OPERATIONAL EFFECTS FOR PEDESTRIAN AND MOTORIZED TRAFFIC OF CHANNELIZED RIGHT-TURN LANES AT URBAN SIGNALIZED INTERSECTIONS

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ABSTRACT

Channelized right-turn lanes (CRTL) are commonly used at urban signalized intersections. They can improve safety, reduce delays for vehicles, and increase an intersection's capacity. However, the effects of CRTL on pedestrians can include delays and affect level of service in ways that are not widely understood. We used VISSIM-PTV and its VISWALK component to study and analyze the combined operational effects of CRTL on both pedestrians and motorized traffic. For this purpose, we propose Total Average Delay (TAD) as a performance indicator. In all cases, CRTL reduced delays for cars and increased delays for pedestrians. For high pedestrian and vehicle volumes, a CRTL can reduce the TAD by up to 27%.

Keywords: Signalized intersections, delay, pedestrians, right turns, indicator, channelized right-turn lanes (CRTL), VISSIM, VISWALK.

1. INTRODUCTION

For decades, transport planning and engineering focused on vehicular traffic with the objectives of achieving higher speeds and greater vehicle capacity. Banister (2008) states that the conventional transport paradigm has led to increased travel distances and speeds which are the basis of unsustainable urban transportation systems due to their high level of dependency on motorized traffic. The sustainable mobility paradigm has emerged in response. Transportation planning and design are no longer focused mostly in motorized traffic, but it has been evolving to multimodal approach (Banister, 2008). Complete Streets movement and multimodal level of service (LOS) methodologies are evidence of that evolution. According to the sustainable mobility paradigm, the design of urban intersections and road networks in walkable and multi-modal cities might consider multi-modal approaches to balance the operational costs and benefits among different actors.

Intersections, characteristic elements of urban networks that are related to most urban travel delays, are the topic of prolific traffic engineering research. Research about urban intersections has increased knowledge and helped the development of better road safety and traffic operations designs. Nevertheless, more needs to be known in order to develop better and more coherent design tools so that transportation engineers and designers can make rational decisions about performance.

Traditional urban at-grade signalized intersections are common in urban networks. Channelized right-turn lanes (CRTL) are frequent at intersections with high volumes of right-turning vehicles and at intersections whose geometry requires larger turning radii (Al-kaisy & Roefaro, 2010). At intersections without CRTLs, turning vehicles need to reduce speed as they approach the turn. This increases delays for approaching vehicles and reduces the intersection's capacity. FIGURE 1 shows interactions between pedestrians and right-turning vehicles at an intersection with a CRTL and at an intersection without a CRTL in Bogotá, Colombia. CRTLs may have effects on pedestrian volumes, delays, and performance, but these parameters are not frequently considered in decisions about installation of CRTLs (Al-kaisy & Roefaro, 2010). In fact, we found no research, manual, or guideline that provides a tool for making rational decisions about CRTL installation based on the trade-off between right-turning vehicles and crossing pedestrians. On this paper, we analyzed this trade-off with the objective of improving service (reducing delay) for the majority of users.

FIGURE 1 Left: Calle 72 and Carrera 11 in Bogotá (no CRTL). Right: Calle 72 and Carrera 7 in Bogotá (with CRTL).

We have used controlled simulation experiments to learn about the operational effects on both pedestrians and motorized traffic of CRTLs at signalized intersections. The aim was to develop a method to indicate the best right-turn treatment in terms of the objective of reducing delays for all users. This study paid particular attention to the inclusion and importance of pedestrians in the design of intersections. Finally, we propose that delays caused for both crossing pedestrians and motorized traffic be used as an alternative indicator for measuring an intersection's operations.

2. BACKGROUND

There is currently a consensus that CRTLs at signalized intersections improves operations of motorized traffic by allowing bigger turn radii, higher turning speeds, avoiding unnecessary stops, reducing vehicle delays and increasing intersections' capacities e.g. Al-kaisy & Roefaro, Potts et. al. and Dixon et. al.. However, high turning speeds have raised concerns about road safety for pedestrians and bicycles (Ling & Li, 2013). In fact, whether or not CTRLs result in operational improvements for vehicles in urban areas with high pedestrian and vehicle volumes is itself a debatable proposition since pedestrians and vehicles interfere with each other and traffic controls end up being included in the channelized lane.

CRTLs have most often been studied for motorized traffic, and studies have typically focused on road safety for motorists (Dixon et. al., Fitzpatricl & Schneider). Vehicular safety and operations have been widely studied, but much less is known about pedestrians. The most complete research about CRTLs is the design guide of the National Cooperative Highway Research Program (NCHRP) published in 2011. Design issues related to CRTLs are presented according to operational and safety considerations for motor vehicle and pedestrian traffic (Potts et al., 2011).

