Pedestrian Crosswalk Law: A study of traffic and trajectory factors that affect non-compliance and stopping distance

Miguel A. Figliozzi *, Chawalit Tipagornwong *

Portland State University, Department of Civil and Environmental Engineering, P.O. Box 751, Portland, OR 97207-0751, USA

ABSTRACT

Walking is encouraged by many transportation agencies as a sustainable mode that contributes to livable downtowns. Since pedestrians are the most vulnerable road users, safe and comfortable crosswalks are essential to ensure that pedestrian travel becomes an appealing alternative. In this context, the goal of this research is to study the traffic and vehicle trajectory factors that affect crosswalk law compliance and stopping distance from the crosswalk. The results of this research provide new insights into the relationships between traffic conditions, vehicle trajectory, and compliance rates. Results indicate that vehicle origin, vehicle type, stopping at upstream traffic lights, and changes in vehicle speed and headways are key factors to predict pedestrian crosswalk law compliance and stopping behavior; changes in vehicle speed and headways have the highest explanatory power.

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1. Motivation

Walking is encouraged by many transportation agencies as a sustainable mode that contributes to livable and healthy downtowns. The need to provide adequate pedestrian facilities has recently gained recognition in the USA as more cities and states aim to provide livable and walkable communities. Pedestrian safety is a necessary condition to sustain and foster more walking in urban areas.

Traffic laws and regulations should provide a legal framework that protects pedestrians when they are most vulnerable. In the USA, state laws typically regulate traffic safety. The majority of states require drivers to yield or slow down for pedestrians. In Oregon, the law is stronger because drivers must stop for pedestrians as soon as they move onto the roadway in a crosswalk with the intent to proceed (NCLS, 2015). In addition, in Oregon, the state law determines that there is a crosswalk at every intersection with or without a marked crosswalk, i.e. for the state law there is a crosswalk at an intersection even if there is no zebra crossing. Furthermore, the Oregon Revised Statutes (ORS) 811.028 requires that a driver, before crossing a crosswalk, stops and remain stopped for pedestrians until pedestrians have cleared the lane in which the vehicle is traveling and the next lane (ORS, 2011). The area determined by

the vehicle lane and the next lane is called the safety buffer. If a pedestrian is in the safety buffer when the vehicle enters the crosswalk the driver may be cited for a fine over $260. Pamphlets from the Oregon Department of Transportation (ODOT) Safety Division illustrate the "safety buffer" concept, see Fig. 1.

A contentious issue is the definition of the circumstances that delineate when a pedestrian is in the crosswalk. In 2011, to increase pedestrians legal protection, it was added to ORS 811.028 that "... a pedestrian is crossing the roadway in a crosswalk when any part or extension of the pedestrian, including but not limited to any part of the pedestrians body, wheelchair, cane, crutch or bicycle, moves onto the roadway in a crosswalk with the intent to proceed." Hence, vehicles must stop for pedestrians as soon as they move onto the roadway in a crosswalk with the intent to proceed. The law further suggests that when stopping for a pedestrian on a multilane road, a driver *should* stop thirty feet before the crosswalk to avoid blocking the sight of drivers in other lanes; i.e. to reduce the risk of multithread crashes. Italics have been added to the word *should* because the Oregon law is clear to indicate that the driver *must* stop when a pedestrian is in the safety buffer but the law does not specify a stopping distance from the crosswalk; thirty feet is a recommendation that is not enforceable by the traffic police.

Pedestrians also have duties, such as obeying traffic signals and crossing the street only utilizing marked crosswalks and/or at intersections. In Oregon, a crosswalk exists at any public street intersection, whether marked with paint or unmarked (ORS 801.220). In addition, pedestrians must exercise due care and walk safely. According to ORS 811.005 (ORS, 2011) "None of the pro-

