
Volume 21F, November 2013
ISSN 1369-8478
ELSEVIER
TRANSPORTATION RESEARCH
AN INTERNATIONAL JOURNAL
Part F: Traffic Psychology and Behaviour
SPECIAL ISSUE
ITERATE and ISI-PADAS
Guest Editors: Andreas Lüdtke, Fabio Tango, Magnus Hjälmdahl and Björn Peters
Editors: Timo Lajunen, Türker Özkan and Bryan E. Porter
Supported by the International Association of Applied Psychology

Transportation Research Part F 21 (2013) 159–172

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

The impact of waiting time and other factors on dangerous pedestrian crossings and violations at signalized intersections: A case study in Montreal

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A R T I C L E I N F O

Article history:
Received 2 September 2011
Received in revised form 28 May 2013
Accepted 15 September 2013

Keywords:
Pedestrians
Violations
Crossing behavior
Signalized intersections
Safety

A B S T R A C T

Pedestrian violations of traffic signals and dangerous crossings at intersections are common. The objective of this study is to determine the impact of pedestrian waiting time at an intersection on the proportion and type of pedestrian violations and dangerous crossings. The amount of waiting depends on signal phasing, time of arrival, and the presence of a pedestrian signal. Thirteen intersections with similar geometry and traffic conditions but different maximum waiting times, seven of which had a pedestrian signal, were observed over at least 2 h to collect crossing information. Data was collected manually for the main analysis and complementary video data was used for validation.

Several factors were identified as having an impact on the proportion of pedestrian violations. In accordance with the literature, age, sex, group size, pedestrian flow and pedestrian signals are associated to pedestrian violations. In addition, other factors were identified in this research, such as maximum waiting time (red phase). It was also determined that an intersection clearing time had an impact on violations and on the proportion of dangerous crossings committed. Also, pedestrians' speeds depended on the type of crossing. The results underline the importance of providing pedestrian signals including countdown displays, which is significantly and negatively linked to dangerous violations and crossings. The results also highlight the importance of pedestrian maximum waiting time as well as clearing time. When designing cycle and phase lengths, particular attention should be paid to pedestrian waiting times that are positively correlated to violations. Minimizing waiting times for pedestrians is expected to reduce dangerous pedestrian behaviors at signalized intersections.

1. Introduction

Pedestrian safety in urban areas is an issue of growing concern. Pedestrian injuries represent an important proportion of total traffic-related injuries in Canada. Between 2004 and 2006, pedestrians represented about 13% of traffic fatalities with an average of 363 pedestrians killed each year (Transport Canada, 2010). In Canadian cities like Montreal, intersections are the most critical roadway elements with a high concentration of vehicle–pedestrian crashes – approximately 60% of pedestrians injuries happened at intersections in this city (Morency and Cloutier, 2005). This is not surprising, given the fact that intersections are where pedestrians are exposed to motorized traffic and are the most vulnerable. They are even more

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http://dx.doi.org/10.1016/j.trf.2013.09.010

vulnerable when crossing outside of an intersection crosswalk or during a red-light phase at a signalized intersection, since other road users will not expect their encounter.

To enhance pedestrian safety, local authorities are seeking a combination of appropriate interventions, often referred to as the 3 E's – engineering, enforcement and education. This reflects the fact that traffic-related pedestrian injuries can be the result of one or multiple contributing factors including human behavior, road design, and built environment. Many recent studies have highlighted the important role of road and built environment factors on pedestrian safety (Elvik, 2009; Harwood et al., 2008; Miranda-Moreno et al., 2011). Some studies have also demonstrated the importance of human factors. A few past works have investigated the factors associated with risky behavior of pedestrians, such as red-light violations – (Guo, Gao, Yang, & Jiang, 2011; Li & Fernie, 2010; Lipovac, Vujanic, Maric, & Nesic, in press; Ren, Zhou, Wang, Zhang, & Wang, 2011; Rosenbloom, 2009; Van Houten, Ellis, & Kim, 2007). While pedestrian–vehicle encounters rarely lead to collisions, pedestrian violations are an important factor in pedestrian fatalities. For instance, pedestrian violations contribute to 13% of the pedestrian fatalities in Canada, (Transport Canada, 2010). Pedestrian violations include crossing outside of designated markings, failure to yield to vehicles and crossing during a red-light phase. In the literature, violations have been associated with individual characteristics (age and gender) (Guo et al., 2011; Rosenbloom, 2009; Tiwari, Bangdiwala, Saraswat, & Gauray, 2007; Yagil, 2000; Zhuang & Wu, 2011), personal attitudes such as attitude towards subjective norms and social conformity (Evans & Norman, 1998; Moyano Diaz, 2002; Zhou, Horrey, & Yu, 2009), level of pedestrian density, group size (Rosenbloom, 2009; Zhuang & Wu, 2011), vehicular traffic conditions (Wang, Guo, Gao, & Bubb, 2011; Yagil, 2000; Yang, Deng, Wang, Li, & Wang, 2005), waiting time duration (Li & Fernie, 2010; Tiwari et al., 2007; Van Houten et al., 2007), length of the crossing (Cambon de Lavalette et al., 2009; Cinnamon, Schuurman, & Hameed, 2011), weather conditions (Li & Fernie, 2010; Yang et al., 2005), land use (Cinnamon et al., 2011; Zhuang & Wu, 2011) and trip purpose (Guo et al., 2011). These findings suggest that interventions to address traffic-rule violations should include enforcement and education actions as well as engineering countermeasures, such as the appropriate design of road geometry and traffic controls.

Despite the growing literature on this subject, very few empirical studies exist on effects of the maximum waiting time (red phase), pedestrian time of arrival at an intersection (moment during a phase at which the pedestrian arrived at an intersection approach), and the presence of a pedestrian signal, in particular in the North American context. Past studies have not classified and modeled violations according to the moment of the crossing with respect to the pedestrian signal. Previous studies have involved a very small sample of intersections in the analysis. Also, the use of video data for validation has been little explored.

This paper presents an analysis of pedestrian violations and dangerous crossings at signalized intersections and their relationship with factors such as maximum waiting time, time of arrival, and the presence of a pedestrian signal. These factors have been rarely studied simultaneously and this study adds to the previous ones by examining wait times based on arrival time during the cycle. Moreover, the sample of studied intersections is one of the largest considered in studies of this type. A discrete choice modeling approach is used to model violation types. In addition, video data is collected for two intersections and processed for validation.

The background of this work is presented in the next section. It is followed by a description of the proposed methodology, the presentation and discussion of the experimental results, and the conclusion.