This study's operational analysis of traffic was conducted with micro-simulation models and focused on three main CRTL issues: (a) the impact of a CRTL on delays of motorized traffic at varying volumes of vehicular traffic, (b) the impact of pedestrians on delays of right-turns, and (c) the impact of key design features on the operational performance of the CRTL. Most relevant operational considerations include the following:

- Right-turn delays for vehicles at intersections with CRTLs combined with yield control are 25 to 75 percent shorter than in conventional right turn-lanes. Reductions of vehicular delays are observed up to a pedestrian crossing volume of 200 ped/h.
- A similar reduction of delays is observed for CRTLs without traffic control.
- Signalized CRTLs produce right-turn delays that are similar to conventional right-turn lanes where right-turn-on-red is permitted. Delays last longer than those observed at yield-controlled CRTLs.
- "Where a signal is provided for pedestrians to cross a channelized right-turn lane on a cycle coordinated with the primary signal at the intersection, vehicle delay with the CRTL is generally greater than vehicle delay for conventional right-turn lanes and for yield- controlled channelized right-turn lanes." (Potts et al., 2011)

To analyze the safety of CRTLs, Potts et. al. collected vehicle and pedestrian crash and volume data from 1999 to 2005 for 103 four-leg intersections in Toronto, Ontario, Canada. They compared three different intersection approaches: (I) shared through/right-turn lanes, (II) conventional right-turn lanes, and (III) CRTLs. They obtained the following safety considerations:

- Motorized traffic safety is very similar for conventional right-turn lanes, shared through/right-turn lanes and CRTLs. This means that there is no evidence that CRTLs improve vehicle safety. In regard to the severity of accidents, this study does not present evidence.
- Pedestrian crash frequency is higher (70 to 80 percent) for conventional right-turn lanes that for shared through/right-turn lanes and CRTL. This might be due to that conventional right-turn lanes produce longer crossing distances.
- CRTLs create refuge islands for pedestrians that provide the possibility of crossing in two stages.
- Design agencies are more likely to provide CRTLs at intersections with low volumes of pedestrian traffic: "Caution should be exercised in using CRTL where pedestrian crossing volumes are high (i.e., greater than 1,000 ped/day)." (Potts et al., 2011)
- In general, it is relatively easy for most pedestrians to cross at a CRTL because they are not wide, and traffic approaches from a single direction.

From the above considerations, it is clear that there is more information on the effects of CTRLs on pedestrians in the research by (Potts et al., 2011) than in other studies. Nevertheless, analysis related to pedestrians is limited to qualitaive analysis, while for motorized traffic it is technical, accurate and quantified (measured by delay).

Motivated by the lack of guidance in the use of CRTLs in the USA, Al-kaisy & Roefaro studied the reasons designers choose CRTL in practice. They surveyed designers from different agencies in the USA about considerations used for inclusion of CRTLs and decisions about which type of traffic control to use in those lanes. They found that vehicular traffic operations was the most prevalent consideration for installing CRTLs and that traffic controls are commonly included because of safety considerations such as controlling pedestrian flows in a CRTL. They also concluded that the guidelines for determining whether or not a CRTL is appropriate and what type of control to use are insufficient (Al-kaisy & Roefaro, 2010).

The article "*Right-Turn Treatment for Signalized Intersections*" by Dixon et al. analyzes crash data history from various right-turn strategies and CRTL configurations from Cobb County, Georgia to identify possible correlations between right-turn treatments and accidentality. This study was limited to vehicular safety so did not present conclusions about pedestrian safety. Nevertheless, the study found that inclusion of a triangular island appears to reduce right turn crashes and that exclusive right turn lanes appear to correspond to larger numbers of sideswipe crashes (Dixon, Hibbard, & Nyman, 2000).

Related to safety in intersections with CRTLs, Fitzpatrick & Schneider established equations to predict speed at the beginning and in the middle of right-turn lanes. In both equations, the variables that influence turning speed are channelization, corner radius, length of right-turn lane, and width of right-turn lane at the start of the right turn. Right-turn speed increases as the corner radius increases and also increases with the inclusion of raised islands and wider lanes. Higher turning speeds are more dangerous for pedestrians. Fitzpatrick and Schneider (2005) claim that "…survival rates of pedestrians struck by motor vehicles are much higher if vehicle speeds are reduced. Eighty percent of pedestrians are killed when struck by motor vehicles traveling 35 to 45 mph; only 5 percent are killed at speeds of 18 mph." (Fitzpatrick & Schneider, 2005). That study found that the configurations with highest crash rates in Georgia included islands (channelized right-turns). As in the study by Dixon et al., Fitzpatrick and Schneider did not study the effects of traffic on pedestrian operations in right-turn lanes. They encourage further research in this area.

Current research and studies have provided quite a good understanding of the use and convenience of CRTLs for motorized traffic but seem to have underestimated effects on pedestrian. While CRTLs might reduce delays for motorized traffic, the effect on pedestrians is poorly studied. Under traditional signal planning, CRTLs may lead to two-stage crossings for pedestrians, which result in longer overall crossing times (longer delays). In addition, the decision to install CRTLs lacks guidance. More and better research will help transport engineers and designers to make better decisions that provide more safety and efficiency for all users. This paper studies CRTLs with special attention to their effects on pedestrians and proposes an indicator for measurement of intersection operations that takes pedestrian usage into account.

3. METHOD

3.1. Operational indicator for intersections

Delay is defined as "the additional travel time experienced by a driver, passenger, pedestrian" (Transportation Research Board, 2000), or the difference between the real travel time (with obstructions, stops, interactions, etc.) and the theoretical travel time with no "interruptions" ("Getting Started : VISSIM," 2015). Delay is a common indicator for the quantification of an intersection's LOS. Guidelines in most recent Highway Capacity Manual (HCM) provide multi-modal LOS methodologies, which consider interactions between pedestrian and a motorized traffic in their separated LOS models. However, there are limited mechanisms for identifying design improvements besides scenario comparison.

As long as pedestrian-car conflicts occur in intersections, the average delays for vehicles and pedestrians are not independent (Transport For London, 2010). A traffic signal plan that aims to minimize the delay for one mode might increase the delay for the other mode and vice versa. Recurently we will refer as the "trade-off" between modes in this paper. Although we did not find evidence that improvement of the delay in one mode will always negatively affect the other mode, it is reasonable to expect an inverse influence.