* Corresponding author.
E-mail addresses: figliozzi@pdx.edu (M.A. Figliozzi), chawalit2@pdx.edu (C. Tipagornwong).
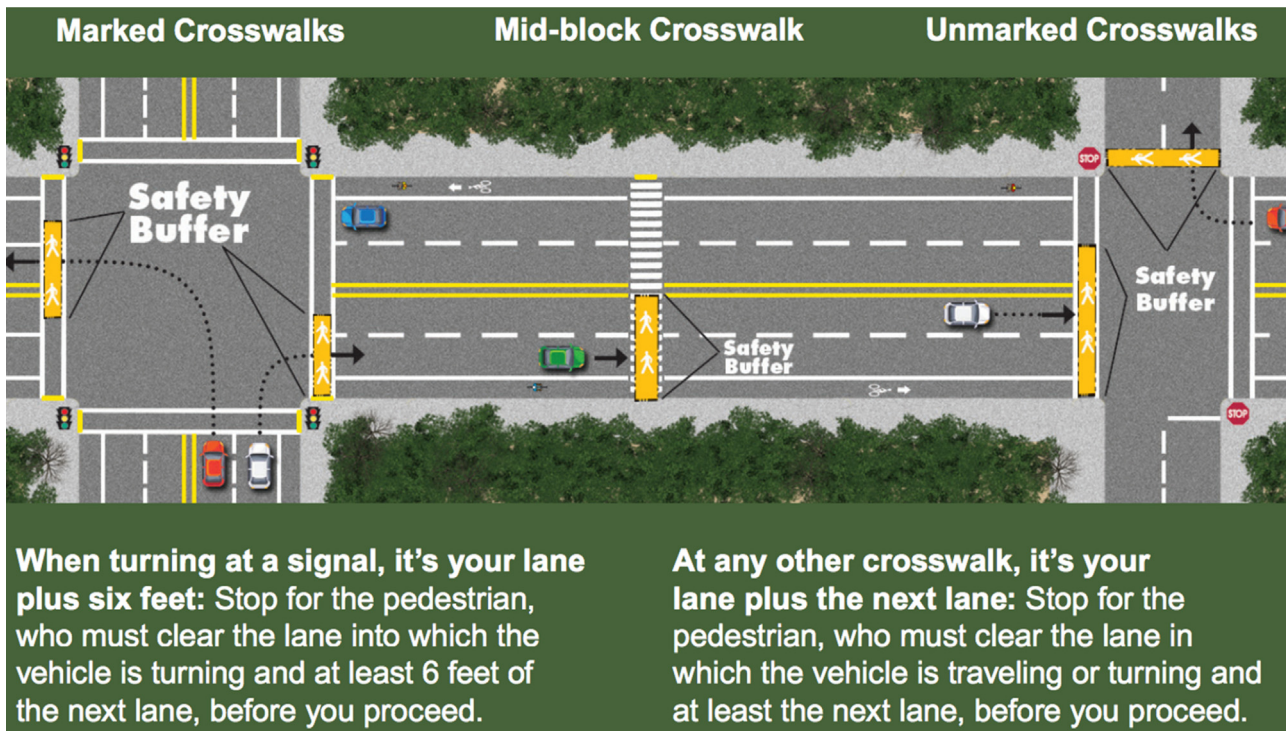
Fig. 1. Illustration of the "safety buffer" concept (ODOT, 2015).

visions of the vehicle code relieve a pedestrian from the duty to exercise due care or relieve a driver from the duty to exercise due care concerning pedestrians."

Enforcement of traffic laws and regulations is another important element to guarantee safe pedestrian activity in a roadway environment. For example, the City of Portland Bureau of Transportation (PBOT) in conjunction with Portland Police Traffic Division periodically conduct "crosswalk education and enforcement actions". One or more pedestrian decoys are utilized at locations that have marked or unmarked crosswalks and police officers control whether drivers show non-compliance of Oregon's traffic laws; the pedestrian decoys follow the law and exercise due care. Crosswalk enforcement actions are conducted approximately once each month (PBOT, 2015). According to PBOT statistics, over 60% of the citations are written Oregon's crosswalk law ORS 811.028 violations and caused by "failure to stop and stay stopped for a pedestrian". Other common driver violations include speeding, use of a cell phone, passing stopped vehicle at a crosswalk, no drivers license, plates, or proof of insurance. The most common pedestrian violations is jaywalking (PBOT, 2015).

The high number of violations during enforcement actions, sometimes over 20 per hour, are *startling* given that enforcement actions are *announced*. Crosswalk education and enforcement actions are typically announced (in the media days before) and also with a red flag, a temporary sign, and cones placed 1 or 2 blocks ahead of the crosswalk during the enforcement action (BP, 2015). The temporary sign reads "Pedestrian Crosswalk Enforcement Ahead." Enforcement actions typically take place in locations with a high number of pedestrian complaints or with a record of recent pedestrian fatalities and/or injuries.