2. Background

Factors associated with pedestrian crossing behavior have been widely studied. These factors are related to the individual characteristics, environment, and other pedestrians' and road users' behavior, and may have combined effects. Studies have determined that men have a tendency to commit more violations than women (Moyano Diaz, 2002; Rosenbloom, 2009; Tiwari et al., 2007; Yagil, 2000) and young adults tend to violate a traffic light more often than other age groups. As people age, they are less likely to take risks while crossing the road, due in part to their decreasing mobility (Guo et al., 2011; Zhuang & Wu, 2011). The people surrounding a pedestrian will also affect her or his crossing behavior. The larger the group of pedestrians, either traveling together or waiting at an intersection, the less likely a pedestrian is to violate the traffic control (Rosenbloom, 2009; Zhuang & Wu, 2011). Teenagers, however, are more likely to violate traffic control in a larger group: Rosenbloom (2009) suggests that teenagers traveling with their peers tend to take bigger risks for reasons such as social acceptance. The trip purpose is also likely to impact the decision to commit violations. People traveling to work or school are more likely to commit violations than people traveling leisurely (Guo et al., 2011).

A pedestrian's decision to violate traffic signalization will also be affected by the characteristics of the intersection. Factors such as the presence of a pedestrian signal (Cambon de Lavalette et al., 2009; Markowitz, Sciortino, Fleck, & Yee, 2006) and of countdown displays (Lipovac et al., in press) have been proven to reduce the proportion of violations. Research has also been undertaken on the waiting duration. Van Houten et al. (2007) examined the relationship between pedestrian waiting time and violations at two signalized midblock crosswalks. Minimum vehicle green time, i.e. pedestrian minimum waiting time, was manipulated from 30 s to 1 and 2 min, and it was found that violation rates increased when the waiting time increased. Similar conclusions were drawn from a study at seven intersections in India (Tiwari et al., 2007). Recent studies have also been done in China. Based on observations at five intersections, Wang et al. (2011) found that people who had violated the traffic signal had a slightly smaller waiting time threshold on average; in a more recent study and using survey data, Ren et al. (2011) studied crossing behaviors at signalized intersections in three cities. They found that the largest proportion of surveyed individuals (30.25%) indicated that they violated traffic rules to save time and for convenience. It is only in cases where the legal crossing must be made in two phases, that pedestrians would have much smaller waiting times if they committed a violation (Li & Fernie, 2010).

The length of the crossing will also have an impact: the longer the crossing, the less likely the violations (Cambon de Lavalette et al., 2009; Cinnamon et al., 2011). Land use and travel generators are also likely to have a correlation with the proportion of violations. At certain travel generators, violations have proven to be more common (Cinnamon et al., 2011; Zhuang & Wu, 2011). Pedestrians crossing illegally will wait for an acceptable gap between oncoming traffic to safely cross the street. When conflicting vehicle flow increases, theses gaps become smaller and rarer, making it more difficult for pedestrians to cross the street (Wang et al., 2011; Yagil, 2000; Yang et al., 2005).

Other factors, such as the day of the week, the period of the year or the time of day also impact the proportion of violations, as they are often linked to trip purpose and therefore change pedestrian behavior (Guo & Wu, 2011; Wang et al., 2011). Weather will affect the level of comfort of a pedestrian and therefore have an impact on their crossing behavior (Li & Fernie, 2010; Yang et al., 2005). A study conducted in Toronto concluded that in winter conditions, people are less likely to wait at an intersection due to the cold. Other weather conditions, such as heavy rain, are also likely to shorten pedestrians' patience (Li & Fernie, 2010).

The cultural context is also very important. Norms of conduct differ from one place to another, making it difficult to compare pedestrians from different cultural or social contexts (Rosenbloom, 2009). Furthermore, most studies are done at a punctual place or in a specific area or city, making it difficult to generalize to other urban areas. Regardless, while results such as the proportion of violations or the average time a pedestrian will wait can rarely be directly applied across locations, factors associated with crossing behavior seem to be constant from one region to another.

Researchers have also explored how personal attitudes can be linked to violations, including violations of the rules of the road. The theory of planned behavior (TPB) is one of the most widely used social psychological models of health and safety related behavior (Ajzen, 1991): one's decision to engage in a particular behavior depends on one's attitude towards that behavior, subjective norms, and perceived behavioral control. The TPB has been applied to understand pedestrians' road crossing decisions, in particular through questionnaires. Evans and Norman (1998) identified all three components of the TPB as significant predictors of road crossing intentions in three scenarios, with perceived behavioral control being the strongest predictor. Moyano Diaz (2002) examined TPB in the task of crossing at midblock: reported violations, errors and lapses appear causally related to the intention to violate traffic regulations. Young people have a more positive attitude towards committing violations, perceive subjective norms as less inhibitory while they have a lower perceived behavioral control. Zhou et al. (2009) also show that the tendency towards social conformity is associated with increased likelihood in crossing the road when other pedestrians were crossing. The variables of TPB, as well as perceived risk, were also significant predictors.

Despite this growing literature on pedestrian crossing behavior, in particular violations, few studies have looked at the link between violations and pedestrian waiting time, in particular in North American cities. To our knowledge, only one previous study (Van Houten et al., 2007) has looked at this issue, but their study examined two midblock crosswalks using precontrolled times. Also, several other factors have been associated with the proportion of violations. However, to the extent of our knowledge, there have been very few studies that examine the association of pedestrian signal presence, pedestrian group size, time of arrival or maximum waiting time with the propensity to commit a violation. Studies on waiting time did not discuss in detail the time of arrival of a pedestrian at the intersection. Do people commit violations because they arrived at the beginning of the red and must wait the whole red phase or do they commit violations whatever their time of arrival?

Moreover, violations are usually not differentiated with other dangerous crossings. Violations can be separated in different categories with different levels of risk. This is not to mention legal dangerous crossings that expose pedestrians to vehicles as much as certain types of violations.

This work contributes to previous research by adding empirical evidence related to the waiting time and other important factors in the North American context. Also, this paper proposes an original analysis of violations classified according to the moment of the crossing with respect to the pedestrian light, making use of a relatively large sample. As an exploratory analysis, the use of video data for validation is also investigated using a trajectory-based approach.