We propose an indicator that combines pedestrian and motorized vehicle traffic delay. The Total Average Delay (TAD) is a weighted arithmetic mean that gives equal consideration to delay in both modes. TAD is defined in Equation 1.

$$TAD = \sum \left(\frac{mode\ users}{total\ users} * mode\ average\ delay \right) \quad (1)$$

To simplify, if Equation 1 is rewritten for a case wtth only pedestrian and motorized vehicle traffic, it is Equation 2.

$$TAD = \frac{\#peds}{\#vehs\ users + \#peds} * PAD + \frac{\#vehs\ users}{\#vehs\ users + \#peds} * VAD \quad (2)$$

TAD: Total Average Delay
#peds: parallel crossing pedestrian volume
#vehs users: number of people in vehicles that use the intersection = number of vehicles x average occupancy
PAD: Pedestrian Average Delay – pedestrian mean delay
VAD: Vehicle Average Delay – vehicle mean delay

The TAD is a person-weighted delay indicator which considers more than one mode. As previously mentioned, Pedestrian Average Delay (PAD) and Vehicle Average Delay (VAD) might not be independent of each other. The rationale behind this indicator is that, since drivers and pedestrians are equally important actors, the objective is no longer to reduce the delay of one mode, but to explore minimization of the overall delay of all actors. In fact, this principle has been applied to transit signal priority since the 1970s in Germany where reduction in delays of all passengers in buses and trams justifies modification of the signal plan in favor of transit.

Exploring solutions to the conflict between right turn motorized traffic and pedestrians is a complex problem due to the high number of interrelated variables that affect both delays. Specifically, the decision about whether to use a CRTL and about what type of control should be used to achieve TAD minimization implies an understanding of which variables might have effects. Besides the aforementioned geometric design (e.g. right turn with or without CRTL) and the traffic control type for the parallel pedestrian-car conflict (e.g. signalized or priority), many other variables affect delays. Traditionally, traffic signal plans (phases and times) are heavily influenced by vehicular demands per access and by turning percentages. The Webster formula, an empirical mathematical expression, has shown good results in optimizing the distribution of green times among different conflicting vehicular streams. Pedestrian are accommodated in between vehicular phases which eventually results in modification of the initial phase layout in order to safely serve them.

3.2. Experiment design

Numerous variables affect the outcome of this problem which makes it very complex. These variables include geometric design (e.g. CRTL), traffic control type, road type, number of lanes, turn radii, lane width, approaching vehicles speeds, and vehicular composition. Since the objective of this study is to quantify the operational effects of CRTL at signalized intersections, it is necessary to set some variables that affect delay constant. Variables such as lane width, approaching speed, and vehicular composition are easy to hold constant because, under normal conditions they do not depend on either PAD or VAD which are the explanatory variables of the TAD.

The traditional signal design process defines green times for all streams based on vehicular traffic volume. Afterwards, pedestrian volumes are accommodated within the previously established design. Eventually, changes are phased-in to accommodate incompatible movements. This implies that both the geometric design and the signal design depend on the explanatory variables of the indicator that is being measured. Due to the complexity of the problem, it was necessary to make some simplifications and assumptions to design an experiment that allows measurement and comparison of the TADs of different right-turn treatments under a series of scenarios of traffic and pedestrian volumes.

Through microsimulation, explanatory variables can be changed systematically to measure their effects on the dependent variable (TAD). We approached the problem presented above by means of microsimulation using PTV-VISSIM and its specialized module for pedestrian simulation VISWALK. The objective was to evaluate the TAD under different combinations of right turn treatments and traffic controls.

Three different right-turn treatments were evaluated in the experiment. As can be observed in FIGURE 2, each case evaluates a pedestrian crosswalk that is parallel to the approaching vehicles and which interferes with the right-turning vehicles. Case 1 has no CRTL and pedestrian signals, which allow crossings simoultanous with parallel motorized traffic. In this case, right turning vehicles yield to pedestrians and no right-turn on red are allowed. Cases 2 and 3 have a CRTL. Case 2 has a traffic signal at the CRTL, which operates synchronized with the main traffic signal of the intersection. This means that the signal for the right turn vehicles in the CRTL is part of the same signal group used for through traffic. Case 3 has a CRTL with a center crosswalk but no signal control in the channel. Right-turning vehicles yield to crossing pedestrians in the CRTL.