This research focuses on the study of the factors that can explain the high number of violations of pedestrian crosswalk laws. More specifically, this paper answers two research questions: (1) What are the factors that affect driver non-compliance? and (2) What are the factors that affect driver stopping distance? To answer these questions detailed video records (several cameras

at different heights) were utilized to analyze driver and vehicle trajectories up to 200 m (650 feet) upstream of crosswalks with a high record of pedestrian crosswalk law violations. This study tests whether more detailed traffic and trajectory variables can be used to explain drivers' non-compliance, i.e. the null hypothesis states that detailed trajectory and traffic variables are not significant or not do not explain drivers' non-compliance. This research only analyses events where pedestrians fully comply with the law; a few events with aggressive pedestrians are excluded from the study.

Next section provides a brief literature review and a posterior section describes the data collection process and study site. Binary logistic and ordered logistic regression models are developed to elucidate the factors that affect non-compliance and stopping distance. The paper ends with a discussion of key results and conclusions.

2. Literature review

In the USA pedestrian crashes are a serious safety issue. In 2013, there were 4735 pedestrians killed in traffic crashes in the USA; pedestrian fatalities accounted for 14 percent of all USA traffic fatalities and fatalities increased 15% between 2009 and 2013 (NHTSA, 2015). The majority of fatalities and injuries are the result crashes where the point of impact is the front of the vehicle, but the undisputable causes of the fatal crashes are not easy to disentangle from the recorded data (NHTSA, 2015).

There have been many studies trying to analyze crosswalk law compliance. Britt et al. observed that approximately 80% of the drivers failed to stop for pedestrians in Seattle (Britt et al., 1995). The authors evaluated a four-year safety campaign in Seattle and concluded that more enforcement seemed to produce a slight to null improvement in compliance. A recent meta-analysis by Phillips et al. (2011) suggests that safety campaigns are likely to be more effective, in the short-term, if they are accompanied by enforcement and personal communications; personal communi-

cation, unlike mass media campaigns, entails lessons or seminars delivered in person or two-way discussions with a peer or group discussions. A review of pedestrian safety research suggests that it is nearly impossible to quantify the impact of enforcement or education campaigns on pedestrian safety or drivers' behavior (Campbell et al., 2004).

Studies that attempt to quantify the impact of traffic variables or engineering design features on drivers' behavior at crosswalks have been more successful. Advance yield markings and prompt signs are likely to reduce pedestrian–vehicle conflicts (Van Houten, 1988); in this particular research effort signs constructed to prompt drivers to stop at a specific location for pedestrians read "STOP HERE FOR PEDESTRIANS" and had an arrow pointing down toward the road at an angle of 45° below the horizontal. When the vehicle speed is lower, a driver is more likely to stop for a pedestrian (Katz et al., 1975). On the other hand, wider roads are associated to higher speeds and more crashes; there is a strong relationship between vehicle-pedestrian crash severity and speed (Gårder, 2005). A vehicle that can safely stop when a pedestrian enters the crosswalk is more likely to yield, especially if the required deceleration rate is less than $10 \, \text{ft/s}^2$ (Schroeder and Rouphail, 2011). A vehicle that is a part of a platoon is more likely to yield than a vehicle that is not a part of a platoon and drivers are more likely to yield when pedestrians are aggressive (Schroeder and Rouphail, 2011). Some treatments such as raised medians, traffic and pedestrian signals, curb extensions, raised islands, tighter turn radii, and adequate nighttime lighting can help reduce crash frequency or severity (Mead et al., 2014); some of these treatments are particularly effective on multi-lane or high-speed arterial roads.

Regarding research that deals with pedestrian crosswalk laws, the focus of this paper, two papers stand out. Kim et al. (2008) studied a new, stronger law introduced in Hawaii in 2005 that requires drivers to stop and yield to pedestrians at crosswalks. Before 2005 drivers had the option of yielding or slowing down at a crosswalk and had to stop only when necessary. Data was collected for one hour at 30 locations and logistic regression models predicting the likelihood of violation of the crosswalk laws by drivers found that senior drivers had higher compliance rates. The highest non-compliance rate, drivers not stopping for pedestrians on the crosswalk, took place at unsignalized midblock crosswalks. In this study high non-compliance was also associated with hotel districts, office areas, and high-density residential areas. Kweon et al. (2009) utilized the Fatality Analysis Reporting System (FARS) database to analyze whether pedestrian laws that require drivers to yield to pedestrians in crosswalks had an effect on pedestrian safety on low-speed roads; the study found no statistically significant reduction in pedestrian-involved fatal crashes but the authors attributed this result to the omission of high quality exposure data.

