedestrians seeking gaps during red is usually unknown. Besides, the willingness – or lack of it – to cross during red signal indication varies by pedestrian and local characteristics, which makes gap acceptance modelling even more challenging. The main objective of this study is to propose a method for estimating pedestrian critical gap at signalized crossings using Vissim. The method considers that all pedestrians seek for gaps on red, and the critical gap parameter is calibrated for each pedestrian type having delay as calibration target. The results showed MAPE values of 2% and 9% for the two studied crossings. This method was compared to three existing methods of critical gap estimation. The results showed that the proposed method yielded the best estimations of delay, followed by the HCM's.

RESUMO
Estimar a brecha crítica é crucial para modelar o nível de serviço de pedestres em cruzamentos. Modelar brechas críticas em travessias semaforizadas é ainda mais desafiador, pois a proporção de pedestres procurando brechas durante o vermelho geralmente é desconhecida. Além disso, a disposição ou não de atravessar a rua durante o sinal vermelho varia de acordo com as características do pedestre e do local, tornando a modelagem da aceitação de brechas ainda mais desafiadora. O objetivo principal deste estudo é propor um método para estimar a brecha crítica de pedestres em travessias semaforizadas usando o VISSIM. O método considera que todos os pedestres buscam brechas no vermelho e o parâmetro de brecha crítica é calibrado para cada tipo de pedestre, tendo o atraso como alvo da calibração. Os resultados mostraram valores de EPAM de 2% e 9% para os dois cruzamentos estudados. Este método foi comparado a três métodos existentes de estimativa de brechas críticas. Os resultados mostraram que o método proposto gerou as melhores estimativas de atraso, seguido do método do HCM.

1. INTRODUCTION

Understanding pedestrian behavior is essential for developing and implement policies and projects that foster the urban environment diversity. One of the most important pedestrian behaviors to be considered is gap acceptance, in which the pedestrian seeks for an acceptable gap to cross the street. In gap acceptance models, critical gap is a key parameter.

Estimating critical gap correctly is crucial to model pedestrian level of service at crossings. Underestimated values of this parameter will lead to underestimated pedestrian delays, as pedestrians in the model will accept smaller gaps. Conversely, overestimated critical gap values will result in overestimated pedestrian delays.

In signalized crossings, pedestrians are not supposed to seek for gaps because their right of way is controlled by the signal phases. However, many pedestrians do look for gaps to cross during red (*don't walk* and *flashing don't walk* signal indications), which makes critical gap a parameter necessary to be incorporated in the model. A pedestrian who seeks for gaps during red, so called *opportunist* (Suh *et al.* ,2013), is also known as a *violator* (Dommes *et al.,* 2015) if he/she gets to cross during red.

Critical gap modelling becomes more challenging in signalized crossings because the proportion of pedestrians seeking for gaps during red is usually unknown. One can never know precisely if a pedestrian who did not violate the red did not intend to cross or if he/she could not find an acceptable gap. Besides, the willingness – or lack of it – to cross during red varies by pedestrian and local characteristics, which makes the gap acceptance modelling even more challenging.

These difficulties in critical gap modelling can be mitigated with the aid of traffic microsimulation tools, such as VISSIM. Such tools provide modelling of detailed behavior of different road users and their interactions. They are useful to estimate parameters that are difficult to observe in the field, such as pedestrian critical gap.

In this context, the main objective of this paper is to propose a method for estimating pedestrian critical gap using microscopic simulation. The proposed method was compared to three known methods for estimating critical gap, proposed by the Highway Capacity Manual 2010 - HCM (T'RB, 2010), Chandra *et al*. (2014), and Raff and Hart (1950).

The remaining of this manuscript is organized as follows. Section 2 presents a summary of the literature review on pedestrian gap acceptance, focusing on three topics: opportunistic behavior; modelling in VISSIM; and existing models for critical gap estimation. Section 3 explains the research method, which is divided in four subsections: data collection; vehicle simulation; pedestrian simulation; and model evaluation. Section 4 shows the results, and finally, section 5 provides the discussion and concluding remarks.

2. LITERATURE REVIEW

This section brings the most relevant studies on three topics: opportunist behavior of pedestrians; pedestrian gap acceptance in VISSIM; and the three existing methods that were used to compare with our approach.

2.1. Red signal violation by pedestrians

Pedestrian delay is an important measure of effectiveness (MOE) of signalized pedestrian crossings, as it represents the level of discomfort experienced by pedestrians. It is defined as the time a pedestrian awaits before he/she starts crossing the street HCM (T'RB, 2010). Delay may be influenced by several factors such as pedestrian age and gender (Guo *et al.*, 2011), vehicular flow (Marisamynathan and Vedagiri, 2017), and pedestrian compliance to red signal (Virkler, 1998).

Pedestrian violation of the red signal indication reduces delay because pedestrians anticipate their crossing, which reduces waiting times. TRB (2010) suggests that pedestrians who are subjected to delays greater than 30 s are more prone to violate, as they become impatient, whereas pedestrians who wait less than 10 s to cross are more likely to comply with the red signal.

In recent years, many authors have studied pedestrian violation rates. In Beijing, China, Guo *et al.* (2011) observed that 10% of the pedestrians assessed at seven intersections violated the signal indication at risky situations, and that half of them violated the don't walk indication after waiting more than 50 seconds. Suh *et al.* (2013) conducted a research at a university campus in Atlanta, USA, and found a violation proportion of 90%. Koh and Wong (2014) analyzed signalized intersections in Singapore, observing a 35% violation percentage; 22% of those violators started crossing before vehicles were completely out of the conflict area. In France, Dommes *et al.* (2015) identified a 32% violation rate at the seven intersections they studied. In Mumbai, India, Marisamynathan and Vedagiri (2017) observed that 1170 pedestrians disobeyed the signal indication, which represents 55% of the pedestrians observed in eight intersections. Finally, Onelcin and Alver (2017) analyzed six signalized intersections in Izmir, Turkey and found that 75% of the 444 pedestrians that crossed within a safety margin of 25 m from the crosswalk violated the red signal.