3. Definitions and methodology

Based on the Quebec Highway Safety Code (QHSC), violations in this study are crossings that started on the yellow light, red light, steady hand, or on the flashing hand (with the exception of countdown displays, in which case only finishing on the steady hand is a violation).[1] Dangerous crossings are crossings performed at least partly on the red light: such crossings expose pedestrians to conflicting traffic, defined as motorized vehicles that have the right of way during the red light for the pedestrians (there are also conflicts between pedestrians and turning vehicles during the green light for pedestrians, but drivers then expect

[1] In the presence of a pedestrian signal, pedestrians can start crossing on the walking man silhouette. Pedestrians cannot start crossing on the flashing hand, unless there is a countdown display present, in which case pedestrians can start on the flashing hand, as long as they finish crossing before the steady hand. If there is no pedestrian signal, pedestrians can only start crossing on the corresponding green light (Government of Quebec, 2011).

pedestrians crossing). Also, according to the same code (QHSC), pedestrians have the legal right of way at an intersection at all times, meaning that if a pedestrian started crossing legally but finished too late, it is not considered a violation, with the exception of countdown displays (Government of Quebec, 2011).

To investigate pedestrian crossing behaviors at signalized intersections and their associated factors, crossing behaviors are classified into the following three groups: regular crossings, dangerous crossings (dang.) and crossing violations (viol.). The two last categories overlap partially and can therefore be divided into three crossing types:

- Dangerous violations (dang. viol.): Pedestrians commit a dangerous violation when crossing during the red phase. They could either have started too early (beginning of crossing on "Anticipation" phase) or crossed during the red phase.
- Non-dangerous violations (non-dang. viol.): Certain violations do not expose pedestrians to conflicting vehicles. They occur when pedestrians start to cross too late (on the yellow light, flashing hand (unless there is a countdown display) or full hand) but still manage to finish before conflicting traffic gets the green light.
- Dangerous legal crossings (dang. leg.): If pedestrians start to cross on the walking man or on the green light, the crossing is legal, even if the end of the crossing is under the red light. While pedestrians have the right of way, the situation may be dangerous due to conflicting traffic.

All the thirteen selected intersections are in Montreal's Plateau-Mont-Royal borough. Twelve of them are on Sherbrooke Street and one is on Saint Denis Street, both of which are major arterials. This assured that all intersections had similar conflicting vehicle flow, similar geometry and land use. Data was collected on days considered similar, either Tuesdays or Wednesdays during two periods: the first between June 21st and July 5th, 2011, and the second between May 16th and June 13th, 2012. The weather on the days selected for data collection was sunny in the low twenties degrees Celsius. Two main considerations dictated when during the day it was decided to collect data. During peak hours, the high number of vehicles would produce fewer gaps, resulting in fewer opportunities for pedestrians to cross illegally. However, during non-peak hours, there would be fewer pedestrians to observe. Therefore, the end of the morning rush hour, between 9:30 AM and 11:30 AM, was selected as the best time period to collect data.

Intersections were also selected so that there would be a variety of maximum waiting times (MWT) for people wanting to cross Sherbrooke or Saint Denis Streets. Approaches on the selected intersections were divided into three categories:

1. Short MWT: those with a red phase between 40 and 45 s.
2. Moderate MWT: those with a red phase between 46 and 55 s.
3. Long MWT: those with a red phase above 56 s. In one of the cases, on the eastern crossing of Montcalm and Sherbrooke, MWT would vary between 55 s and 80 s, depending when the call for the pedestrian phase was made. This crossing was considered to have a long MWT.

Each MWT category has at least one intersection with a pedestrian signal, and one without. The only exception is the short MWT category, since there was no similar intersection in the area under study with a short MWT and a pedestrian signal. In the long category, there are five intersections with different types of pedestrian signals: standard, with countdown display and with a call button. The selected intersections, their location and their characteristics are presented in Fig. 1 and Table 1.

Counts were performed manually by teams of two people, one counting pedestrians and the other violations and dangerous crossings. Pedestrians committing violations or crossing dangerously were therefore counted in both datasets. Data collection was done over 10 days. The following information was collected:

- time of arrival (time at which a pedestrian arrives to the crossing),
- age group,
- sex,
- number of pedestrians moving together, or group size,
- number of pedestrians waiting at the corner at the beginning of the crossing,
- crossing used,
- direction of crossing.

Age was estimated in five age groups:

- child (age 0–8),
- teenager (age 9–17),
- young adult (age 18–35),
- adult (age 36–59),
- senior (age 60+).

For violations and dangerous crossings, additional information was collected:

Fig. 1. Location of selected intersections.

- time of arrival at the intersection,
- start time of crossing,
- end time of crossing,
- speed of crossing.

Time of arrival and crossing was categorized by the light state. These categories were:

- walking man/green,
- flashing hand,
- steady hand/yellow,
- beginning of red (first third of the red light),
- middle of red (second third of the red light),
- end of red (last third of the red light),
- anticipation of green (only for the start time of crossing).

Table 1
Characteristics of selected intersections.

Intersection	MWT (s)		Pedestrian signal	Number of observation periods	Total counts		Conflicting vehicle flow (veh/h)	Road width 5–10 m from intersection (m)	Crossing length (m)	Land use	Clearing time (s)
Amherst/Sherbrooke	Short	42	No	1	Pedestrians Dang. legal crossings Violations	183 16 (8.7%) 15 (8.1%)	1129	18.1	25.4	Urban/mixed	4
Frontenac/Sherbrooke	Short	42	No	1	Pedestrians Dang. legal crossings Violations	62 2 (3.2%) 4 (6.5%)	1855	18.4	22.9	Urban/mixed	4
Peel/Sherbrooke	Short	42	No	1	Pedestrians Dang. legal crossings Violations	725 17 (2.3%) 42 (5.8%)	1430	18.0	20.0	Urban/mixed	5
Fullum/Sherbrooke	Medium	46	No	1	Pedestrians Dang. legal crossings Violations	107 11 (10.3%) 9 (8.4%)	1598	18.7	24.2	Urban/residential	4
Iberville/Sherbrooke	Medium	46	Yes	2	Pedestrians Dang. legal crossings Violations	134 0 (0%) 32 (23.8%)	1812	18.7	23.7	Urban/mixed	15
Crescent/Sherbrooke	Medium	50	Yes, countdown	1	Pedestrians Dang. legal crossings Violations	93 0 (0%) 5 (5.4%)	1346	17.3	17.4	Urban/mixed	15
Hôtel-de-ville/Sherbrooke	Medium	51	No	1	Pedestrians Dang. legal crossings Violations	69 2 (2.9%) 5 (7.2%)	1428	18.8	22.7	Urban/mixed	6
Panet/Sherbrooke	Medium	52	Yes, countdown	1	Pedestrians Dang. legal crossings Violations	147 1 (0.7%) 15 (10.2%)	1757	18.1	21	Urban/residential	18
Montcalm/Sherbrooke (West crossing)	Long	56	No	1	Pedestrians Dang. legal crossings Violations	38 4 (10.5%) 4 (10.5%)	1812	18.7	23.7	Urban/mixed	4
Montcalm/Sherbrooke (East crossing)	Long	80	Yes, on call	1	Pedestrians Dang. legal crossings Violations	50 3 (6%) 36 (72%)	1574	18.8	24.4	Urban/mixed	12
Jeanne-Mance/Sherbrooke	Long	54	Yes	1	Pedestrians Dang. legal crossings Violations	348 0 (0%) 88 (25.3%)	1446	17.9	20.9	Urban/mixed	27
Saint-André/Sherbrooke	Long	58	No	2	Pedestrians Dang. legal crossings Violations	159 13 (8.2%) 53 (33.3%)	1324	17.8	18.4	Urban/residential	4
Saint-Urbain/Sherbrooke	Long	60	Yes, countdown	1	Pedestrians Dang. legal crossings Violations	355 0 (0%) 34 (9.6%)	1235	17.5	21.1	Urban/mixed	17
Saint-Denis/Des Pins	Long	57	Yes	1	Pedestrians Dang. legal crossings Violations	48 0 (0%) 9 (18.8%)	1570	18.2	19.4	Urban/mixed	17

