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Modeling vehicle–pedestrian interactions outside of crosswalks

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ABSTRACT

Pedestrian and driver behaviors as well as their interactions, are essential in planning, designing and operating highway facilities. Pedestrian crossing outside of a marked or unmarked crosswalk (i.e. jaywalking), is one of those pedestrian behaviors that may highly affect safety and operations. Unlike permissible crossings at crosswalks, jaywalking events are not often anticipated by drivers, which may result in less driver reaction time and different vehicle operation dynamics. It is important to understand pedestrian crossing behavior outside of crosswalks, as well as driver yielding behavior towards them. To date, limited quantitative and behavioral research has been conducted to investigate this interaction or simulate it microscopically. This paper aims to explore both pedestrian jaywalking behavior (gap acceptance and speeds) and the corresponding driver reactions (yielding behavior) for modeling the vehicle–pedestrian interactions (VPI) outside the crosswalks in a micro-simulation environment. The study also quantifies the differences between vehicle–jaywalker and vehicle-permissible crossing. An observational study and an instrumented vehicle study were conducted on the campus of the University of Florida to collect data from pedestrian and driver perspectives, respectively.

Crossing speed, yield acceptance and delay of jaywalking crossings and permissible crossings were observed in the study and these attributed can be used for replicating pedestrian operations in simulators. Moreover, behaviors of driver approaching jaywalkers versus pedestrians crossing at designated crosswalks were compared on the basis of yield rates, and vehicle speed profiles. Vehicle yield dynamics were analyzed to model the driver reactions towards jaywalkers. Lastly, it was found that the locations of jaywalking events are highly concentrated and influenced by the crossing environment, such as pedestrian and vehicular volume, bus stops presence and crossing distance.

This paper establishes several quantitative relationships describing interactions between pedestrians crossing outside of crosswalks and approaching drivers, which provide the basis and assumptions for modeling such interactions in a micro-simulation environment for traffic operational analyses.

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1. Introduction

From 2007 to 2011, an average of 12.4% of total crash fatalities were pedestrians [1]. Among those "Pedestrian–Vehicle" crashes, 73.1% occurred at non-intersections (unmarked crosswalks), while only 22.2% were at intersections, or intersection-related locations. Pedestrian crossing in locations other than marked or unmarked crosswalks (jaywalking) is a potentially unsafe behavior. Florida state law 316.130 (11) [2] indicates that pedestrians shall not cross at any place except in a marked crosswalk between adjacent intersections at which traffic control signals are in operation. Vehicle–jaywalker interaction (VJI) occurs where pedestrian volume is relatively high and destination attractions are randomly distributed in the vicinity of a crosswalk (for example a campus environment, a CBD of a major city). Pedestrian behaviors at unmarked crossings are reported to be quite different from crossings at marked crosswalks [3,4]: jaywalkers behave more cautiously (look at both directions, hurry to cross) and are more likely to cross during larger gaps. Several factors influence jaywalking locations [5], i.e. the presence of bus stops, average annual daily traffic, etc. From an operations and planning perspective, it is important to understand how drivers yield to jaywalkers vs. other crossing pedestrians, as well as the jaywalking gap acceptance and speeds. However, there have been few studies analyzing the jaywalker behavior as well as examining the driver reactions to them.

The objective of this paper is to explore and quantity pedestrian jaywalking behaviors (crossing outside the crosswalks) and the corresponding driver yielding dynamics for modeling their interactions in a micro-simulation environment. The data collected and methods developed in this paper provide the basis and assumptions that can be used within micro-simulators to model those interactions. Developing models that estimate the probability of jaywalking at a particular location is outside the scope of the paper, however we do summarize our observations related to jaywalking environments studied here. Our focus is rather in modeling the movement of the vehicle and the pedestrian at locations where jaywalking is expected to occur.

An instrumented vehicle experiment and an observational study were conducted on the campus of the University of Florida, in Gainesville, Florida to study the locations where pedestrians jaywalk and the way drivers react to them. The university campus environment, with high levels of pedestrian activity and significant number of jaywalkers, is ideal in conducting this exploratory study. The paper collects data and analyzes the crossing speed, critical gap and yield acceptance between permissible crossings and jaywalkers, as well as drivers' interactions with those two types of pedestrians. This study was conducted as part of a broader project on pedestrian–vehicle interactions [6].

The next section provides a brief literature review on vehicle–jaywalker interactions, while Section 3 describes the data collection for the instrumented-vehicle and observational studies. Section 4 presents the analysis results and findings, while the last section provides conclusions and recommendations.

2. Literature review

Several previous studies in the past have examined pedestrian crossing behaviors, crossing speed [7–10], gap acceptance [6,11,12], and trip route choice [13–15]. However, few of them have considered pedestrian jaywalking events. Similarly, there have been few studies that have considered driver reaction to pedestrians outside the crosswalks.

According to Golledge [16], and Kneidl and Borrmann [17], pedestrians prefer to walk long and straight routes to a destination in an urban environment (SALL algorithm). Mitman et al. [3] compared pedestrian behaviors at marked and unmarked crosswalks and indicated that pedestrians at unmarked crosswalks are more likely to look at both ways before crossing, to run, and to wait for larger gaps. Zhuang and Wu [4] found that jaywalkers in the urban cities of China are less likely to have a crash when they are middle-aged, are in larger crossing groups, are more attentive to traffic. The highway environment impacts on crossing behaviors or preferences have been examined by several papers. Chu et al. [18] modeled the role of street environment in the way people cross urban roads. Crossing distance and traffic volume were found to highly affect why people cross where they do [5]. A study conducted by the Federal Highway Administration (FHWA) [5] indicated that the environmental factors that ultimately influence pedestrian jaywalking locations were: the distance between marked crosswalks, annual average daily traffic (AADT), physical barriers that might prevent pedestrians from easily crossing the roadway, the presence and location of bus stops, the number of potential pedestrian trip originators and destinations, the presence of a "right turn only" lane, the width of the roadway/pedestrian crossing, and the presence of a T-intersection between the two marked crossings. Several studies applied the "Theory of Planned Behavior" to evaluate people's intentions of road-crossing, and provided useful insights into understanding what affects pedestrian's choice of jaywalking psychologically [19–21]. It was found that pedestrian's perceived behavior control was one important factor on crossing intentions, and it was highly affected by the crossing facilities and environment. Also, pedestrians were aware of the risk of illegal crossing, but sometimes they still chose to jaywalk.