Whereas the violation is easily observed, the opportunistic behavior is hard to be identified precisely, as it is not always possible to know whether a pedestrian is searching for a gap. The decision to seek for gaps to cross on red usually depends not only on pedestrian characteristics such as age and gender (Chandra *et al.*, 2014), but also on external factors such as vehicular flow (Guo *et al.*, 2011; Dommes *et al.*, 2015; Marisamynathan and Vedagiri, 2017), the presence of other pedestrians waiting (Brosseau *et al.*, 2013; Dommes *et al.*, 2015; Rosenbloom, 2009) or crossing (Guo *et al.*, 2011; Ren *et al.*, 2011), and pedestrian delay (TRB, 2010; Guo *et al.*, 2011; Ye *et al.*, 2015).

2.2. Pedestrian gap acceptance in Vissim

In VISSIM version 11 (PTV, 2018) pedestrian movements can be simulated by two modelling options: either Wiedemann, or social force, which is based on the original model created by Helbing and Molnar (1995). Pedestrians modeled by Wiedemann can only move unilaterally along defined links, similar to the simulation of vehicles. The social force model, provided in the *Wiswalk* module of VISSIM, allows pedestrians to move freely in two spatial dimensions, which makes the representation more flexible, detailed, and realistic. Differences between the two models are found in the comprehensive study by Friis and Svensson (2013).

The adequate representation of the conflicts among pedestrians and other road users at crossings is extremely important in pedestrian delay estimation. These conflicts in Vissim can be modeled using the *conflict areas* or the *priority rules* models. The *conflict areas* model identifies the possible areas in the intersection where conflicts among pedestrians and vehicles may exist. The analyst defines if pedestrians or vehicles have the right of way. There are mainly six parameters of interest in this model: visibility, front gap, rear gap, additional stop distance and two other parameters used to determine if, and what proportion of, drivers will keep from blocking the conflict area.

The *priority rules* model determines the moment a pedestrian will choose to cross based primarily on the parameter *minimum gap time*, which is the critical gap parameter of VISSIM. For simplicity, in this paper *the minimum gap time* parameter of VISSIM will be referred to as *critical gap*. There are three additional parameters in the *priority rules* model: the *minimum headway*, which is the minimum space headway that pedestrians accept to cross; the *maximum speed*, which is the speed limit above which the main-street vehicles are not considered in the space headway acceptance (default = 180 km/h); and the *slow down distance*, which is the distance at which pedestrians start reducing their speed to stop at the stop line (default = 3,0m). Unlike the *conflict areas* model, which identifies the conflicting areas of the intersection automatically, the *priority rules* approach requires manual configuration of two elements: the stop line, at which the gap-seeking pedestrian must wait for an adequate gap to proceed, and the conflict marker, used to mark the links on which the gaps are assessed.

An important advantage of the *priority rules* over *conflict areas* is that the former allows the setting of priority rules by pedestrian type (e.g.: male, female, young or senior pedestrians), which means that each pedestrian type has its own critical gap. Also, the *priority rules* model is simpler in terms of number of parameters.

2.3. Existing methods for pedestrian critical gap estimation

Whereas there are numerous studies on critical gap estimation for vehicles, there are very few studies that do so for pedestrians, even for unsignalized crossings, where every pedestrian is seeking for gaps. This section summarizes the three existing estimations methods that were compared with the proposed method: HCM, Chandra's, and Raff's. None of these methods have been designed or applied to signalized crossing in the literature because in those types of intersections the gap acceptance process is not supposed to occur, as pedestrians are supposed to cross only during their green time (*walk* signal indication). However, we used them because pedestrians do seek for gaps during red. Besides, we did not find in the literature any critical gap estimation method designed specifically for crossings during red time.

The HCM (TRB, 2010) for estimates pedestrian critical headway at unsignalized crossings using Equation 1:

$$t_c = \frac{L}{S_p} + t_s \qquad (1)$$

where t_c: critical headway of pedestrian (s);

L: crosswalk length (m);

S_p: average pedestrian walking speed (m/s);

t_s: pedestrian start-up time and end clearance time (s).

The manual suggests an average walking speed of 1.1 m/s and a start-up and end clearance time of 3 s as default values for general population. Based on Equation 1, HCM assumes that a pedestrian's critical gap depends only on the time he/she needs to cross the street (L/S_p) plus an extra time that accounts for a pedestrian's reaction to signal changes (t_s), although other factors affect critical gap such as gender, type and speed of the conflicting vehicle, and if the pedestrian in a group Pawar and Patil (2015).

The critical gap estimation method proposed by Chandra *et al.* (2014) was specifically designed for pedestrians. It estimates critical gap as the intersection of the cumulative distribution of accepted gaps and the complementary cumulative distribution of crossing times. The application of this method by the authors resulted in critical gaps ranging from 3.4 to 9.7 s for crossings with vehicular flows between 1,600 and 2,900 veh/h. They also found that men accepted shorter gaps (8.5 to 10.2s) than women did (9.1 to 11.6s).

Pawar and Patil (2016) estimated pedestrian critical gap at an uncontrolled mid-block crossing using five different methods: the HCM's; Raff's; a binary logit model proposed by Pawar and Patil (2015); a maximum-likelihood procedure; and Ashworth's method (Ashworth, 1968). By doing so, the authors found similar results, with critical gaps ranging around 4 seconds, except for the one obtained using HCM (8.6 s). This indicates that the HCM results in more conservative estimates of critical gap.

A well-known method for estimating vehicle critical gap was proposed by Raff and Hart (1950) and adapted by Fitzpatrick (1991) by using gaps instead of lags. This method defines the critical gap as the gap for which the total number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it. Pawar and Patil (2016) applied Raff's method to pedestrians at unsignalized mid-block crossings in India and found a critical gap of 3.6 s. Depending on the site geometry (e.g. number of lanes to cross) and operational characteristics (e.g. vehicular flow), a critical gap of 3.6 s could indicate an aggressive crossing behavior.

Table 1 summarizes the three methods for estimating critical gap discussed, along with each method's main characteristics and assumptions when applied to pedestrians at signalized crossings. These three methods were applied in this study.

Table 1 – Selected existing methods for estimating pedestrian critical gaps

Method	Critical Gap Concept	Advantage	Disadvantage
Raff's	Critical gap is the gap for which the total number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it.	It is based on field rejected and accepted gaps, so it incorporates local characteristics.	It requires field observation of both rejected and accepted gaps.
HCM	Critical gap is the time the pedestrian needs to cross plus his/her start-up and end clearance time.	Simplicity, as it requires no observation of gaps.	It does not consider local characteristics such as traffic flow and pedestrian aggressiveness.
Chandra's	Critical gap is the intersection between the cumulative distribution of accepted gaps and the complementary cumulative distribution of crossing times.	It is based on field rejected and accepted gaps, so it incorporates local characteristics. Specifically designed for pedestrians.	It requires field observation of both rejected and accepted gaps.