For the start time of crossing, ''anticipation of green'' category was added to distinguish people who started to cross in the last third of the red light from people starting only a few seconds before the green light. Speed of crossing was separated in three categories: running, walking and disabled.

Two intersections required a second day of counts to verify preliminary results or to complete counting when there were too few pedestrians. In one of the cases, at the intersection of Saint-André and Sherbrooke, the additional information collected for violations and dangerous crossings (time of arrival at the intersection, start and end time of crossing, speed of crossing) was collected for all crossings. This allowed a better comparison of all types of crossings. Saint-André/Sherbrooke had a lower pedestrian flow which made this detailed data collection possible.

Because they were recorded separately, combining the violations and dangerous crossings dataset with the counts dataset was necessary. This was done by sequentially grouping entries with identical information together. In some cases, both entries did not match exactly. Small differences in age group, the number of pedestrians at the corner or the group size were ignored. If the information of both entries differed, the violations and dangerous crossing information was considered accurate. All violations and dangerous crossings were matched to a pedestrian crossing.

Video data was also collected for 3.5 h at two intersections, one with a pedestrian signal (Iberville/Sherbrooke) and one without (Amherst/Sherbrooke) (see Fig. 7). Manual counts were conducted simultaneously at these intersections. The purpose was to verify the observations made in the field, and to complement these observations by providing information on pedestrian crossing behavior, trajectories and position on the crosswalk. Using an open source automated video analysis tool (Saunier & Sayed, 2006; Jackson, Miranda-Moreno, St-Aubin, & Saunier, 2013) employed previously for pedestrian studies (Ismail, Sayed, & Saunier, 2010), road users' trajectories were extracted from 2 h of video starting at 10:00 AM at the two intersections. Pedestrians are identified based on their average speed, since it is smaller than cars', and a screen line orthogonal to the crosswalk, in the middle of the roadway, was used to select the trajectories relevant for the analysis. The timing of the pedestrian light could be easily manually synchronized to the video and used to identify the portion of trajectories in the roadway during the yellow and red phases.

4. Results and discussion

Results are presented in three parts: exploratory analysis, video-based validation and trajectory visualization, and statistical regression modeling results.

4.1. Exploratory analysis

After preliminary analysis, the data from Montcalm/Sherbrooke East crossing was removed from the main dataset and analyzed separately. The analysis is presented later in a separate sub-section.

The main dataset is presented in Fig. 2. Since intersections did not have the same number of pedestrians, the proportions of violations among all crossing events were used so every intersection would have the same weight in the average. For every type of violation, the presence of a pedestrian signal with countdown display reduces the proportion of violations. A standard pedestrian signal increases the proportion of violations, but almost two thirds were non-dangerous violations. All types of pedestrian signals reduce the proportion of dangerous crossings, which is consistent with the literature (Cambon de Lavalette et al., 2009; Lipovac et al., in press; Markowitz et al., 2006). For all types of violations, dangerous and non-dangerous violations, the longer the MWT, the higher the proportion of violations. The trend is unclear for dangerous and legal dangerous crossings, but this is related to the sample of intersections with a pedestrian signal, which reduces the proportion of dangerous crossings. There are four intersections with pedestrian signals in the long MWT category, three in the medium category and none in the short category. Results could therefore be caused only by the intersection sample.

The relation between intersection clearing time and type of crossing is presented in Table 2. Most intersections without a pedestrian signal had a yellow time of 4 s. The time necessary to cross the street was calculated with a walking speed of 1.1 m/s and the length of the crossing. On Jeanne-Mance/Sherbrooke, people walking normally can start crossing 8 s after the beginning of the flashing hand and still finish crossing the street in time. This leads to a high percentage of pedestrians crossing completely on the flashing hand. As the length of the flashing hand decreases, the share of this type of violation decreases. On Iberville/Sherbrooke, where the length of the flashing hand is 7 s shorter than the time needed to cross, very few people were able to complete their crossing during the flashing hand. Many more people finished crossing on the steady hand.

The difference between the time required to cross and the time offered is related to the proportion of dangerous crossings ending on the red light. Generally for intersections without pedestrian signals, the bigger the difference, the higher the share of dangerous crossings ending on the red light. Amherst/Sherbrooke has the biggest difference and one of the highest proportions of dangerous crossings ending on the red light among intersections without a pedestrian signal. Some standard pedestrian signals (Iberville/Sherbrooke, Crescent/Sherbrooke and Jeanne-Mance/Sherbrooke), which have a longer clearing time, seem to lower even more the proportion of people ending their crossings en the red light.