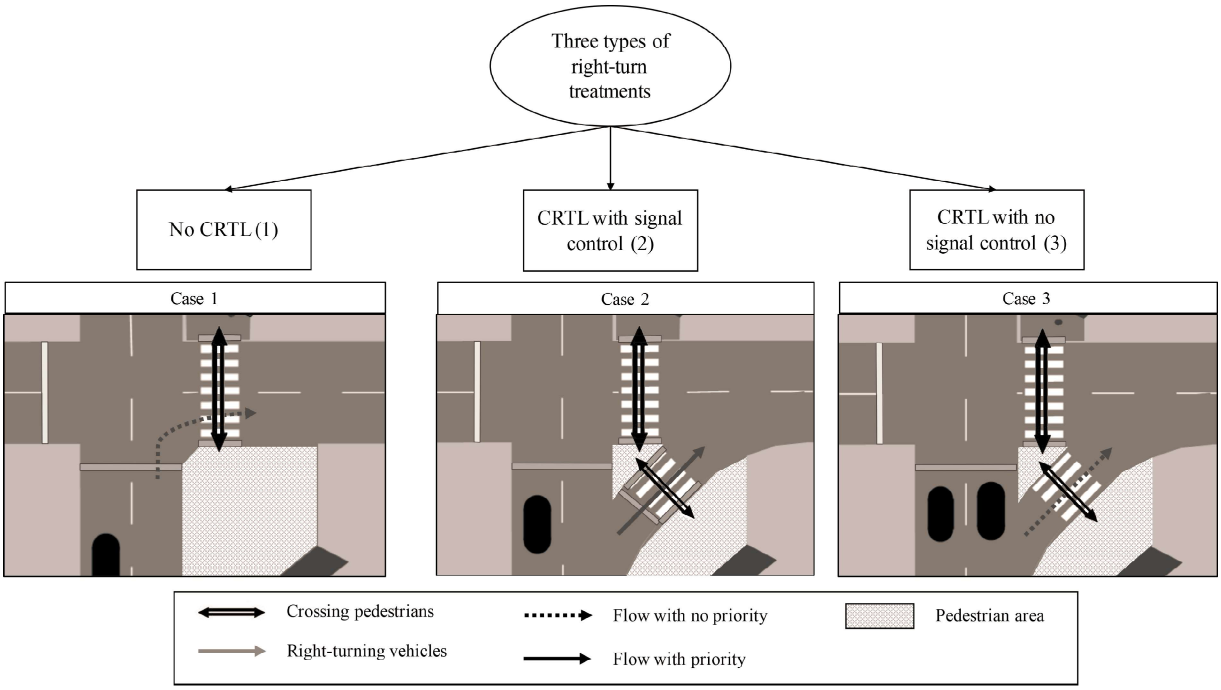

FIGURE 2 Types of right-turn treatments evaluated

The behavior of VAD, PAD and TAD, the dependent variables, was studied for each type of right-turn treatment presented in FIGURE 2. Vehicular traffic volume and crossing pedestrians, the other explanatory variables, were systematically varied. The TAD was calculated for each combination of crossing pedestrians and traffic volume in each type of right-turn treatment. From these calculations, we obtained a three dimensional surface that represents the operation efficiency of the intersection (see FIGURE 7).

The experimental design is based on several assumptions, and some of its variables were held constant. Since many analyses are carried out in equivalent vehicles, it was assumed that only cars compose the traffic. Also, given that the conflict between right-turning vehicles and crossing pedestrians is the main source of delay and the main subject of this study, the right-turn proportion of the approaching vehicles was set at a medium-high constant value of 25%. The average occupancy of vehicles that use the intersection was determined as a value around the occupancy rate of passenger cars in Bogotá, Colombia: 1.4 passengers per vehicle (Ardila, 1995).

Finally, for the experiment, the traffic light cycle and green light duration were held constant (2-phase signal of 90 seconds with 50/50 split). This was done because, as shown in FIGURE 3, the VADs for the four traffic volumes evaluated, 200, 400, 600 and 800 vehicles/hour, are very similar: between 12 and 14 seconds. This made it possible to obtain the effects of the geometric design on VAD because the VAD produced by the traffic light with a green time of 45 seconds does not vary with the approaching traffic volumes evaluated.

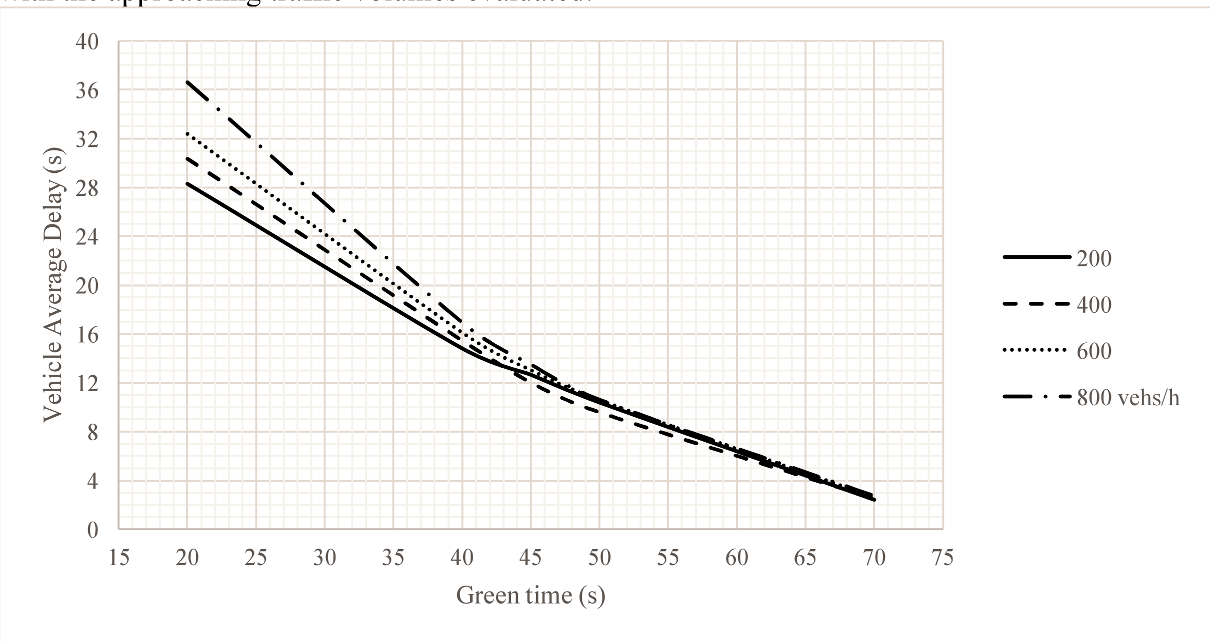

FIGURE 3 VAD for a 90 second cycle traffic light and different combinations of green-red times.