In terms of driver reactions for permissible crossings, Schroeder and Rouphail [22] found that drivers are more likely to yield when they are traveling at low speeds, have low deceleration rates and to more assertive pedestrians. They developed a logit model to simulate driver yield behaviors at unsignalized intersection crosswalks. However, no studies have focused on the analysis of vehicle operation dynamics nor the speed behavior towards the crossing pedestrians.

3. Methodological framework

An instrumented vehicle study was conducted firstly to understand driver's attitudes and their behaviors to jaywalkers, as well as jaywalker's crossing location and characteristics. The research team recruited subjects who then drove along two predetermined routes within the University of Florida campus. After that, an observational study was conducted to collect data at the high jaywalking frequency locations identified from the instrumented vehicle experiment. The details of each of the two data collection efforts are provided below.

3.1. Instrumented vehicle study

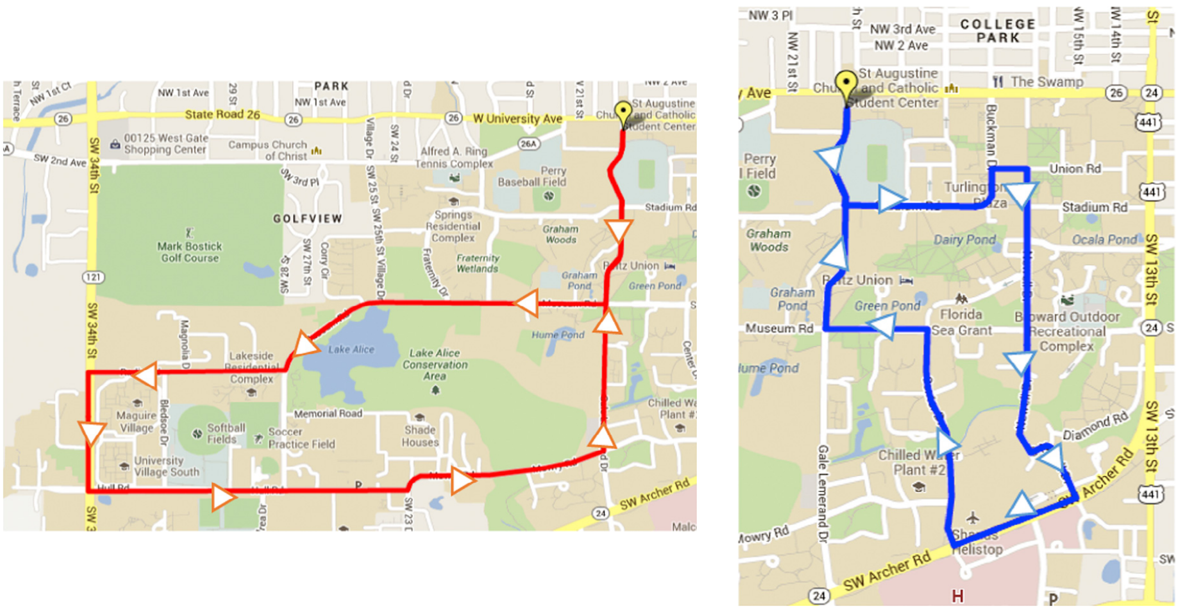
The instrumented vehicle study enables real-time recording of speed, location, etc., using a data acquisition system [23,24]. The instrumented vehicle used in this study is a Honda Pilot SUV, owned by the University of Florida Transportation Institute (UFTI). The vehicle has a built-in GPS where all information about vehicle position and speed data is displayed and recorded on a Honeywell Mobile Digital Recorder (HTDR400) system.

The study team selected two routes on the campus in University of Florida, each with approximately 18 midblock crossings. The total distance of Route 1 is 4.7 miles and the estimated travel time is 16 min. There are 17 midblock and 7 signal crossings along the route. The total distance of Route 2 is 2.8 miles and the estimated travel time is 20 min. There are 19 midblock and 7 signal crossings along the route. More pedestrian interactions exist along Route 1 than Route 2. Fig. 1 provides maps of the two routes. After IRB (Institutional Review Board) approval was obtained, 15 participants with varying driving characteristics were selected based on age, gender, driving experience, occupation, and vehicle ownership through a prescreening questionnaire (Table 1 provides an overview of the participant characteristics).

Data were collected on weekdays starting at 4:30 pm. Each participant was asked to meet the researchers at a pre-specified point. Upon arrival, a check-in procedure was followed: showing a valid driver's license, signing the informed consent form, and completing the pre-driving survey. Drivers were not told about the exact objective of this study in advance, so that they were not looking for jaywalkers or pedestrians specifically during the experiments. One researcher accompanied each subject and took notes regarding driver behavior and traffic conditions. After the completion of each route, drivers were asked to complete a questionnaire regarding their actions and choices throughout the route. Questions related to lane-changing, yielding, and actions around pedestrian walkways, bikeways, and transit vehicles. After the completion of both routes, a final questionnaire was used to summarize drivers' experiences during the entire experiment. The total duration of each experiment was approximately one hour.

The following data were collected for each participant and each route they drove:

- Vehicle trajectory (speed, acceleration), and vehicle yield/no-yield decision to jaywalkers.
- Pedestrian and jaywalker's reactions to driver yields.
- Traffic flow conditions and roadway environment.



(a) Route #1 **(b) Route #2**

Fig. 1. Maps of two study routes for the instrumented vehicle data collection.

Table 1
Overview of the participants and their characteristics.