There is a particularly high proportion of people finishing on the red light for intersections with countdown displays. Strikingly on Saint-Urbain/Sherbrooke, none of the pedestrians finished their crossing on the steady hand, while many people finished on the red light (similarly only 7% finished their crossing on the steady hand at Panet/Sherbrooke while 80% on

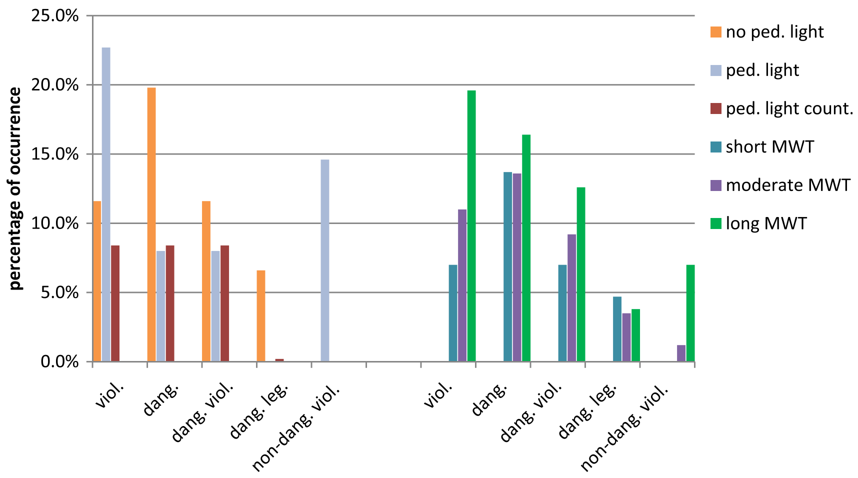

Fig. 2. Overview of data, showing average proportions of various types of violations per crossing event per group of intersections, based on the presence of pedestrian light and the length of the MWT.

Table 2
Effect of clearing time on violation type.

Intersection	Clearing time t_{cl} (s)	Necessary time to cross t_{cr} (s)	Difference $t_{cl} - t_{cr}$ (s)	% Observed out of all crossings		% Observed out of dang. crossings
				Beginning and end of crossing on the flashing hand	End of crossing on the steady hand	End of crossing on the red light
Amherst/Sherbrooke	4	23	−19	–	75	
Montcalm/Sherbrooke W	4	23	−19	–	50	
Fullum/Sherbrooke	4	22	−18	–	70	
Frontenac/Sherbrooke	4	21	−17	–	50	
Hôtel-de-ville/Sherbrooke	6	21	−15	–	0	
Saint-André/Sherbrooke	4	17	−13	–	30	
Peel/Sherbrooke	5	18	−13	–	27	
Iberville/Sherbrooke	15	22	−7	2	8	0
Saint-Urbain/Sherbrooke	17	19	−2	6	0	76
Crescent/Sherbrooke	15	16	−1	0	3	3
Saint-Denis/Des Pins	17	18	−1	6	6	67
Panet/Sherbrooke	18	19	−1	0	7	80
Jeanne-Mance/Sherbrooke	27	19	8	18	5	10

the red light; Crescent/Sherbrooke has low proportions of pedestrians finishing both on the steady hand and on the red light). This result seems to support the findings of Wanty and Wilkie (2010), who suggested that when a countdown display is present, people tend to cross according to the time remaining, but often underestimate their crossing time. People therefore probably either made sure to complete their crossing before the end of the countdown or underestimated their crossing time and finished too late, on the red light.

The number of pedestrians traveling together also seems to have a correlation with the number of violations. A clear trend can be observed in Fig. 3. As the group size increases, the proportion of violations decreases. This is consistent with the findings of Rosenbloom (2009) and Zhuang and Wu (2011). A similar pattern is observed with the number of pedestrians waiting at the corner; however, this is not reported and used since a large proportion of the information was missing – this variable was difficult to collect with accuracy in the field.

The relation between speed of crossing and crossing type was also studied. Out of the observed dangerous crossing and violation data, three types of crossings have a higher occurrence of people running: end of crossing on the red light (36% running), end on the steady hand (12%) and crossing on the red light (28%). Other types of crossings have a lower running occurrence (3%). The same tendency can be observed with the complete data of Saint-André/Sherbrooke, where people ran 33% of the time when ending on the red light, 10% of the time when crossing on the red light, but only 4% of the time while crossing completely on the green light or starting by anticipation. This seems to support the findings of Zhuang and Wu (2011) who reported that people run for two reasons: either to complete their crossing or to avoid vehicles.

The characteristics of the pedestrians committing violations are represented in Fig. 4. On average, men seem to commit more violations of both types, dangerous or not, than women, and young adults seem to commit more violations than other age groups. These findings confirm what can be found in the literature (Guo et al., 2011; Rosenbloom, 2009; Tiwari et al., 2007; Yagil, 2000; Zhuang & Wu, 2011). Types of crossings also differ with age. For instance, more than 50% of seniors'

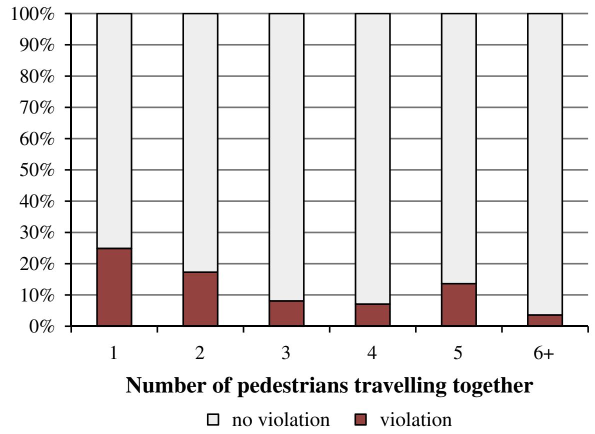

Fig. 3. Proportion of violations as a function of the number of pedestrians waiting at corner and group size.

dangerous legal crossings are people ending on the red light (dang. leg.) compared to around 35% for others. This would be consistent with decreasing mobility due to age. Children were not represented on this figure because of the limited number of observations.

Fig. 5 illustrates the moment of arrival of pedestrians and the moment they decide to cross. Only the average of all crossings was presented for dangerous crossings and violations because they all had very similar patterns of arrival and departure. There are two darker zones, the diagonal and the first and last columns. The diagonal represents people arriving and starting to cross almost instantly. The second darker zone can be observed on the anticipation column and the green column of the Saint-André/Sherbrooke data which also shows legal crossings. This group represents the people who waited for the green light. The two groups correspond to the groups described by Yang et al. (2005) and Tiwari et al. (2007). These findings may explain why previous studies have observed similar waiting times whether people commit violations or not (Wang et al., 2011). Some pedestrians will cross shortly after they arrive, whether the light is green or red. Only their moment of arrival will determine if they commit a violation or not. The second category, people who will wait for the green light, will also be divided between violations and non-violations. If people wait during the red light but start to cross seconds before the green light (“anticipation”), it is still a violation. This means that time of arrival at the intersection has little impact on the behavior of people. The proportion of illegal crossings will be related to factors concerning pedestrians themselves or external factors.

4.2. Video-based validation and trajectory visualization

The validation was made on the basis of groups of pedestrians and not individual pedestrians, which cannot be distinguished by the automated tracking system. The validation results are reported by type of violation for Amherst/Sherbrooke in Table 3. The false detection is actually a cyclist riding his bike on the crosswalk and finishing his crossing on the red light. The missed detections happen when the pedestrians are not tracked at all. It can also be noted that 87 groups were tracked automatically, while 79 were counted by observers. Although the count of crossings is small, this result is on par with previous evaluations (Saunier & Sayed, 2006) and confirms the potential of video-based technologies for pedestrian behavior analysis.