At the same time, FIGURE 4 shows that PAD is also very similar at all the pedestrian volumes evaluated for a green time of 45 seconds. Due to the characteristics of pedestrian flow of high acceleration and deceleration when traffic lights turn green, the flow of accumulated pedestrians who wish to cross starts almost immediately, regardless of the volume of the pedestrian flow. Because of this, it is expected that the PAD will not vary among different pedestrian volumes when the green time is held constant.

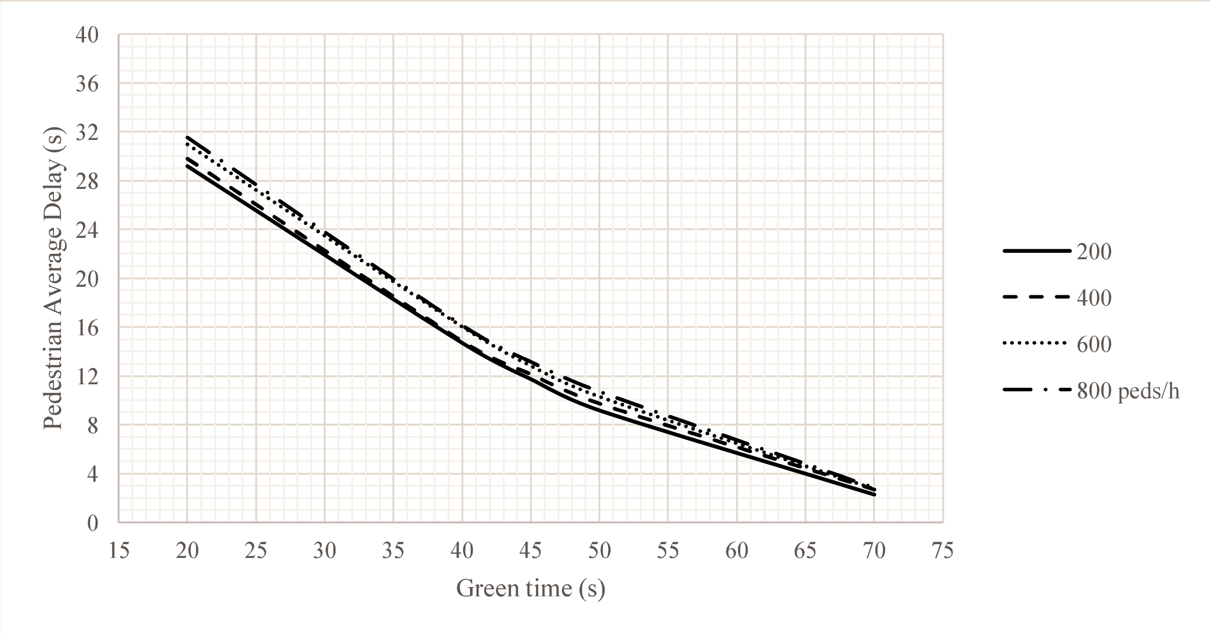

FIGURE 4 PAD for a 90 second cycle traffic light and different combinations of green-red times.

It is not necessary to change the traffic light design from scenario to scenario to compare VAD, PAD and TAD. Additional simplifications, assumptions and controlled variables of the experiment are presented in TABLE 1.

TABLE 1 Simplifications and controlled variables of the traffic simulation experiment

Simplifications/Assumptions	**Conditions**
Signal	2-phase 90 sec signal with 50/50 split
Lane width	3.6 m
Crosswalk width	3.0 m
Vehicle approach speed	50 km/h (30mph)
Vehicle composition	100% cars
Conflict areas	Red/Red
Pedestrians' directions	50/50
Turn radius	5 m without CRTL and 15 m with CRTL
Walking behavior	Social force model (VISWALK default)
Vehicle turning speed	15km/h (no CRTL) and 30km/h (CRTL)
Vehicle average occupancy	1.4 passengers/car (Bogotá's mean)
Right-turn proportion	25%
Controlled	**Range**
Geometric design (3)	No channelized right-turn lane (Case 1)
	Channelized right-turn lane with signal control (Case 2)
	Channelized right-turn lane with no signal control (Case 3)
Traffic volume (4)	200-400-600-800 vehicles/hour
Pedestrian volume (4)	200-400-600-800 pedestrians/hour

3.3. Microsimulation

Systematic variation of motorized traffic volume and parallel pedestrian volume within the three right-turn treatments results in a total of 48 scenarios. We adopted the microsimulation software's VISSIM and its VISWALK complement to run the simulations to calculate TAD using Equation 2. Since the experiment is done at generic intersections, there are three requirements for designing the simulation process: determination of the simulation time, a warm-up period and determination of the number of runs (R).