Characteristics	Number of participants	Percentage of participants (%)
Age		
<25	2	13.33
25–35	9	60.00
35–45	1	6.67
45–55	2	13.33
>60	1	6.67
Gender		
Female	7	46.67
Male	8	53.33
Identification group		
Caucasian	8	53.33
Hispanic	4	26.67
African American	3	20.00
Driving hours per week		
<4	3	20.00
4–8	6	40.00
8–14	4	26.67
>14	2	13.33
Total	15	100

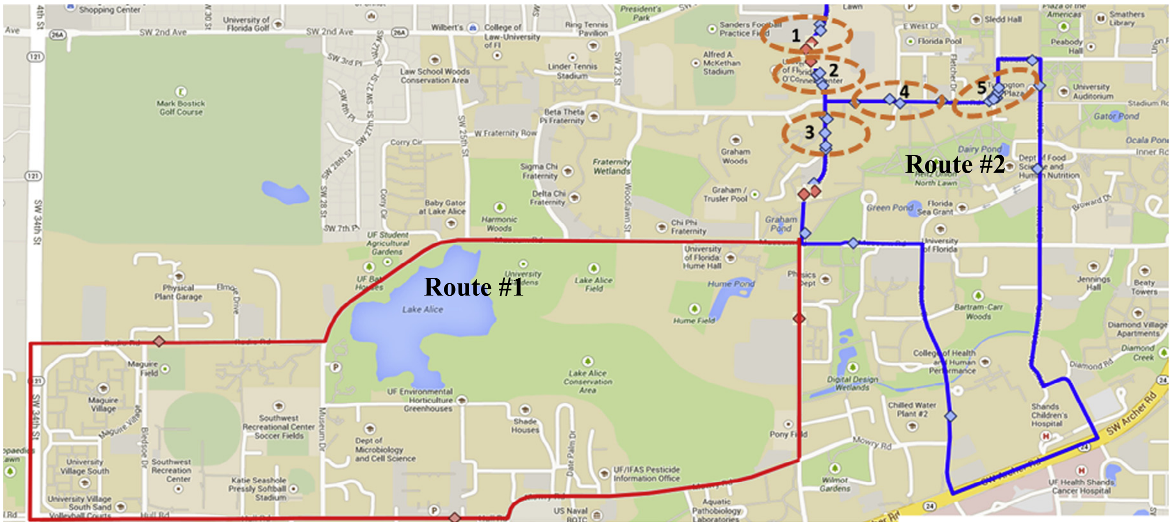


Fig. 2. Observed Jaywalking Locations.

3.2. Observation study

At the locations where a high number of jaywalkers were observed from the instrumented vehicle study (Fig. 2), the research team conducted a follow-up observational study of pedestrian behavior at the same time period as the in-vehicle study (weekdays from 4:30 pm). The observation duration at every location was 45 min (3 times of 15-min period). A total of 487 jaywalking events were observed. The following data were collected at each location, and based on those, the average jaywalker, pedestrian and traffic volumes were obtained:

- Number of jaywalkers per minute.
- Number of pedestrians (both crossing directions) per minute.
- Number of vehicles (both directions) per minute.
- Pedestrian and jaywalker characteristics (speed, delay).

4. Data analysis and findings

This section provides the data analysis results related to vehicle–pedestrian interactions outside the crosswalks. The VJI framework is firstly introduced and then the pedestrian behavior as well as the driver behavior reacting to them are analyzed separately in the scope of the framework.

4.1. Vehicle–jaywalker interaction framework

A framework for the vehicle–jaywalker interactions is shown in Fig. 3. The presence of jaywalkers triggers the vehicle reactions and the driver starts to make a yield/no-yield decision. As he/she determines the yield choice, the vehicle proceeds with the corresponding dynamics (keep car following, stop as a leading vehicle, soft yield, etc.). Data were collected to model the VJI, from the pedestrian perspective, observe where pedestrians are more likely to jaywalk, and measure the crossing speed and the corresponding driver behaviors; from the driver perspective, to observe and quantify the driver yielding behavior, including the probability of yielding, likely location, and vehicle trajectories after a yielding or no yielding decision. The results are provided in the following sections.

4.2. Jaywalking behaviors

A jaywalking event is defined as a pedestrian crossing more than 10 ft outside of a marked or unmarked crosswalk at an intersection, or 10 ft outside of a marked midblock crosswalk. As specified by Florida state law 316.130 (10) [2], jaywalkers (crossing a roadway at any point other than within a marked crosswalk or within an unmarked crosswalk at an intersection) shall yield the right-of-way to all vehicles upon the roadway. Other than that, a pedestrian crossing at marked or unmarked crosswalks is defined as a permissible crossing. The pedestrian jaywalking behaviors considered in this study include crossing location and surrounding roadway environment, pedestrian crossing speed, yield recognition and wait time.

4.2.1. Jaywalking locations and environment characteristics

Through the instrumented vehicle experiment, most jaywalking events (72.5%) were found to occur at specific locations (Fig. 2). Others were randomly located along the two routes. Among the five locations identified in Fig. 2, Location 5 had the highest probability of a jaywalking event (53.33%), i.e. there was a 53.33% frequency in encountering a jaywalker when passing through this location during the hour of analysis. The frequencies for Location 1–4 are: 13.33%, 16.67%, 30.00%, and 20.00% respectively.

Operations were observed at each of these locations to collect jaywalker rates, pedestrian and vehicle volume (per min), crossing distance and number of bus stops. The results of the data collection are shown in Table 2. On-site observation indicated that jaywalkers are more likely to perform single-stage crossings even when there is a median. Jaywalkers seem to select gaps that are acceptable at all the lanes simultaneously.