The analysis of the pedestrian trajectories was done by visualizing in Fig. 6, the spatial density of the pedestrian crossings for the two intersections where video was collected. The first observation is that most pedestrians seem to be walk beside the crosswalk: this problem is caused by the low angle of the camera (a mobile video recording system described in Jackson et al. (2013) was used, where the camera is about 7 m high), the perspective and the tracking of pedestrian typically at mid height, as can be seen in Fig. 7. This makes spatial violations difficult to detect automatically. The small number of crossing observations at both locations does not permit to develop and validate a method for the detection of spatial violations. It is nevertheless clear that there is a fair share of pedestrians walking outside of the crosswalk, in particular taking shortcuts at the beginning or the end of their crossing. It seems that the spatial density is more diffuse at Amherst/Sherbrooke, which could indicate more spatial violations in the absence of a pedestrian light, but more work is needed to draw any conclusion.

4.3. Statistical modeling results

This section presents the discrete-choice analysis based on the logistic regression technique that was carried out to analyze the three different types of violations. This analysis allowed identifying the factors associated to the propensity of violation and the magnitude of their effects. In this case, $y_{ik} = 1$ if individual i ($i = 1,\ldots,n$) commits a violation of type k ($k = 1, 2, 3$) and 0 otherwise. The statistical model for logistic regression is then given by $\log\left[\frac{p}{1-p}\right] = \beta x$, where p is a binomial (violation) proportion, x is the vector of associated factors and β is the vector of parameters estimated from the data. The attributes (x) included in this analysis are those defined in Section 3, which include traffic control and geometry factors (pedestrian

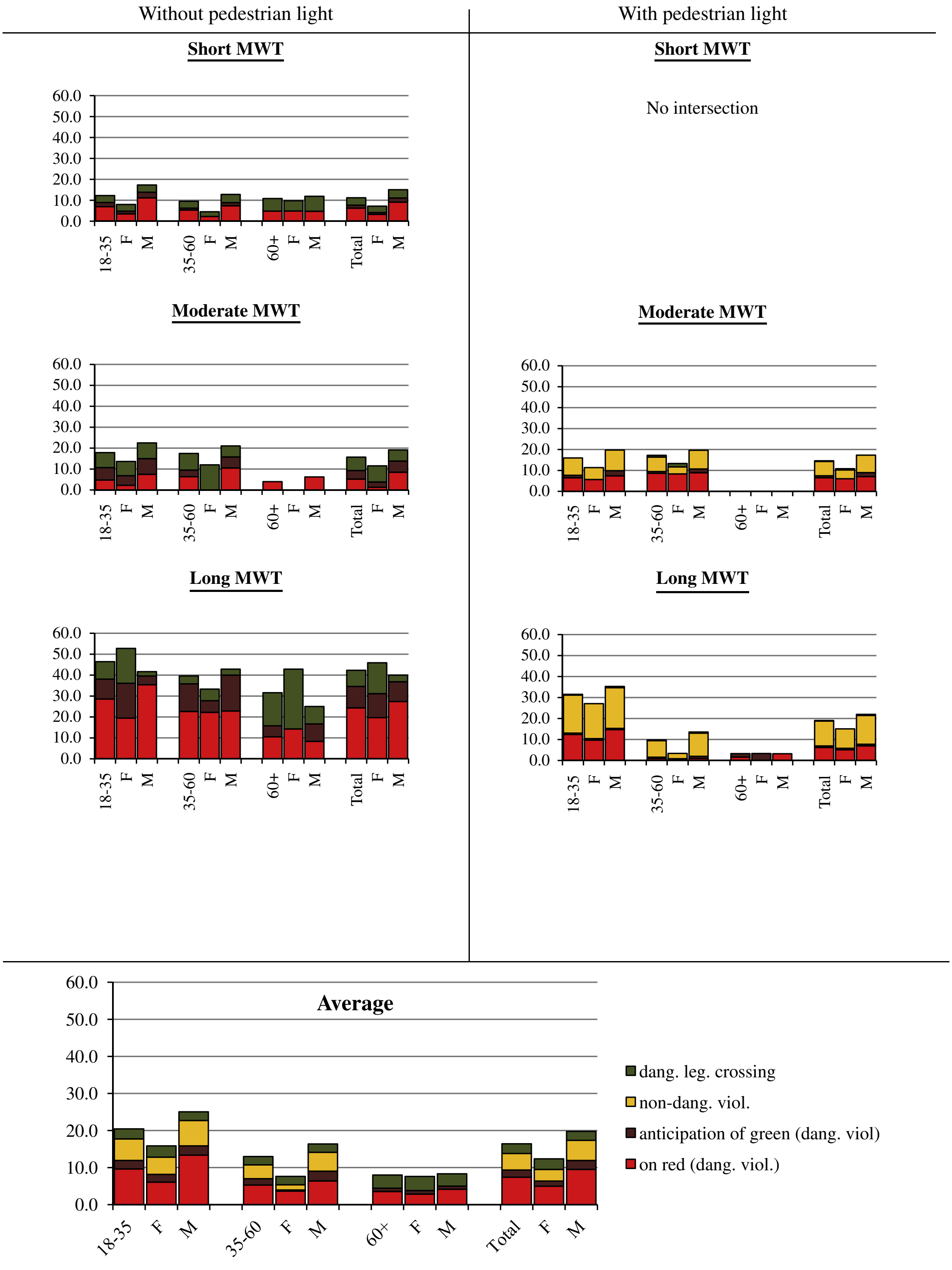

Fig. 4. Average number of violations for 100 pedestrians for each age and sex category for the 3 categories of MWT, with and without a pedestrian signal.

signal, countdown pedestrian presence, MWT and crossing length), individual factors (sex and age) as well as vehicular and pedestrian flow attributes (group size, pedestrian and vehicular flow intensity in the approach). For variable selection, p-values and confidence intervals were considered; variables with p-values less than 5% were retained in the final model. Correlation among explanatory variables was also verified to avoid collinearity issues. All models were estimated with the open source econometrics software Biogeme (Bierlaire, 2008, 2003). Variables tested included information on intersection characteristics, such as crossing length, but these characteristics were not significant in the models, which confirmed that the selected intersections had similar configurations. Different models were estimated using the maximum likelihood technique. The likelihood ratio test was used to determine the significance of adding one or more new variables (compare models). Also,