The modeler inserts the number of vehicles or pedestrians per hour into the network in VISSIM so that, when the simulation runs, the network starts to receive vehicles and other simulation inputs. A warm-up period is necessary because vehicles do not start flowing in an instant in real traffic. During the warm-up period, all inputs are in the network but no results are being evaluated. The warm-up period is usually 15 minutes, but there are methods to calculate it for each particular simulation model. It depends essentially on the network size (Transport For London, 2010). The network was small because these simulations were at a single intersection, so a warm-up period of 15 minutes (900 seconds) was long enough. After the warm-up period, the network stabilizes and the measures obtained are more representative of reality. The period of time needed to obtain information from the simulation was determined to be one hour (3600 seconds), so the simulation lasts a total of 4500 seconds including the warm-up period.

Microsimulation models have a stochastic component so that the randomness of traffic variables can be taken into account. This means that conclusions cannot be made from a single run of each scenario since each run is likely to result in different outputs. Running each scenario a number of times can minimize variability in accordance with the confidence interval and percentage error allowed by the modeler. Hollander and Liu (2008) present a formula for calculating the number of runs (Hollander & Liu, 2008):

$$R = \left(\frac{s.t_{\propto/2}}{x.\varepsilon}\right)^2 \qquad (3)$$

R: required number of runs
s: standard deviation of the examined traffic measure
x: mean of the traffic measure
ε: the required accuracy, as a fraction of x
$t_{\propto/2}$: critical value of Student's t-test at confidence level ∝

The mean of the traffic measure and the standard deviation are obtained from running the simulation. With an iterative process starting at 10 runs, a confidence interval of 99%, and an accuracy of 5%, after three iterations R converges to 9 runs. Every scenario was run 9 times.

4. RESULTS

The analysis developed with VISSIM/VISWALK, that allowed estimating the Vehicle Average Delay (VAD), the Pedestrian Average Delay (PAD) and the Total Average Delay (TAD), provided interesting results in regards the channelized right-turn lanes (CRTL) in urban signalized intersections.

Case 1, which has no CRTL, confirmed the intuitive idea that PAD and VAD are not independent. The result of the conflict between right-turning vehicles and crossing pedestrians is that any decrease in one delay results in an increase of the other delay. FIGURE 5 (case 1) shows that VAD increases considerably as the volume of pedestrians crossing the intersection increases. This is due to the priority of the pedestrian volume over turning vehicles in this conflict. When the pedestrian volume increases, it becomes difficult for the turning vehicles to find a gap between pedestrians and the VAD increases as seen in FIGURE 5.

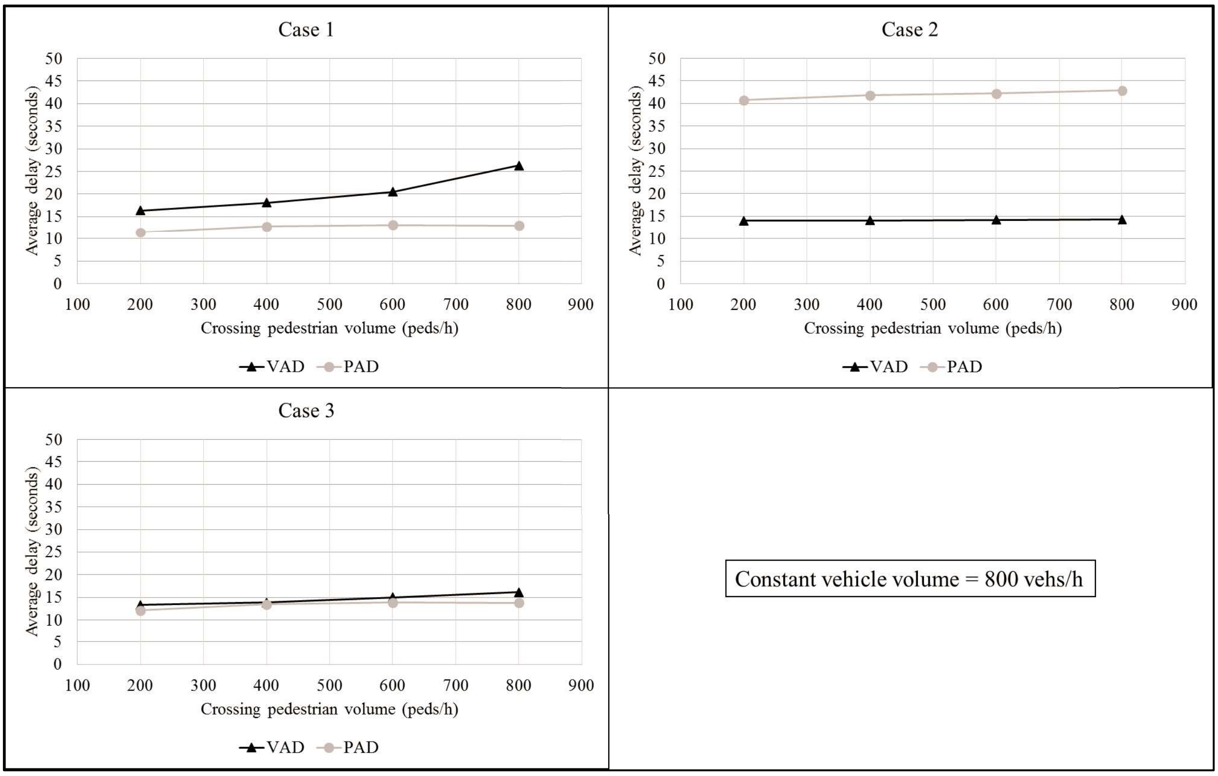

FIGURE 5 PAD and VAD with constant vehicle traffic (800 vehs/h) while pedestrian volume is varied

Another interesting finding from Case 1 is the little variability of PAD in high pedestrian volumes. Pedestrian can walk side-by-side, and the delays caused by substantial pedestrian increase are very small. Since pedestrians have priority in Case 1, high vehicle volumes do not affect PAD, but increasing pedestrian volumes do not increase PAD as would happen if pedestrian flows remained constant but vehicle traffic increased (FIGURE 6). In that case, the increased volume of vehicles alone would generate increased VAD.