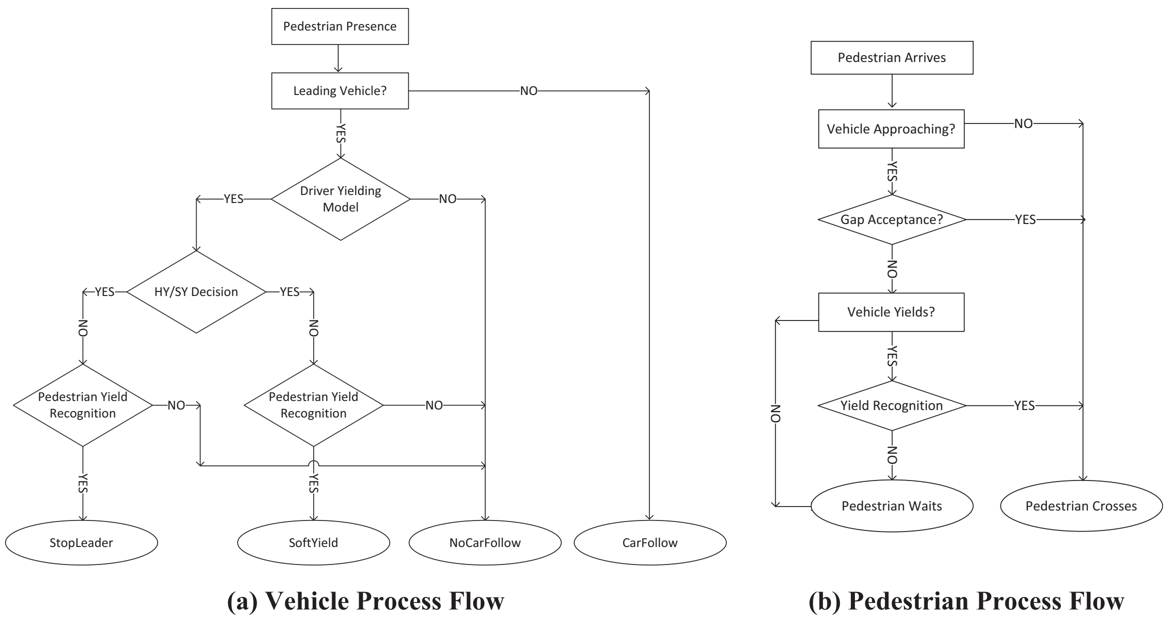


Fig. 3. Vehicle–jaywalker interactions framework.

Table 2
Traffic and environmental variables for each jaywalking location.

Location	1	2	3	4	5
Jaywalker volume (/min)	1.467	0.733	2.933	1.667	4.033
Average pedestrian volume Along the sidewalk (/min)	1.8	2.333	2.55	3.233	5.633
Average traffic volume (/min)	6.1	5	5.583	1.367	2.95
Crossing distance (ft)	40	45	35.5	40	38.5
Nearby bus stops	1	0	1	2	2
Distance between crosswalks on either side of this location (ft)	360	444	1023	747	487
Median	No	Yes	No	No	No
Comment	Parking Lot	Parking Lot			Food Plaza

Note: The crossing distance of Location 2 is the total lane width of both directions plus the median size.

The data were analyzed to evaluate the correlations of those traffic and environmental variables with the observed jaywalker volume (from observational study) and the number of encountered jaywalking events (from instrumented vehicle study). Results (Table 3) indicate that:

- There is a high correlation of jaywalking events between the instrumented vehicle study and the field observations (0.937 correlation at 95% confidence), which indicates the results from the two studies are consistent.
- Pedestrian volume along the sidewalk has a significant impact on the number of jaywalkers (0.794 correlation at 95% confidence).
- The presence of bus stops results in more jaywalking events, since people are more likely to cross to or from their destinations.
- Crossing distance and vehicle volume have negative correlation to jaywalking frequency. Longer crossing distance increases pedestrian's critical gap; higher traffic volume reduces the vehicle headway and gap availability.
- The number of jaywalking events has a positive correlation with the distance between crosswalks. Pedestrians prefer to cross illegally if the crosswalks are too far away.

4.2.2. Jaywalking crossing speed

Pedestrian crossing speed is one quantitative measure of pedestrian crossing behaviors and has been explored by several prior studies [7–10]. For instance, the HCM 2010 [7] assumes 4.0 ft/s as the default value of pedestrian average speed in all traffic/geometry/treatment conditions (i.e. signal intersection and midblock crosswalks). However, little previous research was found that has examined the pedestrian crossing speed outside the crosswalks, or any differences with permissible crossings. Fig. 4 provides the probability distributions of pedestrian speeds on campus (permissible crossings and jaywalking).

There were a total of 343 permissible crossing observations and 487 jaywalker observations. The analysis indicates the average permissible crossing speed on campus is 5.05 ft/s, while the value for jaywalkers is 5.18 ft/s for jaywalkers. There is no significant difference between these means based on statistical analysis. However, as shown in Fig. 4b, jaywalkers are more likely to run and the distribution of jaywalker speed is much flatter. The standard deviation for permissible crossings is 0.66 ft/s, while for jaywalkers it is 1.65 ft/s. There is higher variability in crossing speed outside the crosswalks. Jaywalkers crossing when vehicles yield or during shorter gaps would prefer to walk faster; jaywalkers crossing during large gaps do not need to cross in a hurry, resulting in low crossing speeds. As expected, the average crossing speed on campus for both permissible crossings and jaywalkers is higher than the default value in the HCM 2010 (4.0 ft/s for all ages and genders nationwide) [7].

Table 3
Correlation analysis of traffic and environmental variables.

	Jaywalker volume	Pedestrian volume	Traffic volume	Crossing distance	Nearby bus stops	Distance between crosswalks	% Jaywalking events
Jaywalker volume	**1**						
Pedestrian volume	*0.794**	1					
Traffic volume	−**0.224**	−0.620	1				
Crossing distance	*−0.744**	−0.249	−0.013	1			
Nearby bus stops	**0.639**	0.681	−0.735	−0.547	1		
Distance between crosswalks	**0.303**	−0.042	−0.126	−0.670	0.196	1	
% Jaywalking events	*0.937**	**0.926***	−**0.337**	−**0.472**	**0.555**	**0.124**	**1**

* 95% confidence level.