3. METHOD

The method proposed in this research is divided into three major steps: data collection; vehicle simulation; and pedestrian simulation. These steps are detailed as follows.

3.1. Data Collection

We selected two mid-block, signalized crossings located in the city of Fortaleza, Brazil. The crossings were chosen according to the following criteria:

- Pedestrian demand should be at least moderate, to provide large enough samples.
- Vehicle demand should be at least moderate, to better assess the interactions among pedestrians and vehicles and their impact on pedestrian gap acceptance and delay.
- The presence of video cameras is preferred, to make data collection more precise and less time-consuming.
- Signal programming should be pretimed, to make it possible to replicate it exactly in the simulation.

We collected the data using four sources: (i) traffic enforcement cameras, from the Autarquia Municipal de Trânsito e Cidadania de Fortaleza (AMC); (ii) drone images, recorded and provided also by AMC; (iii) BRT station surveillance cameras, from the Empresa de Transporte Urbano de Fortaleza (ETUFOR); and (iv) 22 field observers. The data were collected on pedestrian peak hours on a business day. The collected data are described as follows:

- *Geometric characteristics:* lane width; number of lanes to cross; width of the sidewalks, of the pedestrian waiting areas, and of the pedestrian crossing; and obstacles dimensions were obtained from *Google Earth* ®.
- *Land-use characteristics,* assessed visually on the field and based on the researchers' knowledge of the areas.
- *Signal programming,* obtained from the Fortaleza Traffic Control Center (CTAFOR) and confirmed by field observations.
- *Directional 15-minute flows*, *c*ollected by the field observers, using manual counters and spreadsheets.
- *Vehicle gaps,* collected from the drone videos.
- *Pedestrian types,* collected from the enforcement cameras*.* Pedestrians were classified based on the observers' perception into four types – men (18- 60 years old), women (18-60 years old), seniors (both men and women older than 60 years), and youngsters (both men and women of younger than 18 years);
- *Pedestrian violation rates,* collected from the enforcement cameras. Based on the signal indication at the moment a pedestrian arrived at the waiting area and the time he/she started crossing, he/she was classified into three categories: violators (pedestrians who arrived and crossed during red), non-violators (pedestrians who arrived during red but only crossed during the green), and pedestrians who arrived and crossed the street on green.
- *Crossing times, walking speeds, delay, accepted gaps, and rejected gaps.* Collected for each pedestrian, from the video images, using manual chronometers and computer worksheets.

The network was coded in Vissim based on the collected data. We ran preliminary simulations with parameters on default values to verify model inconsistencies and to make any necessary corrections.

3.2. Vehicle Simulation

Gaps acceptance models assume that the gaps are represented adequately. Therefore, the vehicle arrival behavior in the simulation should replicate those from the field. The vehicle arrival patterns were analyzed per lane type – general traffic lane and bus-exclusive – and per flow direction – westbound or eastbound.

To satisfactorily match the simulated and observed vehicle arrivals, on the westbound lanes we inserted fictitious signal heads and reduced speed areas. We also adjusted car-following parameters (*ax*, *bx_add*, and *bx_mult*) and desired speed distribution. These adjustments might have resulted in scenarios that do not fully represent the study area in relation to motorized modes; however, in line with the research objectives, we were interested in replicating the field gap distributions available for pedestrians.

We used a simulation resolution of 0.1 s/time-step and replicated each scenario 5 times. We compared the distribution of the simulated gaps of each scenario with the distribution of the field gaps using chi-square goodness-of-fit statistics, with the simulated output making the expected frequencies. In this way, using a 5% significance level, the chi-square goodness-of-fit test verified the null hypothesis that the field gaps could have come from the distribution of the modelled gaps.

3.3. Pedestrian Simulation

The pedestrian simulation modelling was divided into two steps: modelling opportunistic behavior, and critical gap calibration.

3.3.1. Opportunistic behavior

Modeling the opportunistic behavior of pedestrians is crucial for representing pedestrian level of service in signalized crossing. Ideally, the modelling should include the estimation of the proportion of opportunists at the crossing, as did Martín (2018) and Suh *et al*. (2013); in both studies, the authors used pedestrian delay as target measure for estimating the proportion of opportunists. However, such methods are applicable only to current situations, not to future or hypothetic cases, because the proportion of opportunists depends on the characteristics of the scenario, such as vehicle demand and signal timing. Therefore, a more useful, replicable model should eliminate the need of estimating the proportion of opportunists.

Since it is hard, or sometimes impossible, to estimate the proportion of opportunists in hypothetical scenarios, and that even for existing situations it is not always possible to know whether a pedestrian is gap-seeking during red, we recommend assuming that all pedestrians at signalized crossings are opportunistic.

By treating all pedestrians as opportunists, delay becomes more sensitive to critical gap, so the estimation of this parameter is key to a reliable estimation of pedestrian delay at signalized crossings. For hypothetical simulated scenarios, in which the traffic demand may vary, it can be assumed that the critical gap will remain the same.

3.3.2. Critical gap estimation

The proposed method estimates the critical gap for pedestrians by using microscopic simulation, in which the critical gap - *minimum gap time* parameter of Vissim - was calibrated for each pedestrian type, using increments of 0.25s. The calibration target was the average delay per pedestrian type, and the goodness-of-fit measure was the mean absolute percentage error (MAPE) between simulated and observed 15-minute average delays.

To better assess the calibrated critical gap, we conducted statistical hypothesis tests (α=5%) for the differences between observed and simulated average delays. The null hypothesis is that the simulated and the field delays have equal means.

3.4. Model Evaluation

We evaluated the proposed approach by comparing it with the three existing methods detailed in section 2.3 – HCM, Chandra's Raff's. The comparison was conducted in two steps. First, we discussed the resulting critical gap values. Then, we simulated the crossings in Vissim using each method's critical gap to compare their 15-minute delay estimations. The assessment was based on MAPE between the simulated and observed delays. For this step, we ran 30 replications with resolution of 0,1 s/time step, keeping the same set of random seeds across the methods.