This paper also studies factors associated to the likelihood of violation of the crosswalk laws by drivers. However, unlike previous research efforts, Kim et al. (2008) and Schroeder and Rouphail (2011), this study focuses mostly on drivers and the inclusion of novel traffic variables that capture driver trajectory and behavior before arriving to the crosswalk area (i.e. speed change, headways, origin, stopping at upstream traffic lights, etc.); trajectory and upstream traffic variables are not included in previous studies. In addition, this study also models stopping distance; previous research efforts have not modeled this dependent variable. Finally, the data collection environment is different from other studies; this research analyses crosswalks in a multilane one-way street in a downtown area with mixed commercial, office, residential, and educational land uses. Next section describes the data collection process.

2.1. Study site and data collection

The study site selection process was guided by two considerations: (a) finding a site with a high number of crosswalk law violations and (b) finding a site where it was possible to readily collect detailed vehicle trajectory and traffic data. For the former consideration, the research team utilized statistics collected by PBOT in the last 10 years; for the latter consideration, the research team conducted site visits to analyze the location of video recording equipment.

The location chosen for this research was the intersection of SW 4th Ave. and SW College Street (see crosswalk in Figs. 2 and 3). At this location, an enforcement action resulted in 40 traffic law violations in a period of two hours, between 11 am and 1pm. Out of the 40 violations, the vast majority (36 violations) were the result of failing to stop for pedestrians. Another advantage of this location was that the research team had access to a university building rooftop to install video recording equipment. From this rooftop, it was possible to record video to track detailed vehicle trajectories up to 200 m (650 feet) upstream of the crosswalk at SW 4th Ave. and SW College Street. Hence, it was possible to see whether the vehicles arrived from SW 4th Ave., the Interstate 405 (freeway) off-ramp, or the side street (SW Lincoln). At this site, it was also possible to complement the rooftop camera with two cameras placed on lampposts. The first lamppost camera was located near the SW 4th Ave. and SW College to capture pedestrian and driver behavior at both crosswalks. The second lamppost camera was located at SW 4th Ave. and SW Lincoln (one block upstream) to capture events at this signalized intersection. SW 4th Ave. is a one-way multilane minor arterial with average daily weekday traffic of 11,292 vehicles per day in 2010 (PBOT, 2014).

Vehicles that arrive at the study intersection come from three origins: Interstate 405 (I-405), minor arterial SW 4th Ave., and local SW Lincoln Street. There is a signalized intersection one block upstream and downstream of the study location (see Fig. 2). On SW 4th Ave. there are three central lanes for traffic and there are two outer lanes (one on the right and on the left) for parking. However, parking is not allowed 40 feet before the crosswalk because there are curb extensions and ramps for vehicle access to office buildings (east/right side) and a gas station exit (west/left side). At the study site, SW 4th and SW College, there are no traffic signals but there are two crosswalks with a continental design pattern (see Fig. 3). For the sake of simplicity, herein, the upstream crosswalk and downstream crosswalk will be denoted CW1 and CW2 respectively and for sake of clarity speed lines for CW2 are not shown in Fig. 3.

Along SW 4th Ave. there are no in-street signs to encourage yielding and there is no advance stop/yield line. At each crosswalk there is a bulb out and pedestrians utilizing a crosswalk only have to cross three lanes of traffic instead of five lanes of traffic. There are several office buildings nearby the crosswalks. Based on video observation the majority of pedestrian traffic goes to or comes from the University Building and/or City of Portland/Office buildings located on the east (right) side of SW 4th. Around lunchtime, the majority of pedestrian traffic utilize the crosswalks to access the food cart area on the west (left) side of SW 4th Ave. As shown in Fig. 3 the distance between CW1 and the upstream intersection at SW Lincoln is approximately 120 m or 400 feet; this figure can be obtained summing the partial distances. The distance between CW2 and the downstream traffic signal at SW 4th Ave. and SW Hall is approximately 80 m (260 feet).