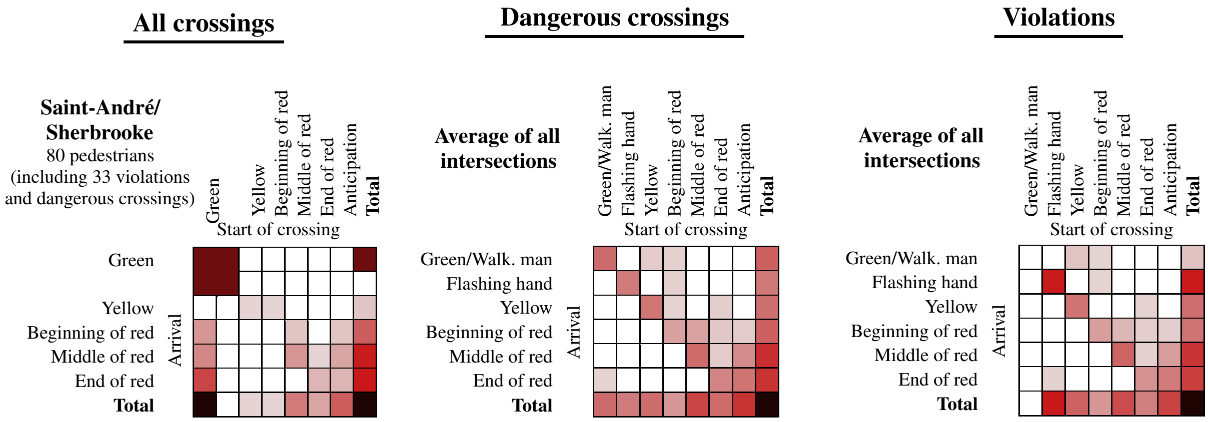

Fig. 5. Cross tabulation of the times of arrival and of start of crossing (the darker the color, the higher the proportion of observations with respect to the total number of observations). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Validation of the automated detection of pedestrian violations, by type, at Amherst/Sherbrooke.

Type of violation	Correct detections	Missed detections	False detections
Anticipation	3	0	0
End on red	7	1	1
On red	1	1	0

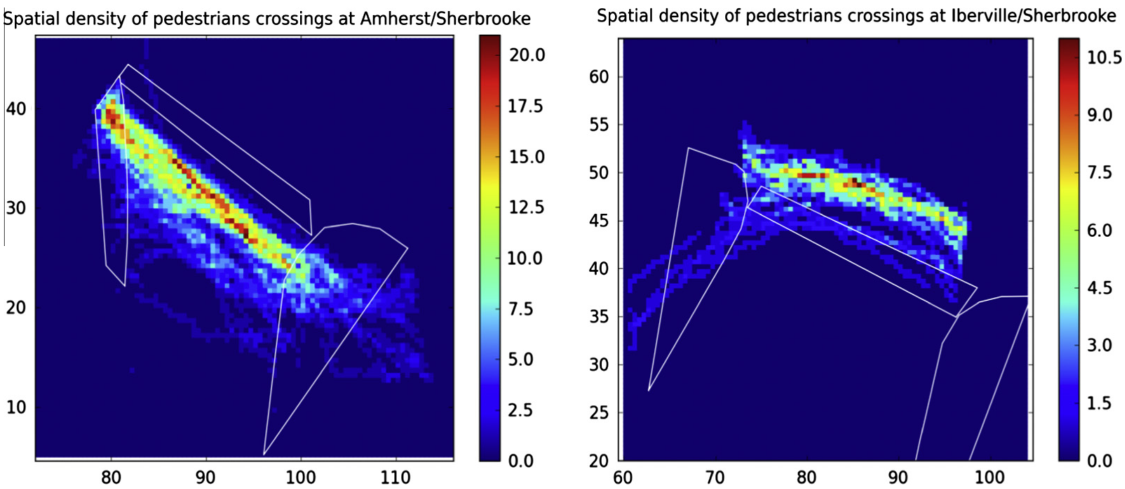

Fig. 6. Spatial density of pedestrian crossings for 2 h (10:00 AM–12:00 PM) for the west crosswalks at Amherst/Sherbrooke (left) and Iberville/Sherbrooke (right) (in white are overlaid the crosswalk and the corresponding sidewalks).

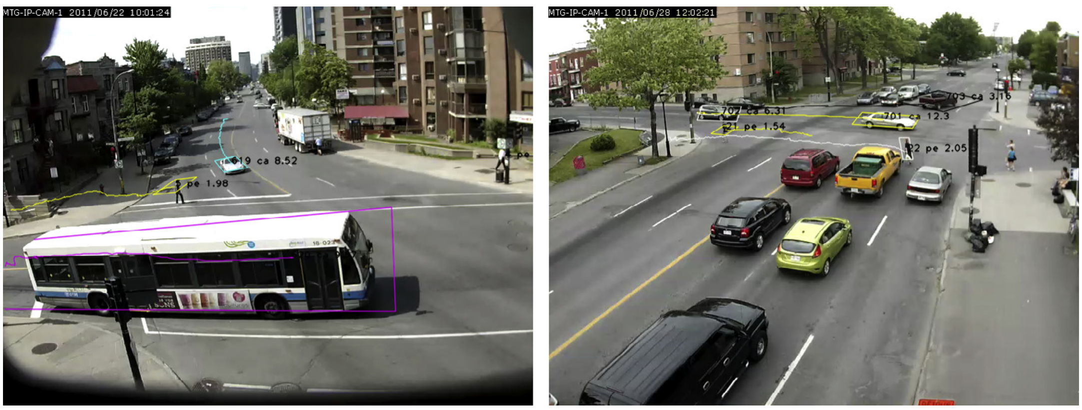

Fig. 7. Example of pedestrian crossings and their tracks overlaid over the camera image at Amherst/Sherbrooke (left) and Iberville/Sherbrooke (right).

Table 4
Logistic regression models.