4. RESULTS

4.1. Data Collection

Based on the site selection criteria, we selected two crossings located at Bezerra de Menezes Avenue, in Fortaleza. This avenue, which is one of the main arterial streets of Fortaleza, has 3,30 km of extension. The main reasons that made these crossings stand out were: the multimodality of the street generates frequent interactions between pedestrians and vehicles; the predominant commercial land use brings moderate to intense pedestrian and vehicular flows, thus providing large enough samples of accepted and rejected gaps as well as of pedestrian types; and the presence of surveillance cameras, whose video recordings allowed us to observe of several variables required for the four applied methods.

Since it is a bidirectional arterial with heavy commercial land use, this avenue serves a large volume of road users daily, including vehicles, motorcycles, buses and minibuses, bicycles, and pedestrians. On eastbound direction, it has two traffic lanes plus two exclusive bus lanes. On westbound, it has two traffic lanes and one exclusive bus lane. Dividing both ways there is a bidirectional bicycle lane.

The selected signalized mid-block pedestrian crossings, located between Moreira de Sousa and Raimundo Vitor streets, is shown in Figure 1. The crossing directions identified as crossing 1 and crossing 2 were studied in this research; they connect the sidewalks to the median, where bus stops (Area 3) and a BRT station (Area 4) exist. Both crossings have a relatively high volumes of pedestrians due to the presence of a shopping mall (Area 1), a popular bank (Area 2), and several stores and business buildings around them. The large flow of people and other road users results in a significant level of interaction between pedestrians and other transportation modes, one of the main reasons that lead us to choose this area.

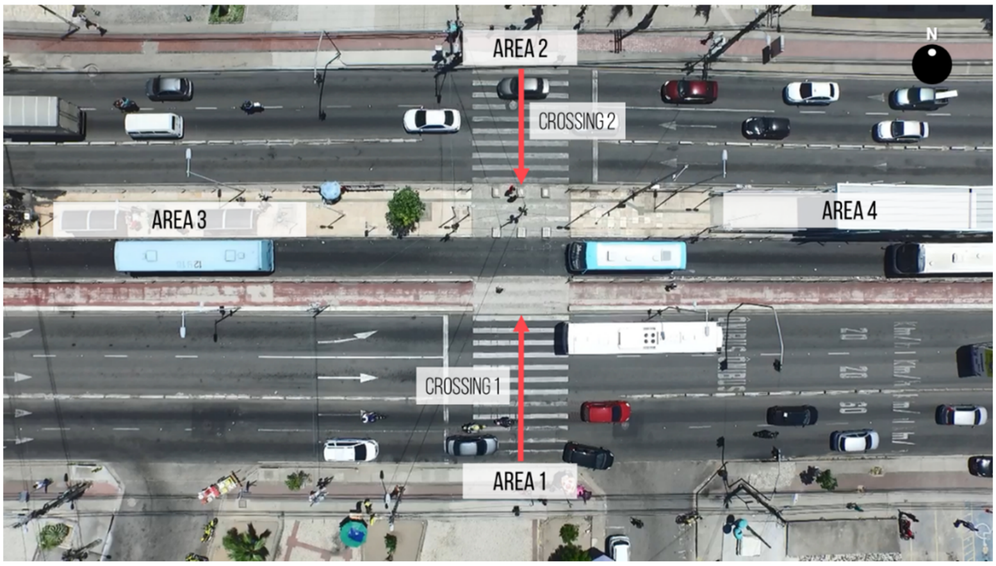

Figure 1. Mid-block pedestrian crossings studied.

As seen in Figure 1, crossing 1 refers to pedestrians going from area 1 to the median and crossing 2 to pedestrians going from area 2 to the median. We chose these crossings due to their physical and operational differences, such as the number of lanes to cross – three and four lanes, respectively; their pedestrian and vehicular demands; their red violation percentages; and because the video quality of these two crossings and their waiting areas were superior.

The data were collected on the September 5th (Tuesday) 2017, between 10:30am and 12pm, resulting in six 15-minute intervals. We chose this period because it presented a high volume of road users at both crossing. At crossing 1, we collected 216 observations of crossing on red – 78 men, 100 women, 26 seniors and 12 young pedestrians. At crossing 2, only 35 pedestrians crossed during red – 18 men, 11 women, 3 seniors and 3 young pedestrians. Crossing 2 presented the lowest violation proportion most probably because it has the highest conflicting traffic flow, which discourage pedestrian red violation. Since we considered the samples sizes per pedestrian type on crossing 2 to be small, we joined the data from the two crossings to estimate the critical gaps per pedestrian type, except for the HCM method, as it does not require observations of gaps.

Table 2 summarizes the data collected and provides a simple comparison between crossings. Crossing 1 showed a violation proportion of 59% (CI95% [55,9-63,8] %) and crossing 2 of 10% (CI95% [7,2-12,4] %).

Table 2 – Operational characteristics of the crossings

Crossing	Pedestrian flow (ped/h)	Violation rate (%)	Number of lanes	Vehicular flow (veh/h)	Bus flow (veh/h)
1	440	59	4	1052	135
2	590	10	3	1303	30

The desired walking speed of each pedestrian type was observed when the pedestrian moved freely while the crossing. For this, the pedestrians' crossing times were collected from 7am to 10am due to low pedestrian flows at that time. We used the following criteria: pedestrians crossing outside the marked crosswalks were not considered as well as those who ran or those who abruptly changed their speed during crossing; pedestrians were considered to be at their desired walking speed from the second traffic lane until they reached the sidewalk/median. The sample sizes for each pedestrian type was of at least 100 pedestrians.

The results were as expected: youngers were, on average, faster than seniors (4,7 and 3,6 km/h respectively); compared to these two types, men and women showed intermediate average values of 4.1 and 4.4 km/h, respectively. Chi-square normality tests with α=5% did not reject the null hypothesis of normality of these four variables.

4.2. Vehicle Simulation

For the westbound traffic lanes, the sample size was 1,872 gaps. The comparison between observed and simulated gap distributions are shown in Figure 2. Both distributions look similar, with most gaps shorter than 2 seconds. The $\chi 2$ goodness-of-fit test rejected the null hypothesis that the observed sample comes from the simulated distribution. However, this result may have been affected by the relatively large sample size; the sample size may so large that small differences between the distributions will result statistically significant, although not necessarily significant in practice.

As for the eastbound traffic lanes, the sample size was 1,304 gaps. Some adjustments had to be made in the simulation to make it replicate the observed gaps precisely. We inserted a fictitious signal 65m upstream of crossing 1 with a cycle of 160s, green time of 99s and offset of 2s. In addition, we adjusted the car-following parameters (*ax* = 2,0m, *bx_add* = 2,0m, and *bx_mult* = 4,0) and the *desired speed* distribution (30 [30-35] km/h for passenger cars and 20 [20-25] km/h for heavy vehicles). The results are shown in Figure 3.