At the time of the data collection, SW 4th Ave. traffic received the largest proportion of green time (approximately 65% of the cycle) at the upstream and downstream-signalized intersections. The pedestrian and vehicle datasets were collected in March in a
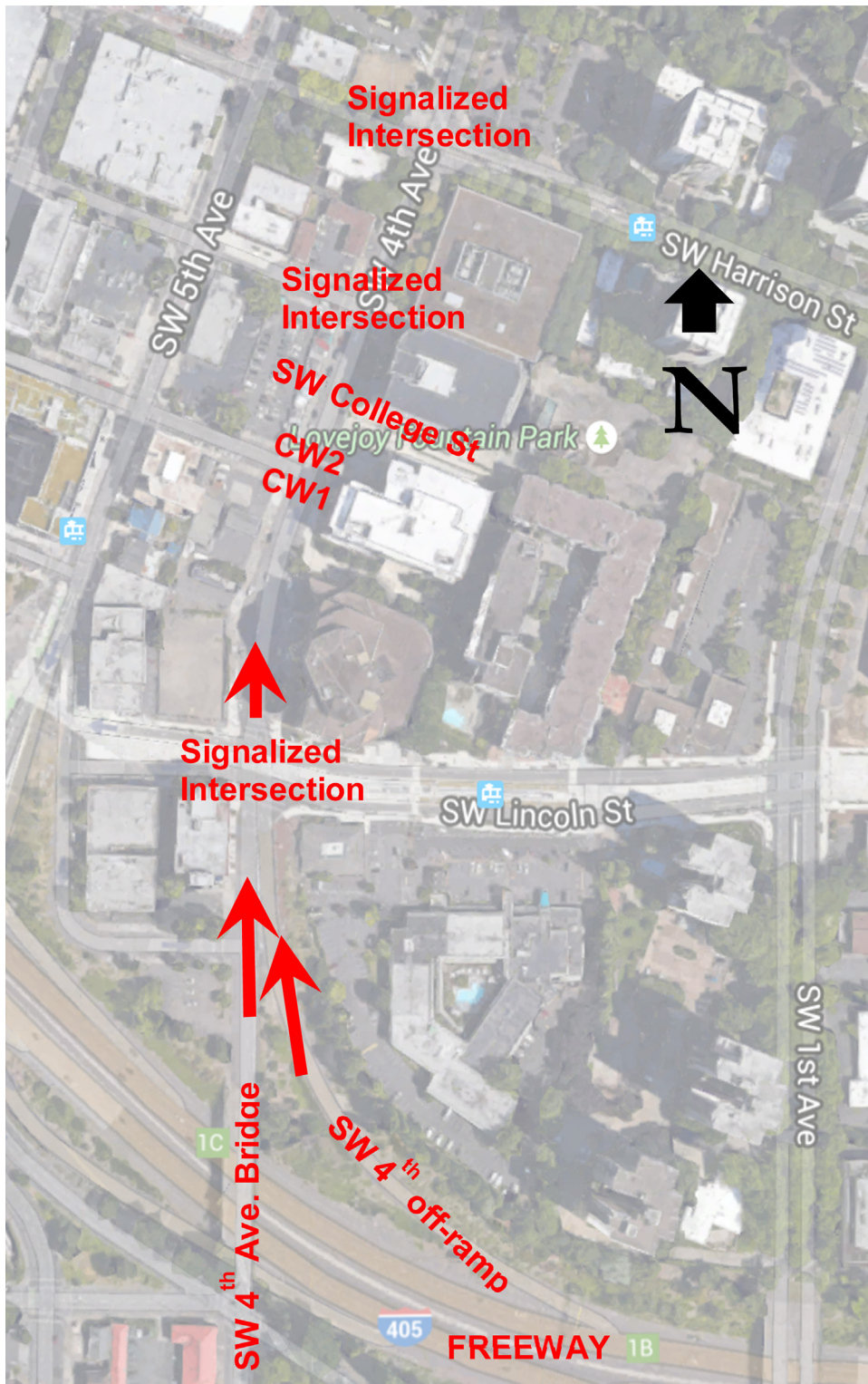
Fig. 2. Aerial view of the study site.

day when the sky was clear and there was no rain, i.e. no visibility problems. The datasets were collected during the late morning and early afternoon, from 11:30 a.m. to 12:30 p.m. During the data collection period, the following numbers describe traffic flows, vehicle origin, and pedestrian flows:

• Overall, 684 vehicles traveled on SW 4th Ave. across the study site.