Case 1 is the most convenient for pedestrians since it represents the easiest way to cross and assures that vehicles turn at low speeds. Pedestrian only need one stage and they just need to wait to get green in order for crossing the main street. However, VAD increases considerably as pedestrian volume increases (FIGURE 5) since cars need to find a gap between pedestrians to maneuver. In contrast, PAD does not increase significantly as traffic volume increases in this case (FIGURE 6).

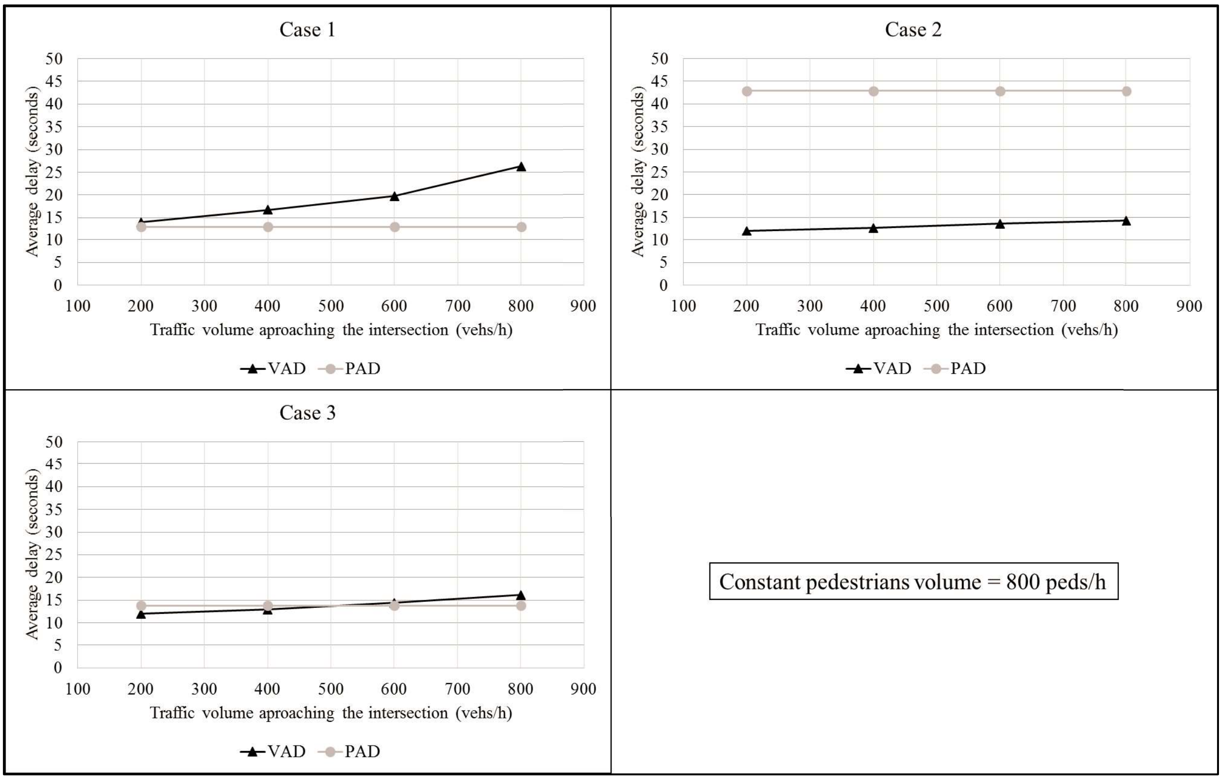

FIGURE 6 PAD and VAD with constant crossing pedestrians volume (800 peds/h) while traffic volume is varied

Adding a CRTL increases PAD but decreases VAD. In contrast to Case 1, results show that Case 2 and Case 3 increase PAD and reduce VAD for every scenario evaluated. This confirms previous research findings about the convenience of CRTLs for improving operational indicators for motorized traffic, considered in isolation. Conversely, if only VAD were taken into account, Case 1 would always be the worst right-turn treatment in terms of operations for motorized traffic.

CRTL with signal control for right-turning traffic (Case 2) is frequently used, but its benefits for pedestrian and vehicular traffic might not be the most convenient. To a large measure signal control determines delays for both pedestrians and vehicles. FIGURE 5 and FIGURE 6 show that PAD increases amost threefold in Case 2 while VAD remains low (similar to Case 1). Both results are consistent with reality. PAD increases substantially because pedestrians cannot cross the intersection in one phase. They have to wait to cross the channelized right turn lane until the parallel motorized traffic stops. When that occurs, and pedestrians cross the CRTL, they find the main crossing light red. Notice that PAD and VAD have very little variation when traffic volume or pedestrian volume increases in Case 2. In other words, traffic signals produce fixed delays so that a timing design that benefits one mode might magnify the delay for the other mode.