As it happened on the westbound lanes, on the eastbound lanes the observed and modelled gap distributions were similar and the null hypothesis of the $\chi 2$ goodness-of-fit test was rejected, also likely due to the large sample size. However, we considered the observed and simulated distributions to be similar. The same modelling approach was applied to the exclusive bus lanes.

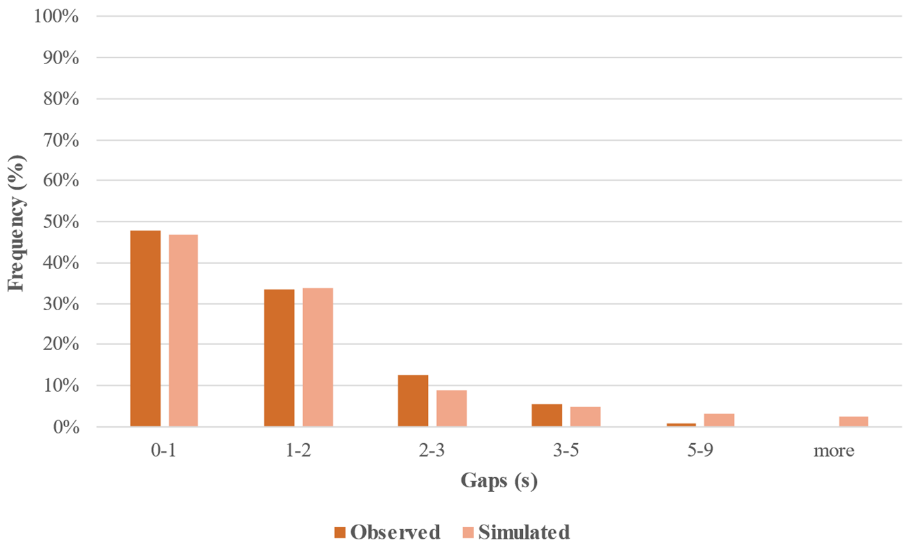

Figure 2. Simulated and observed vehicle gap distributions on westbound lanes

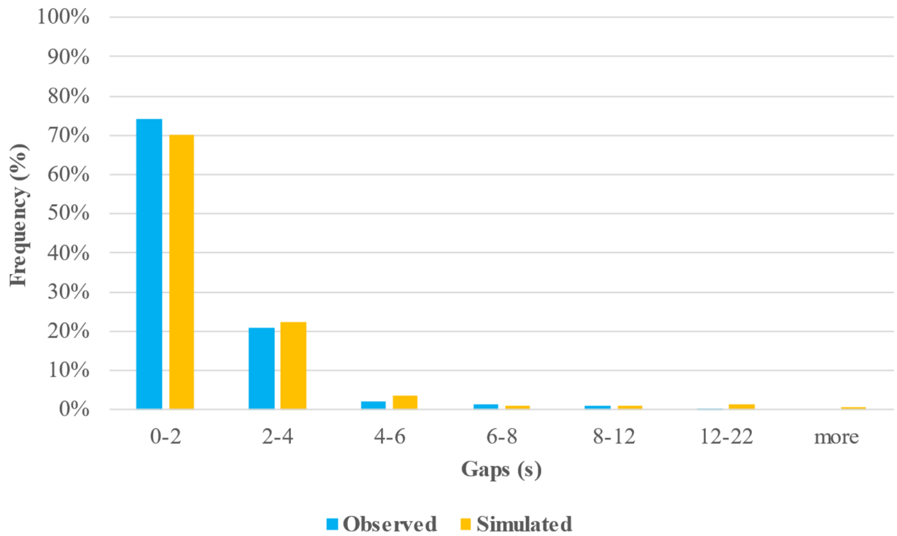

Figure 3. Simulated and observed vehicle gap distributions on eastbound lanes.

4.3. Pedestrian Simulation

An important aspect of the proposed method is that we considered 100% of the pedestrians as opportunists. If one wishes to set a different percentage in VISSIM, one must create a pedestrian type that do comply with signal heads, as done in Martín (2018).

We varied the critical gap parameter by increments of 0.25s for each pedestrian type and each crossing, comparing the resulting average delay based on MAPE. Figure 4 shows the resulting critical gaps. Figure 5 shows the observed and simulated delays per pedestrian type using the calibrated critical gaps, along with the MAPE values.