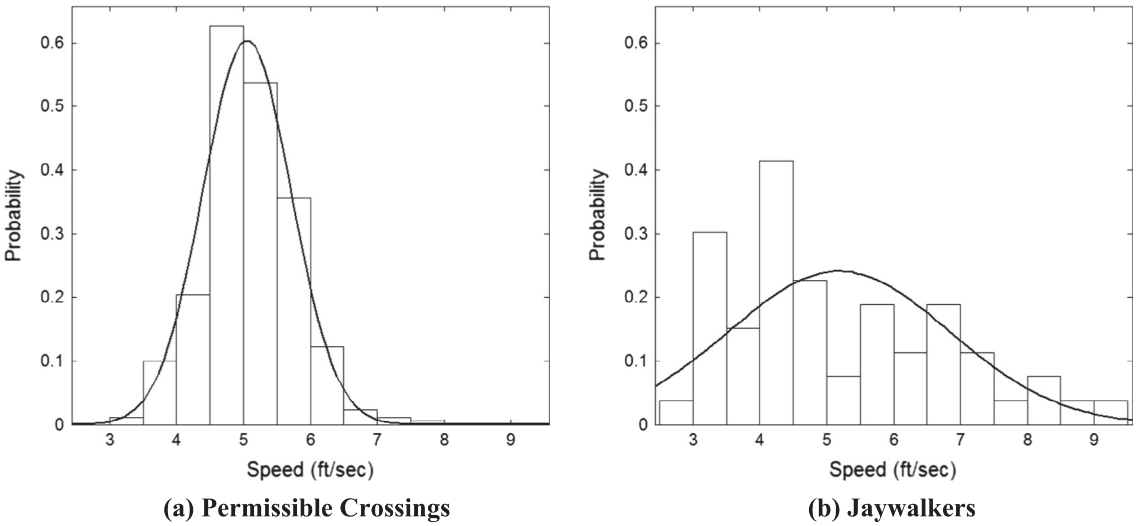


Fig. 4. Frequency distributions of pedestrian speeds.

4.2.3. Jaywalking yield recognition

Drivers have three options when encountering a crossing pedestrian: No-Yield (NY), Hard-Yield (HY), and Soft-Yield (SY). Hard yield means that the vehicle slows down to complete stop for pedestrians, while soft yield means that the vehicle slows down without a full stop. The pedestrian yield recognition was observed in this study, which refers to the pedestrian's reaction to driver's yield behavior, either accepting the yield or reject it. The yield acceptance rate is important when modeling or simulating pedestrian behavior and VPI/VJI, and it helps to more realistically replicate the pedestrian delay, vehicle delay, etc.

As observed in this study, pedestrians crossing at crosswalks and outside the crosswalks have different expectations towards driver yielding. It was found that in permissible crossings at crosswalks, pedestrians would accept all yields (100%), no exceptions. But jaywalkers prefer to cross during larger gaps rather than during yields [3]. Their HY utilization rate is 98.33%, and SY rate is 91.67%. The lower yield utilization rates of both hard and soft yields confirm that the jaywalkers don't expect drivers to yield and they are less likely to cross during yields. Meanwhile, the HY utilization rate is higher than that the SY one, which is consistent with former studies – people are more likely to accept a hard yield rather than a soft yield. Driver yielding behavior is discussed in a later section.

4.2.4. Jaywalking delay at the curb

Pedestrian delay at the curb (the time difference between their arrival at crossing point and starting to cross) was observed in the study. The average delay of jaywalkers is 0.87 s, and of pedestrian crossing at crosswalks is 3.65 s. Obviously, jaywalker's wait time at the curb is much lower, because jaywalkers can make crossing decisions (look for gaps) while still walking.

4.2.5. Summary on jaywalking behaviors

The following observations are made with respect to jaywalking behaviors:

- Jaywalking events are concentrated around 5 locations along the two routes tested. The location with the highest number of jaywalking events has the highest pedestrian volumes along the sidewalk, a short crossing distance and two bus stops in the vicinity.
- Roadway environment characteristics of each jaywalking location are correlated to jaywalking events: pedestrian volume, number of bus stops and distance between crosswalks have positive correlation; vehicle volume and crossing distance have negative correlation.
- The average pedestrian crossing speed outside the crosswalks is not significantly different from permissible crossings at the crosswalks (5.18 ft/s and 5.05 ft/s). However, there is more variability among jaywalker crossing speeds, which is represented by a flatter distribution and a higher standard deviation. The speed distributions can be used for replicating pedestrian operations in simulators.
- Pedestrians crossing outside the crosswalks do not always accept all the driver yields. They have lower HY and SY utilization rates than permissible crossings (the latter accepts all the HY and SY).
- As expected, the average wait time of jaywalkers is significantly lower than that of permissible crossings.

4.3. Driver reactions

Jaywalking events are unexpected for drivers along their trip and they may not anticipate to yield to pedestrians away from crosswalks. According to previous research [11,22,25], their yield/no-yield decision is made based on traffic conditions, pedestrian characteristics, driver characteristics, etc., similarly to driver yielding models for permissible crossings. Also, hard-yield vs. soft-yield depends on the vehicle deceleration rate and the distance to the jaywalker crossing point. This section describes driver reactions to jaywalkers using data from the instrumented vehicle study. The driver reactions considered here include the yield rate, vehicle speed–distance at the decision point (i.e., the decision to yield or not), and yield dynamics.

4.3.1. Driver yield rates

The average driver yield rates were measured during the in-vehicle study: the rate of yielding to jaywalkers is 50.67%, while to permissible crossings it is 72.66%. These average rates are represented by the dash-dot line in Fig. 5. A total of 80% of the subjects indicated in the surveys (they answered during the in-vehicle study) that they were aware of the local laws regarding right-of-way at pedestrian crossings. As expected, drivers are much more likely to yield to pedestrians at marked crosswalks (permissible crossings).

In addition, a comparison of driver yield behaviors to jaywalkers and permissible crossings was conducted next. As discussed in another paper [26], driver's yielding behavior to pedestrians at marked crosswalks can be applied as one effective measure to classify driver types within a high level of pedestrian activity environment. In that paper, drivers were categorized into 4 types using a yield-behavior-based scheme [26], with group 1 being the least aggressive and 4 being the most aggressive. Driver yield rates (%Yield) with their respective driver type (x axis) are shown in Fig. 5 with straight lines as linear regressions (Fig. 5a – the %Yield to jaywalkers, Fig. 5b – the %Yield to permissible crossings). It is found that compared with permissible crossings, yielding to jaywalkers seems to be random among all driver groups, and there's no clear relationship that can be drawn from the data. Drivers do not anticipate to encounter with a jaywalking event, so that when encountering jaywalkers, it's highly possible that their reactions are based on the existing conditions and environment (speed, distance, jaywalker volume) rather than the driver attitudes.