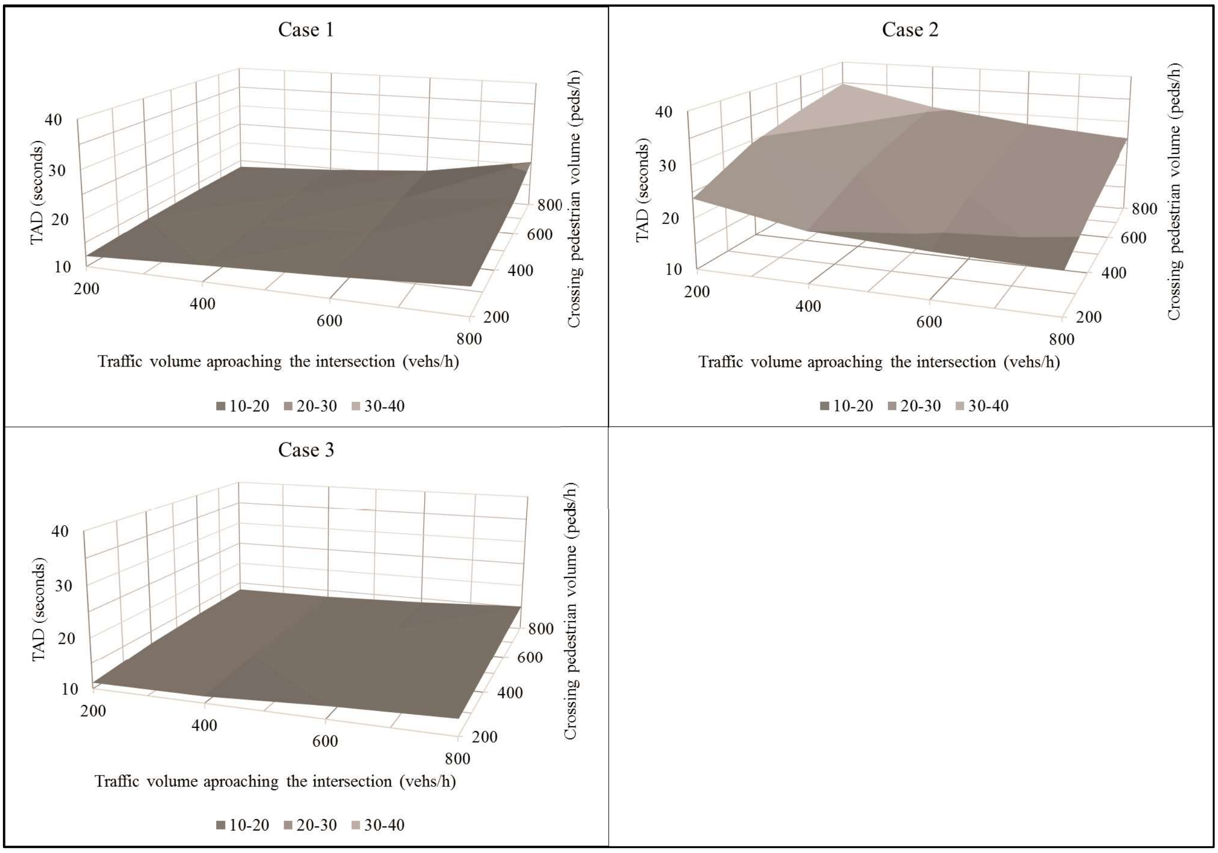

FIGURE 7 TAD for all combinations of pedestrian and vehicle volume evaluated

TABLE 2 Optimal right-turn treatment among Cases 1, 2 and 3 based on TAD

	Optimal right-turn treatment based on TAD				
		Traffic volume approaching the intersection (vehs/h)			
		200	400	600	800
Crossing pedestrian volume (peds/h)	200	Case 3	Case 3	Case 3	Case 3
	400	Case 3	Case 3	Case 3	Case 3
	600	Case 3	Case 3	Case 3	Case 3
	800	Case 1	Case 3	Case 3	Case 3

Case 3 provides the most convenient scenario in the majority of situations.

For Case 3, where pedestrian have priority in the unsignalized control of the CRTL, PAD and VAD remain low and constant as volumes change. It can be observed in FIGURE 5 and FIGURE 6 that variation of VAD and PAD are very similar. This is also consistent, since the situation for pedestrians is likely to be similar to that in Case 1. In contrast to Case 1, cars have more chances to make the right turn because they can find a gap during a red light since right turns in the CRTL are permitted on a red light. This means that cars have twice the time to find a gap because they can turn on both the green light and the red light.

Total Average Delay (TAD) considers the overall situation including delays of the various users. TABLE 2 present the most convenient cases for different pedestrian-traffic volume combinations as shown by evaluation with TAD. This evaluation shows that CRTL with no signal control (Case 3) is the right-turn treatment with less TAD in the majority of scenarios simulated. Right turns without CRTL (Case 1) are shown to be very convenient at low traffic volume (<200 veh/h) and high pedestrian volume (>800ped/h).

5. CONCLUSIONS

CRTLs in urban signalized intersections have effects on both vehicles and pedestrians. In general, this study confirmed that CRTLs can improve delays for vehicle traffic, but depending on the control type in the CRTL, effects on pedestrian flows might vary substancially. For pedestrians, intersections without CRTLs are the most convenient and intersections with CRTLs with signal control (Case 2) have the longest PAD. By using the Total Average Delay (TAD) as the performance indicator to evaluate different scenarios, we found that CRTLs with yield control represent the best option within a great range of pedestrian-vehicle volume combinations. Nevertheless, implementation of this type of solution requires that all measures to assure safety must be taken into account due to possible increases in turning speeds by motorized traffic and the possibility that an inconvenient visibility angle will be created for pedestrians.

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