	Model 1: All violations (viol.[+])			Model 2: Dangerous violations only (dang. viol.)			Model 3: All dangerous crossings (dang.[++])		
	Coef.	Elasticity	*p*-Value	Coef.	Elasticity	*p*-Value	Coef.	Elasticity	*p*-Value
Constant	−5.76	–	0.00	−3.74	–	0.00	−2.94	–	0.00
Standard ped. signal	–			−0.980	−5.2%	0.00	−1.41	−10.7%	0.00
Count. ped. signal	−1.54	−15.9%	0.00	−1.48	−7.3%	0.00	−2.30	−15.7%	0.00
Group size	−0.319	−0.9%	0.00	−0.383	−0.5%	0.00	−0.326	−0.7%	0.00
Sex (*M* = 1)	0.501	6.6%	0.00	0.719	4.6%	0.00	0.326	3.2%	0.01
Age: 18–35	0.543	7.3%	0.00	0.543	3.6%	0.00	0.345	3.4%	0.01
Ped. flow (in hundreds)	−0.0469	−0.6%	0.00	−0.0936	−0.6%	0.00	−0.113	−1.1%	0.00
MWT	0.102	7.9%	0.00	0.0585	2.1%	0.00	0.0663	3.6%	0.00
Log-likelihood ratio	1367.9			2019.1			1654.2		
Number of observations	2475			2475			2475		
Rho-square	0.40			0.59			0.48		

[+] Viol. = dang. viol. + non-dang. viol.
[++] Dang. = dang. viol. + dang. leg.

the rho-square statistic is used as a measure of goodness-of-fit with values between 0 and 1 that correspond to perfect fit. In the literature, values between 0.2 and 0.4 indicate good results.

The best models obtained are presented in Table 4. Model 1 predicts general violations (viol. = dang. viol. + non-dang. viol.) from the crossing data. Models 2 and 3 are similar to model 1, but Model 2 predicted dangerous violations only (dang. viol.) and Model 3 dangerous crossings (dang. = dang. viol. + dang. leg.). This table also includes the elasticities that were calculated at the mean values. For continuous variables, the reported elasticities are for an increase of 10%. The model goodness-of-fit statistics indicate a relatively good fit of the selected models to the data. The results show that:

- Regarding factors associated with traffic control, one can see that the presence of a pedestrian signal (of any type) decreases significantly the probability of dangerous crossings and violations, which is consistent with past studies (Cambon de Lavalette et al., 2009; Markowitz et al., 2006). The addition of a countdown display to a pedestrian signal is also negatively linked with the probability of violations as found in (Lipovac et al., in press). At intersection crosswalks with countdown display, the propensity of violation or dangerous crossing is about 15% lower than at intersection crosswalks without a countdown. MWT also appears to have an impact on violations. A 10% increase in MWT is associated with increases in the probability of violation and dangerous violation of 7.9% and 2.1%, respectively.
- Group size and pedestrian flow decrease the probability of violations being committed; reducing either variable by 10% separately will decrease the probability of violations by a maximum of 0.9% and 0.6%, respectively. Also, the probability of committing a violation is higher for men. Moreover, being a young adult has a high impact on a person's probability of committing a violation or a dangerous crossing. These results are in accordance with previous works which found that young adults, men and smaller groups all increased the probability of violations (Guo et al., 2011; Rosenbloom, 2009; Tiwari et al., 2007; Yagil, 2000; Zhuang & Wu, 2011).

4.4. The special case of call buttons (Montcalm/Sherbrooke)

Montcalm/Sherbrooke's East crossing was removed from the main dataset. At this intersection, the phasing on the West crossing is not the same as the East crossing. On the West crossing, there is no pedestrian light: people must cross during the vehicle phase. On the East crossing, there is an exclusive pedestrian phase activated on call. The fact that the two crossings are different seems to create confusion among pedestrians since 72% of pedestrians on the East crossing did not cross legally. 66% crossed on the green vehicle light, and therefore committed a violation. Of the 50 people who used the East crossing, only 11 used the call button and crossed legally. The MWT is 80 s on the East crossing. This might explain why 3 people used the call button but crossed on the West crossing. On the West crossing, results were similar to other intersections, with 89% of crossings being legal (compared to 80% in average). This demonstrates the importance of clear and consistent signalization.

5. Conclusion

This study was conducted to evaluate the impact of pedestrian waiting time (due to phasing length and time of arrival), of time of arrival, and of the presence of a pedestrian signal on the proportion of pedestrian violations and dangerous crossings. Variables such as being male, being a young adult, and intersection MWT increased the proportion of violations. Other variables decreased the probability of violations, such as the presence of a pedestrian signal or group size. The results highlight the importance of engineering countermeasures as part of the solution to pedestrian violations. When designing the cycle length and effective green/red times for each phase, particular attention should be paid to pedestrian waiting times. Some variables will have an impact on the type of violations. If the clearing time is longer than the time needed to cross the street, people are likely to start crossing during this period and therefore commit a violation. On the other hand, especially on intersections without pedestrian signals where the clearing time is always shorter than the time needed to cross, the higher the difference between the time given and needed, the more people will cross dangerously by finishing their crossing on the red phase. This work shows the importance of properly timing pedestrian signals. To reduce violations and dangerous crossings, the clearing time should be as close as possible to the required time of crossing. A shorter clearing time endangers pedestrians who will have to finish on the red light and all extra time available should be given in the walking man phase.

The moment of arrival at the intersection seems to have little impact on people's crossing behavior. Pedestrians can be classified in two types: people who will start crossing almost immediately after they arrive and people who will wait for the green light (even if they often commit a violation by anticipating it by a few seconds). This may explain why other studies have found similar average waiting time for pedestrians before crossing (Wang et al., 2011).

In future research, these findings could be validated by collecting data from a larger sample of intersections and different Canadian cities. The data used in the analysis was collected manually, which may lead to errors by people collecting data such as missing pedestrians, age being wrongly evaluated or errors in transcription. Automated data collection methods using video data can be used to improve accuracy, with fewer efforts and less processing time, and provide very detailed spatial information as demonstrated in this work. Trajectories obtained from video could provide insight on interactions between pedestrians and cars. It would also be interesting to compare the results from this study to crash records to see if dangerous situations are correlated to higher crash rate.

This study focused on a sample of intersections in the central area of Montreal, Canada. Despite our efforts, results might be specific to these intersections. A larger scale study with more intersections and different cities could confirm findings. A study done with complete data, like the one collected at Saint-André/Sherbrooke, would allow a better comparison of all types of crossings.

Acknowledgments

The authors wish to acknowledge the help of Jean-Simon Bourdeau, Aleksiina Chapman Lahti, Georges Rizkallah, Abdessalih Sedrati, Thomas Nosal, and Aurélien Taine who participated in the data collection, and the Montreal borough of Plateau Mont-Royal for the opportunity to collect count and video data. The authors thank Thomas Nosal for proofreading the manuscript and the anonymous journal reviewers for their helpful comments. We would like also to acknowledge the financial support of the Fonds de recherche du Québec – Nature et Technologies (road safety research program FQRNT-MTQ-FRSQ).

An initial version of this work, relying on data collected at seven of the intersections in 2011, has been presented at the Transportation Research Board annual meeting in Washington DC in January 2012.

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