The surveys also indicated that 53% of the subjects mentioned (unprompted) specifically the existence of jaywalkers on campus and felt unsafe because of them. Although over half of the subjects reported the existence of jaywalkers, the No-Yield behaviors among "jaywalker-reported" drivers and "jaywalker-unreported" drivers are almost the same, around 49% (Fig. 6a and b). The average %No-Yield of "jaywalker-reported" drivers is even higher than for the "jaywalker-unreported" ones. That is to say, driver yield rate is independent of whether drivers mentioned the presence of jaywalkers in our survey. It could be that the yield/no-yield reaction is more related to specific traffic and roadway environment conditions. It could also be that drivers who mentioned jaywalkers are more sensitive to their presence for other reasons.

Based on the analysis of driver yield rates, it is found that driver yielding behaviors to jaywalkers are independent with their overall aggressiveness and awareness of jaywalkers. The potential impacts of vehicle speed/distance on driver yield behaviors were thus explored in the next section.

4.3.2. Driver decision point and distance–speed relationship

The driver decision point is defined to be the location where the driver starts to react to the presence of pedestrians. At that point, he/she decides to yield/no-yield to the pedestrians waiting at the curb or currently crossing during a pedestrian crossing event.

For each VPI and VJI, the driver decision point was processed based on the GPS data from the instrumented vehicle study. The average distance between driver decision point and jaywalkers is estimated to be 85.81 ft, while the average distance for permissible crossings is 132.37 ft. A statistical test of means indicates that these two distances are significantly different – drivers

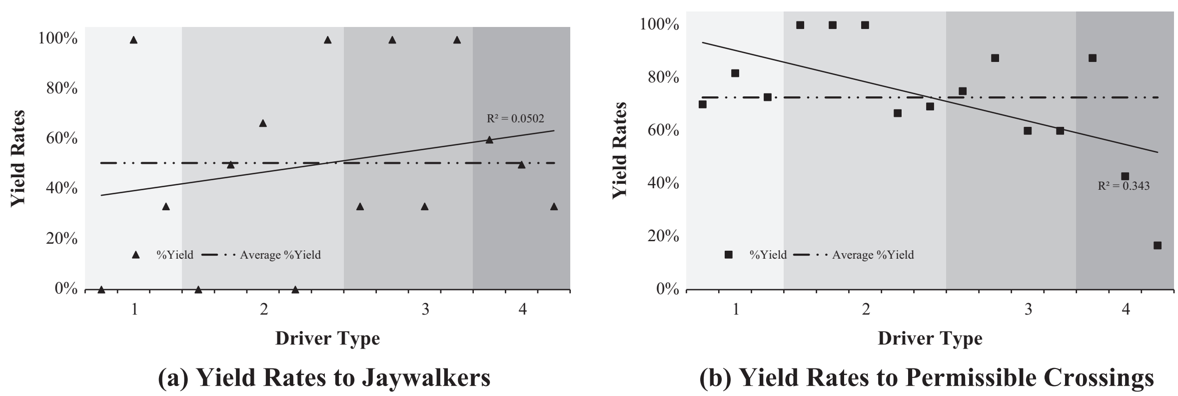


Fig. 5. Driver yield rates to jaywalkers and permissible crossings.

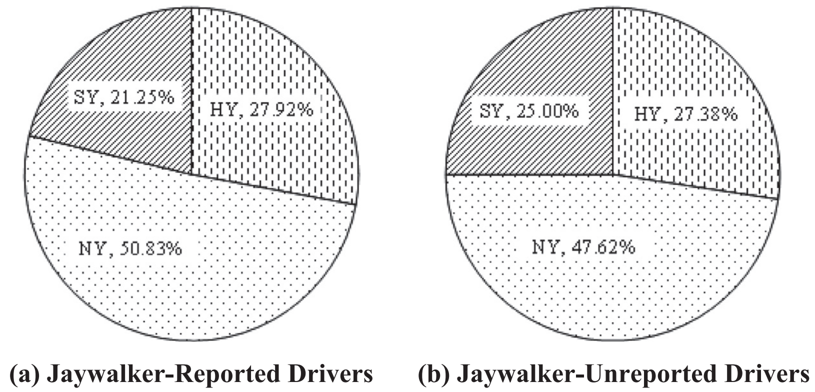


Fig. 6. Percentage of NY, SY, and HY behaviors.

have a much shorter reaction time to jaywalkers than to permissible crossings. This result also supports the finding that drivers have a lower probability of yielding to jaywalkers than to pedestrians at marked crosswalks.

The vehicle speed at decision point was also obtained and the distance–speed relationship at that point for all the yielding decisions (i.e. HY, SY, and NY) to jaywalking events is provided in Fig. 7. It is clear that the yield decision can be classified by the distance–speed relationship. The drivers are more likely to hard yield to jaywalkers if their speed is low and they are quite close to the crossing point at the time they make a decision. Drivers with higher approaching speed decide to soft yield to jaywalkers if they are far away from the crossing point, otherwise they cannot stop and choose not to yield when the decision distance is short. This result points out the importance of vehicle distance and speed at the decision point, both of which highly affect driver reactions and vehicle trajectories towards jaywalkers.

4.3.3. Vehicle dynamics

Based on the discussions on driver yield rates to jaywalkers and the distance–speed relationship at decision point, the vehicle dynamics (distance–speed profile) can be obtained to further analyze driver reactions and the vehicle trajectories. The distance–speed profiles for the three decisions to jaywalking events (NY, HY and SY) are shown in Fig. 8. As shown, in general, high speed and long distance result in drivers' NY decision, low speed makes it possible for drivers to stop completely, and the speed and distance cause of SY decision is in between (HY and NY). The deceleration rates for the three types are significantly different: NY vehicles did not slow down, but stayed in car-following mode; SY vehicles decelerated, but did not stop and started to accelerate after passing the pedestrian crossing point; HY vehicles had the highest deceleration rate and finally slowed down to a speed lower than 5 mph (considered as a stop).

Next, this paper further analyzes vehicle HY dynamics and SY dynamics in detail, which would help modeling vehicle operations in micro-simulation. The NY vehicles stay in car-following mode and there is no large difference between VPI and VJI, thus the vehicle NY dynamics are not further analyzed in this paper.