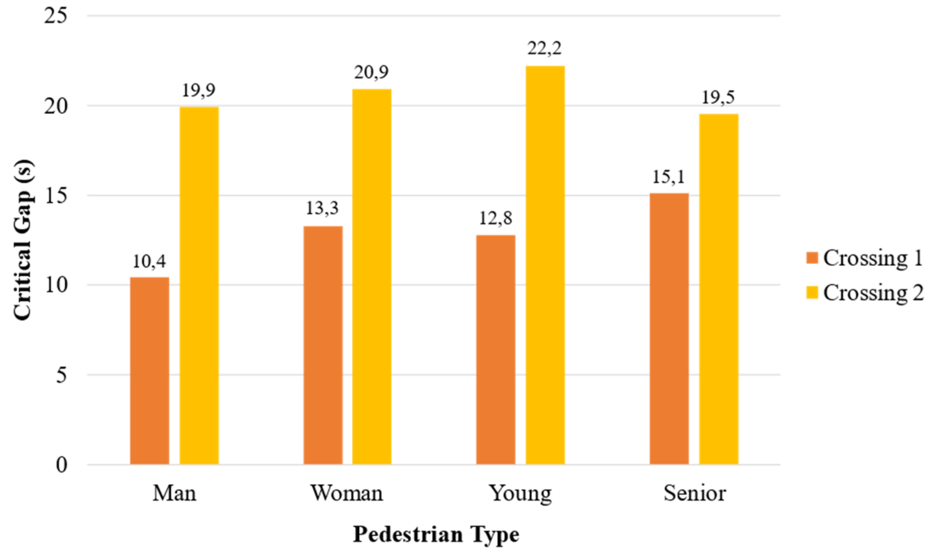

Figure 4. Critical gap estimation using Visim

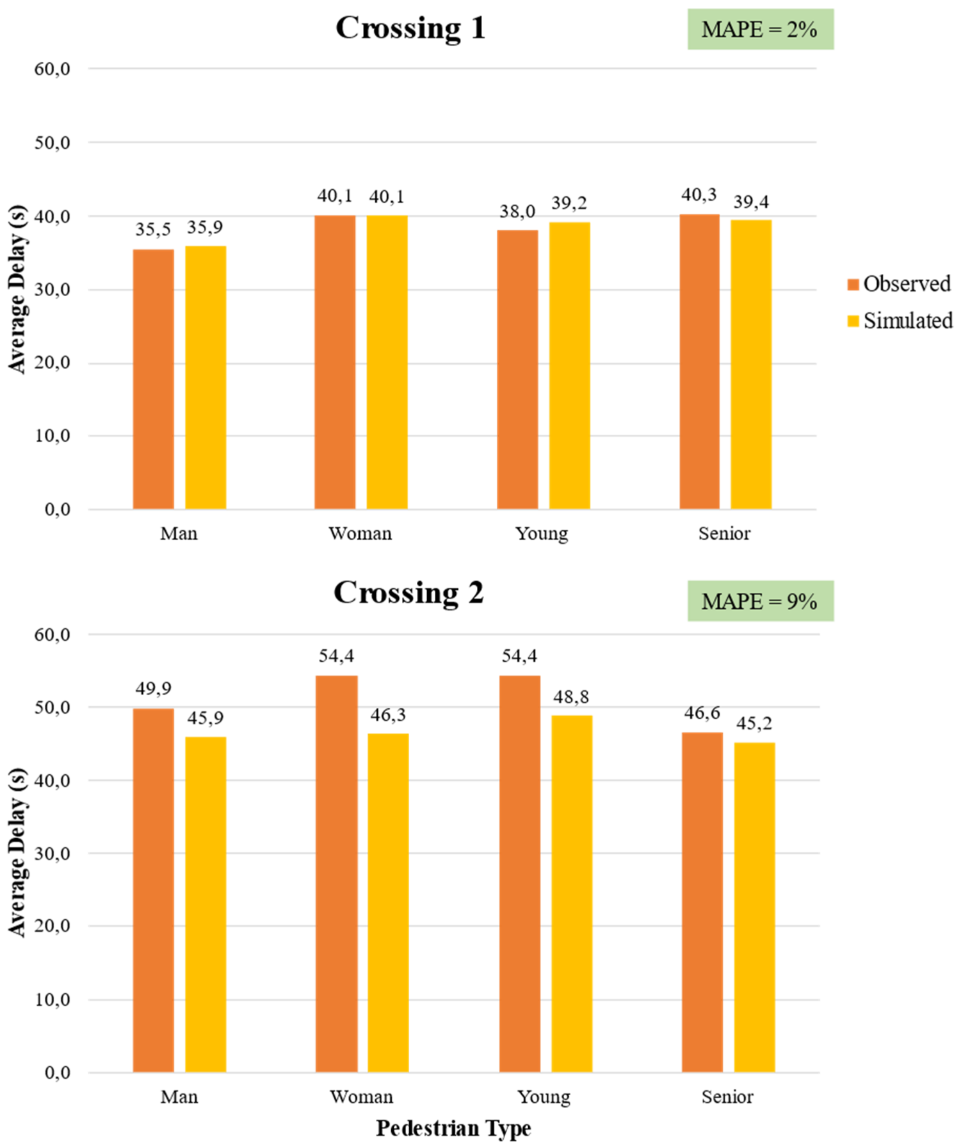

Figure 5. Average delays using the critical gaps estimated in VISSIM

The hypothesis tests (α=5%) to evaluate the differences between simulated and observed average delays for each pedestrian type and each crossing yielded the following results. None of the tests – except for women at crossing 2 (p-value=0.09) – rejected the null hypothesis that the means are equal. For women at crossing 2, the delay difference was 15% of the observed mean delay, or 8s, a considerable difference. The highest MAPE (9%), for crossing 2, may have been caused by the low field violation rate (10%), which differs considerably from the simulated value (100%).

4.4. Model Evaluation

We evaluated the proposed approach by comparing it with existing methods. The first method applied was the HCM. The pedestrian start-up and end clearance time (t_S) was kept at the default value of 3s, as suggested by the manual. The other two variables – crosswalk length and average walking speed – were collected for each pedestrian type. Figure 6 shows the estimated critical gaps.

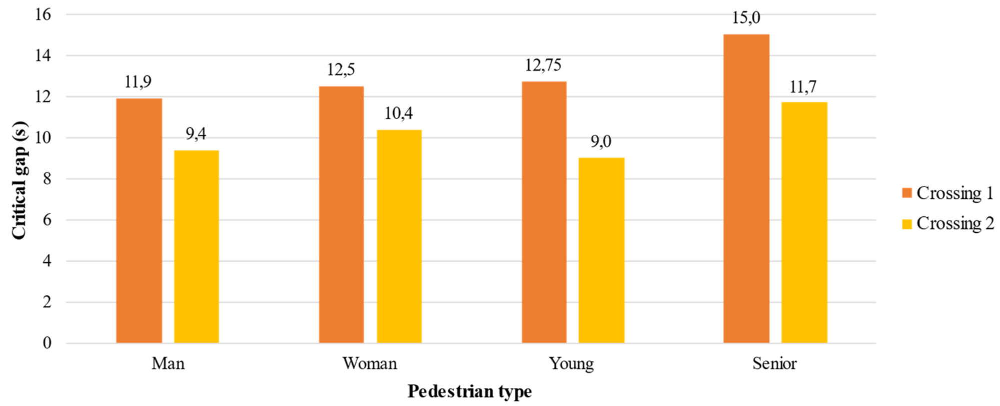

Figure 6. Critical gaps estimated by the HCM method

In general, the results followed the expectations: seniors have longer critical gap than youngers, and men have lower critical gap than women do, although in the latter comparison the differences were not as large as in the former. Those differences resulted from the differences in walking speeds. Crossing 1 presented the longest estimated critical gaps, which indicates that pedestrians need more time to complete that crossing.

The estimation of the critical gaps using Chandra's method are shown in Figure 7. As expected, the shortest critical gaps were for men and youngers. A comparison with Figure 4 shows that the critical gaps estimated by Chandra's were lower than those from HCM

Raff's estimation is based on the cumulative distributions of accepted and rejected gaps. Rejected gaps were recorded from the moment a pedestrian arrives at the waiting area until the moment he/she starts crossing. Figure 8 shows the results. The critical gap among pedestrian types were practically equal. Among all methods, Raff's yielded the lowest critical gaps.