○ 160 vehicles came from I-405 (23%),
○ 341 vehicles came from SW 4th Ave (50%), and
○ 183 vehicles came from SW Lincoln Street (27%).

• The majority of the vehicles were passenger cars:

○ 397 passenger cars (58%),
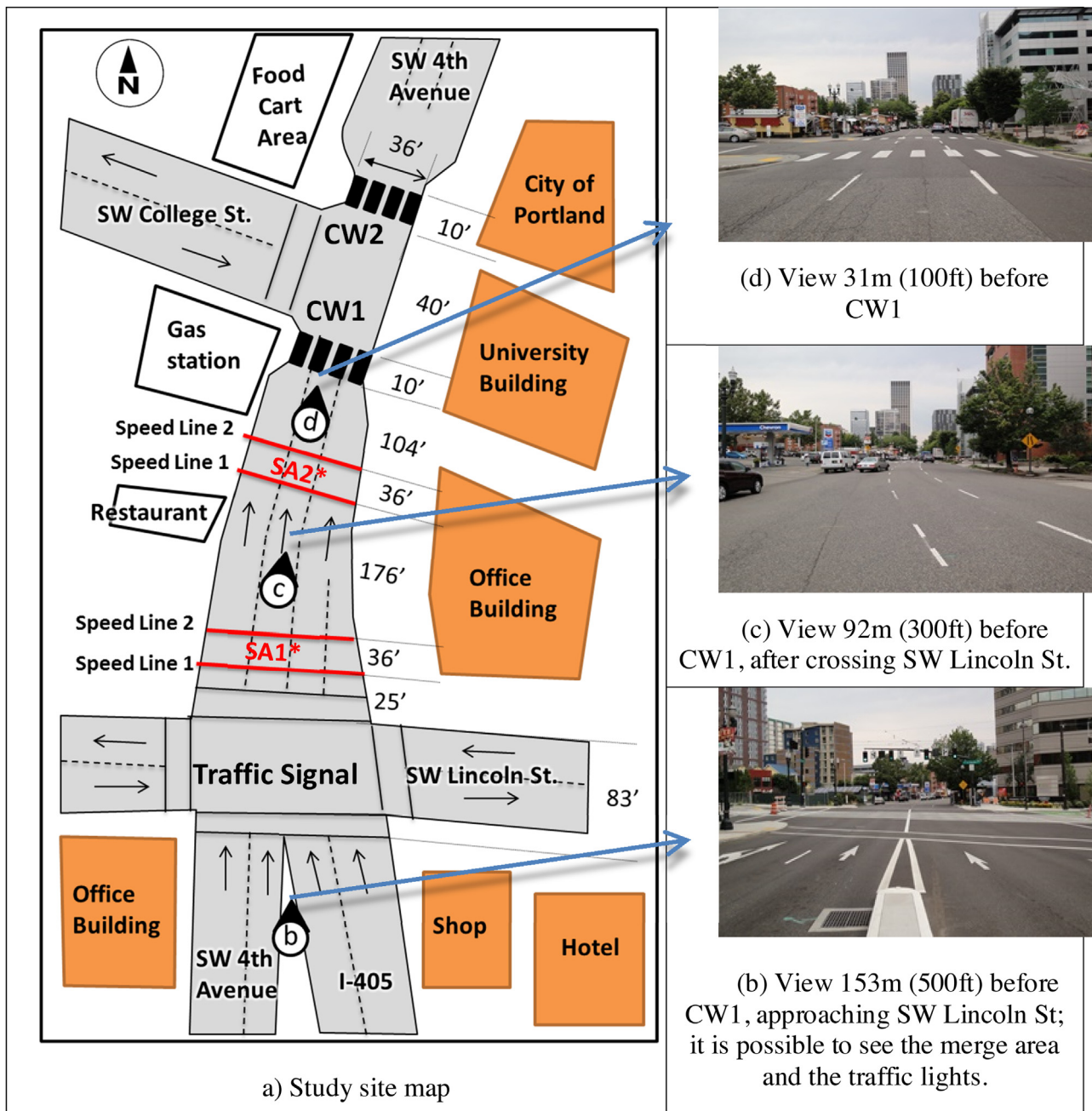○ 232 SUVs/pickup trucks (34%), and

Fig. 3. Schematic view of the study site, distances (in feet) and three drivers' perspectives *For the sake of clarity, only Speed Areas 1 and 2 (SA1 and SA2) for CW1 are drawn.