The speed profiles for vehicles that perform HY and SY are analyzed within a distance of 100 ft, considering that the average driver decision point for jaywalking events is 85.81 ft. The vehicle dynamics in the presence of pedestrians are classified according to Time To Conflict (TTC): less than 4 s, 4–6 s, 6–8 s, 8–10 s and more than 10 s. TTC is determined at the driver decision point – the distance to the crossing point divided by the speed at that moment. The mean speed is estimated and plotted in Fig. 9 (SY) and Fig. 11 (HY) for each TTC condition for every 10 ft.

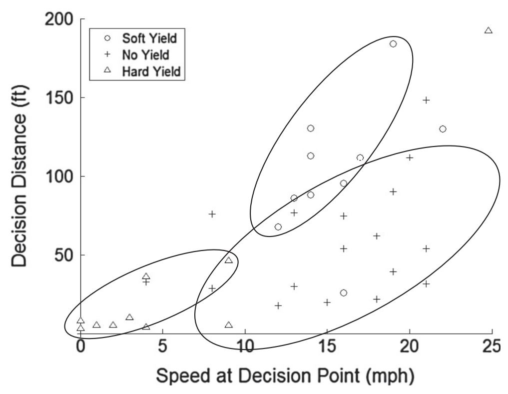


Fig. 7. Distance–speed relationship at driver decision point of HY, SY and NY for jaywalking events.

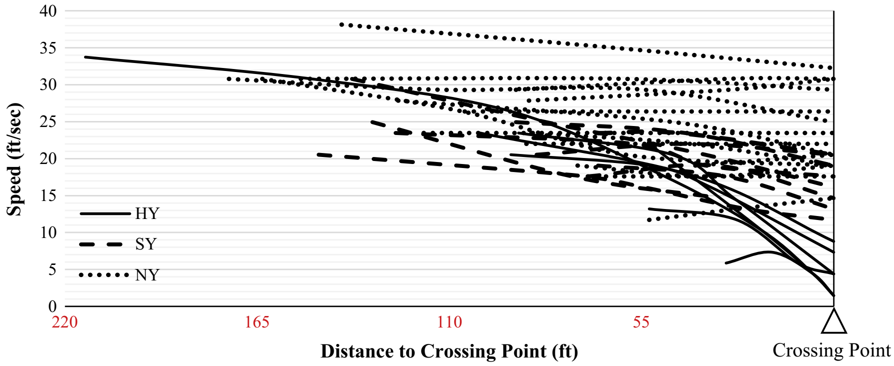


Fig. 8. Speed vs. distance (HY, SY, NY).

4.3.3.1. Soft yield. As defined, SY vehicles do not necessarily have a complete stop, they prefer to decelerate and coast towards the crossing pedestrians. As shown in Fig. 9, the vehicles that choose to soft yield have different initial speeds, but they mostly share a similar deceleration rate – the slopes are much flatter than the HY one (Fig. 11). A statistical regression analysis was conducted to estimate the vehicle SY deceleration rate corresponding to different TTC and distance (results are shown in Table 4). A regression line (dash line) is also plotted in Fig. 9 and indicates that the average deceleration rate is approximately -0.818 ft/sec^2 through the vehicle travel distance. The SY dynamics to permissible crossings were processed as well. The average SY deceleration rate is approximately -1.3 ft/sec^2 through the vehicle travel distance. The simplified speed–time profiles of VPI and VJI are shown in Fig. 10 with a starting speed of 20 ft/s. It is obvious that the drivers tend to slow down more to permissible crossings than to jaywalkers – resulting in a lower coasting speed towards pedestrians at marked crosswalks.

4.3.3.2. Hard yield. As defined, HY vehicles proceed to a complete stop in front of the crossing jaywalkers/crosswalks. As shown in Fig. 11, the vehicles that choose to hard yield, have the similar deceleration rates as they approach the jaywalker regardless of TTC. A statistical regression analysis was conducted to estimate the vehicle HY deceleration rate corresponding to different TTC and distance (results are shown in Table 4). A regression line (dash line) is also plotted in Fig. 11. The average deceleration rate is approximately -3.27 ft/sec^2. The average HY deceleration rate is -3.4 ft/sec^2, which is not significantly different from the HY deceleration rates to jaywalkers. The simplified speed–time profiles of VPI and VJI are shown in Fig. 12 with a starting speed of 15 ft/s.

4.3.4. Summary on driver reactions

We can conclude the following with respect to driver reaction to jaywalkers:

- Driver yielding rates are higher for pedestrians in permissive crossings (72.66%) compared to jaywalking events (50.67%).
- The average yield rate to jaywalkers on campus is about 51%, and does not differ between drivers who mentioned the presence of jaywalking in the survey (“jaywalking-reported”) and those that did not (“jaywalking-unreported”); Moreover, drivers’ yield-to-jaywalker behaviors are not influenced by their driver type as classified based on level of aggressiveness.

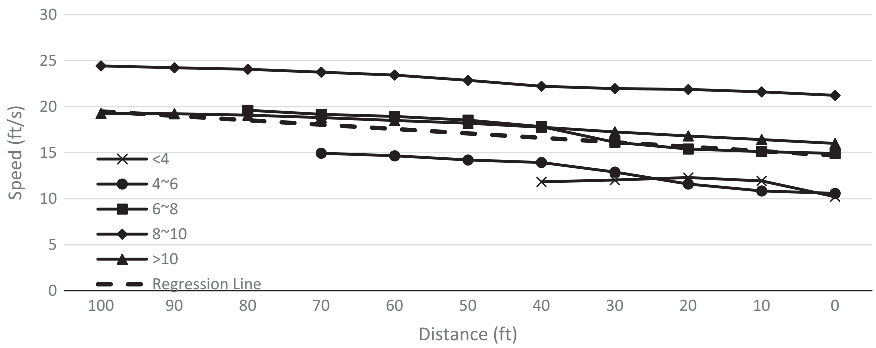


Fig. 9. Vehicle SY dynamics (distance–speed profile).

Table 4
Vehicle deceleration rate (ft/s) in yielding behaviors.