Considering all methods, the highest critical gap estimations came from the microsimulation approach. The highest value was for youngers on crossing 2, basically twice the value estimated by HCM. Considering that in the simulation 100% of the pedestrians are opportunists, the chances of violations in the model are increased; to compensate for that, longer critical gaps were needed so that simulated average delay per pedestrian match the observed.

On the other hand, for crossing 1 the estimations were closer to those from HCM, because the observed violation rate on this crossing is higher.

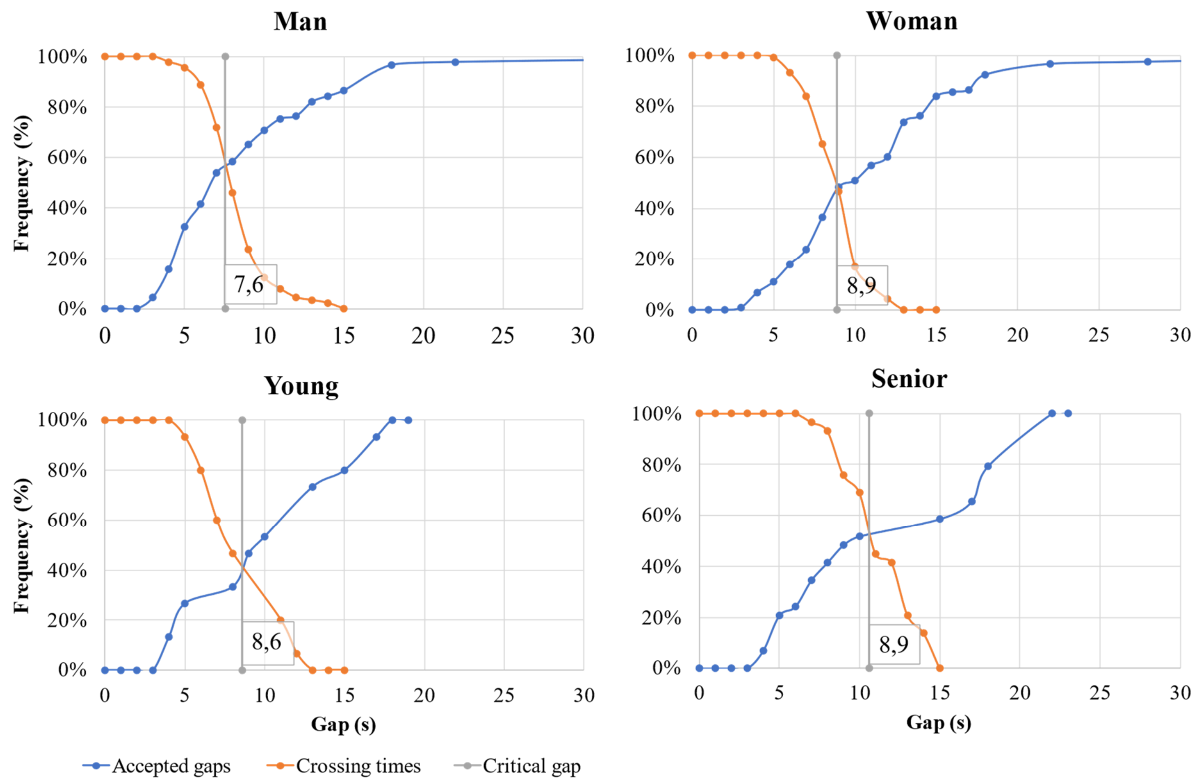

Figure 7. Critical gaps estimated by Chandra's method

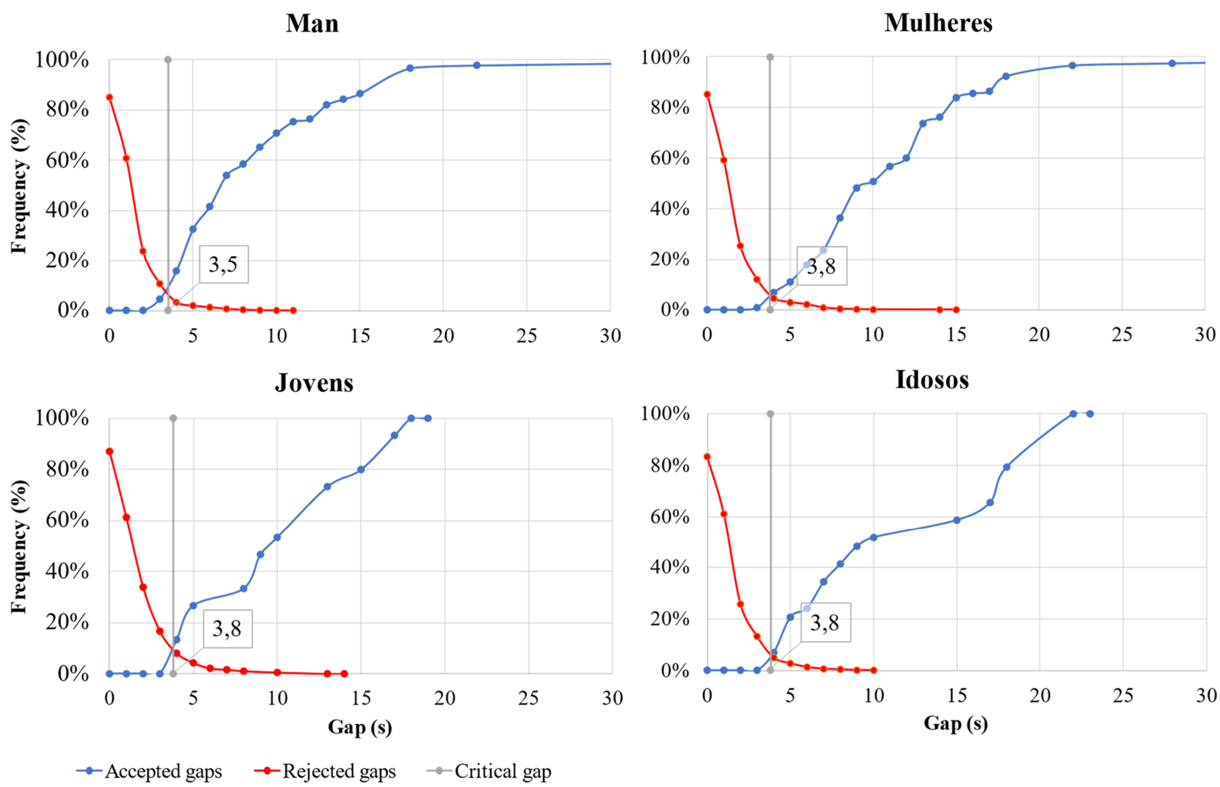

Figure 7. Critical gaps estimated by Raff's method

Figure 9 shows the VISSIM results of 15-minute average delay of each critical gap estimated by the four methods. For crossing 1, the proposed and the HCM methods provided the best delay estimations, with MAPE = 18%. The reason these two methods resulted in similar outcomes is that their estimated critical gaps are similar. These two methods also provided the best estimated delays every 15 minutes on crossing 2, with MAPE of 7% for the proposed approach and of 13% for the HCM.

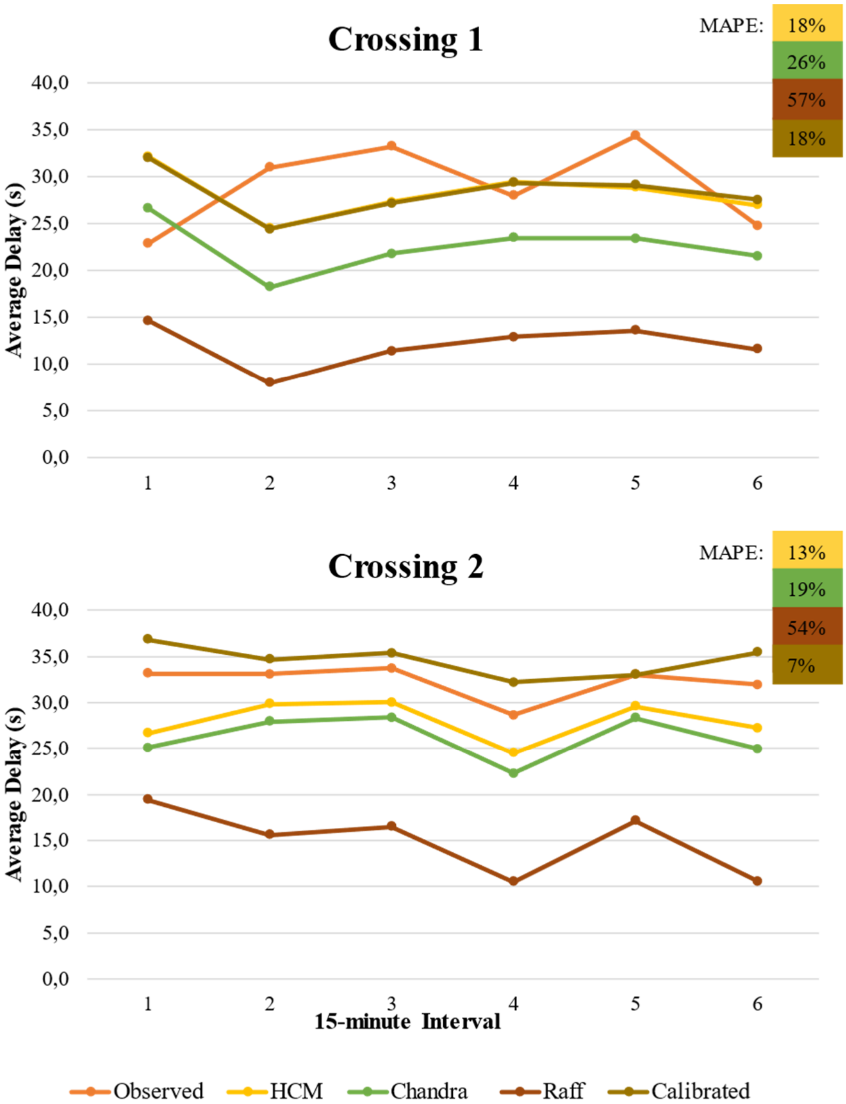

Figure 9. Delay estimations using each method's critical gap in VISSIM

5. DISCUSSION AND CONCLUDING REMARKS

The main goal of this research was to propose a method for estimating critical gap of pedestrians at signalized crossings using microsimulation. Since knowing the proportion of opportunists in hypothetical/future scenarios is difficult, or even impossible, we recommend modelling all pedestrians as opportunists and estimating critical gap using average delay as calibration target. Unlike the proportion of opportunists, critical gap is not expected to vary considerably in hypothetical/future scenarios of varying vehicle or pedestrian demands. Besides, it is likely that almost all pedestrians would accept large enough gaps during red.