Driver reactions	TTC (s)				
	<4	4–6	6–8	8–10	>10
Soft yield	−0.422	−0.975	−1.208	−0.788	−0.621
Hard yield	−3.963	−4.180	−3.127	−2.664	−2.555

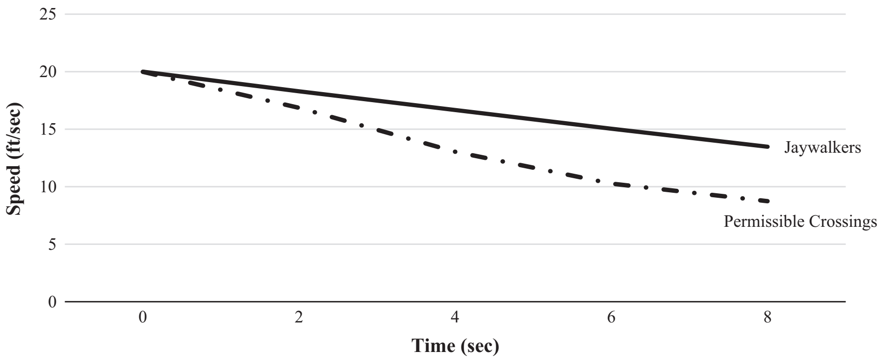


Fig. 10. Simplified SY reaction to jaywalkers and permissible crossings.

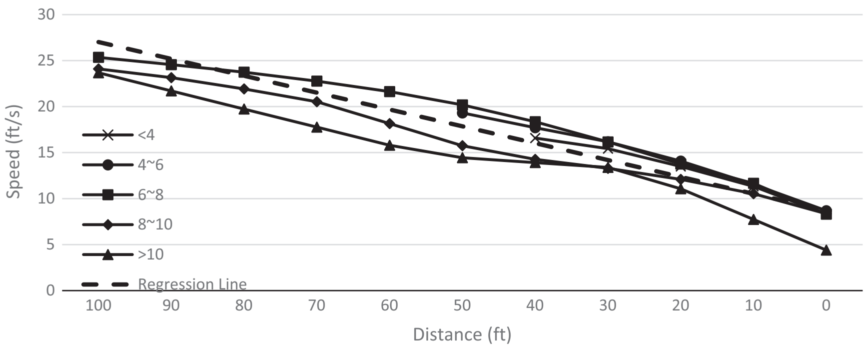


Fig. 11. Vehicle HY dynamics (distance–speed profile).

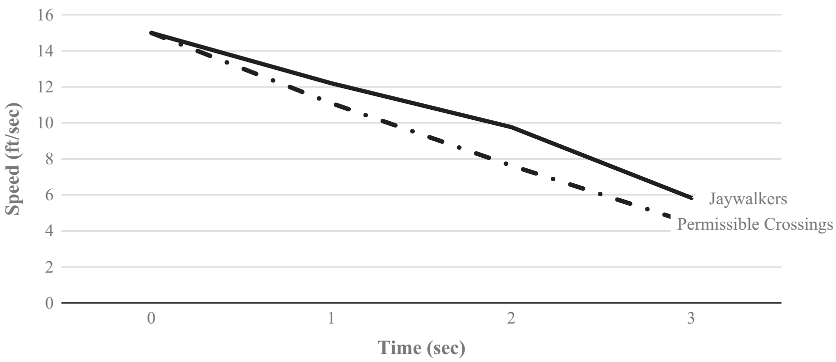


Fig. 12. Simplified NY reaction to jaywalkers and permissible crossings.

- Speed and distance at the driver decision point highly correlate to driver's yield choice to jaywalkers. The decision point determines the start (time) location of vehicle–jaywalker interactions. It is shown that the decision point for reacting to jaywalkers is approximately 85.81 ft, while the average distance for permissible crossings is 132.37 ft.
- Detailed vehicle SY and HY dynamics are obtained corresponding to different TTC to jaywalkers. The simplified models for both are developed and can be applied into micro-simulators.

5. Conclusions and recommendations

This research investigated jaywalking behavior as well as driver reaction to jaywalkers on the University of Florida campus. The objective of the research was to quantify driver and pedestrian behaviors as well as to model their interactions outside of designated crosswalks. Data were collected through an instrumented vehicle study and an observational study.

Firstly, the pedestrian crossing behavior outside the crosswalks was examined. Consistent with past studies, it was found that the locations where pedestrians are more likely to cross outside the crosswalks are highly influenced by the surrounding roadway environment and characteristics, such as pedestrian volume, number of bus stops, vehicular volume, distance between crosswalks and crossing distance. Significant differences were observed between jaywalkers and pedestrians during permissible crossings in: crossing speed distribution, yield utilization and delay. Jaywalkers are less likely to accept driver's yielding behaviors (both Hard Yield and Soft Yield), resulting in an overall lower yield utilization rate.

Next, driver reactions to jaywalkers were examined. Driver yielding decision point to jaywalkers is closer to the crossing point, and the average yield rate to jaywalkers is lower than that to pedestrians at permissible crossings. It was also observed that drivers decelerate more for pedestrians within a crosswalk than for jaywalkers. These differences may in return affect jaywalker behaviors.

This paper points out the specific jaywalking and vehicle reaction behaviors, establishes quantitative relationships of VJI, and provides the basis and assumptions for modeling VJI/VPI in a micro-simulation environment based on the data and observations obtained in this study. Research implications and recommendations for future work are as follows.

- The jaywalker crossing speed distribution can be used within micro-simulation packages when replicating jaywalker operations.
- The pedestrian delay at the curb collected in this study can be used to validate the simulation results.
- The distance–speed relationship at driver decision point can be used for yield choice modeling with further statistical analysis (cluster analysis, etc.) and then applied in simulation.
- The simplified models of vehicle soft-yield and hard-yield dynamics refine the vehicle operational performance and provide the basic algorithms that can be implemented in a micro-simulator.
- The methodology developed for data collection and analysis, as well as the trends and insights in these from the data collected can be used to develop larger scale studies for generalizing the results reported here. The data and methods developed can also be implemented in micro-simulators which require detailed trajectory information of both vehicles and pedestrians.
- The yield recognition rate, can be used to develop jaywalker delay models for planning level applications (for example, when determining the optimal path a pedestrian may take, and consequently the attractiveness of jaywalking at a specific location.).

The findings from this study have implications related to research, planning, and engineering solutions for future work on pedestrian safety, crosswalk design and location, as well as modeling of driver behaviors for traffic operational analyses. They can also be used as the basis to formulate planning and engineering strategies to minimize jaywalking.

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