The modelling of vehicle arrivals was evaluated using histograms and chi-square goodness-of-fit tests. It should be noted that that in this test – as in any hypothesis test – the null hypothesis tends to be rejected as the sample size increases. In these cases, we should consider the practical, not the statistical, goodness of fit.

For the simulation of pedestrian gap acceptance in VISSIM, we recommend using the *priority rules* model – not *conflict areas* – because it allows setting specific critical gaps per pedestrian type, and it also has the mostly used gap acceptance parameter, the critical gap. We also recommend the use of the *social force* model – not Wiedemann's – because it represents pedestrian behavior much more realistically.

Regarding the comparison of the models, the proposed approach achieved the best delay estimations, followed by the HCM. One advantage of the HCM is simplicity; on the other hand, the microsimulation method results in better estimates and can model pedestrian type individually. As for the critical gap estimations, the highest value was obtained by the proposed approach and the lowest by Raff's. A possible explanation for the low estimations by Raff's method may be that it was originated for motorized vehicles; the low critical gaps may indicate that Raff's method is not suited for pedestrians. The critical gap values obtained from the method presented in this work could not be compared with those from previous studies because we did not find publications on pedestrian critical gap on crossings with similar characteristics.

Since the presented method is based on microsimulation, it requires that all other parameters related to pedestrian crossing must be calibrated, otherwise the resulting critical gap estimation may not be adequate. A limitation of this study is that joining samples from the two crossings to apply the Chandra and Raff's method is a limiting factor to understanding the differences between the crossings.

Future studies should combine the proposed method of critical gap estimation with a method for estimating the proportion of opportunistic pedestrians, which is challenging. Besides, the proposed method should be tested in other crossings, including non-signalized ones.

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