○ 55 other types including buses and commercial vehicles (8%)

• Overall, 531 pedestrians utilized the crosswalks:

○ 133 pedestrians utilized CW1 (25%) and
○ 398 pedestrians utilized CW2 (75%)
○ 266 pedestrians crossed the road in the eastbound direction (50%) and
○ 265 pedestrians crossed the road in the westbound direction (50%).

2.2. Data processing and definitions

This research utilized detailed video records from several video cameras situated at different locations and heights to capture the behavior of drivers and pedestrians before, during, and after cross-ing the crosswalk. Data processing was a very demanding effort in terms of staff-hours. It took several weeks to process all the traffic data and complete the data quality control checks. A video obser-vation protocol was developed and data quality was monitored throughout the data processing task.

The day before the data collection the pavement was marked at predetermined distances. Fig. 3 shows the lines used to determined speed after Lincoln St., Speed Area 1 (SA1), and before College St, Speed Area 2 (SA2). In addition, other lines were drawn to estimate the speed and distance of the vehicles when a pedestrian entered the crosswalk. The video data quality was enough to accurately estimate speeds and headways. Vehicles speeds are measured from the video, with 10 frames per second researchers were able to stop or advance the video in 1/10 s increments.

The data processing involved several steps: (i) video was ana-lyzed to measure pedestrian and vehicle volumes and speeds, (ii)

video was analyzed to record the time when there was a pedestrian-vehicle interaction, (iii) for each event recorded in step (ii), each graduate student (independently) recorded detailed information about the vehicle trajectory, traffic conditions, and pedestrian behavior, and (iv) for quality assurance each pedestrian-vehicle event collected in (iii) was compared. In a few occasions, if there was any discrepancy both graduate students reanalyzed the video until there was complete agreement. Overall, there was a very high level of agreement the first time the data was processed independently.

In the final models only include compliance and non-compliance events where the pedestrian exercised prudence and due care as requested by the law. As in previous studies (e.g., Bennett et al., 2014) this condition is met if the pedestrian entered the crosswalk area when the approaching vehicle was located at a distance equal or larger than the dilemma zone for traffic signals. The total stopping time as defined by the Institute of Transportation Engineers (ITE) for traffic signals (ITE, 1999) is:

$$Y = t + \frac{v}{(2a + 2Gg)}$$

where Y = Total time (s or seconds)
v = Vehicle speed (ft/s)
t = Reaction time (s or seconds)
a = Deceleration rate (ft/s^2)
G = Roadway grade (percent)
g = Gravity acceleration (ft/s^2)

The operational reaction time of an average driver in an urban area is assumed to be 1 s and maximum deceleration rate is assumed to be 10 ft./s^2 or 6.8 mph. The safe stopping distance (SSD) is obtained multiplying, Y and v, time and speed. For a speed of 25 miles per hour (40.2 km/h) a vehicle SSD is 104 feet (31.7 m); for a speed of 30 miles per hour (48.3 km/h) a vehicle SSD is 141 feet (42.9 m). Note that in this study $G = 0$ and with the 1 s reaction time the SSD can be calculated as $v + \frac{v^2}{2a}$.

Pavement markings where utilized to determined vehicle location and speed when the pedestrian entered the crosswalk. A speed pilot data collection study showed that the speed distribution 85th percentile was approximately 27.5 mph. The stopping distance for a speed of 27.5 mph is 122 feet and the location of SA2 was chosen so that the center of SA2 is 122 feet away from CW1. Likewise, lines were drawn 122 feet before CW2. For the sake of clarity, lines SA1 and SA2 for CW2 are not shown in Fig. 3. Note that the ITE formula is very conservative, modern vehicles can safely break at deceleration rates much higher than 10 ft/s^2 (NCHRP, 1997). Furthermore, the speed limit on SW 4th Ave. is 20 mph which is less than the utilized 85th speed percentile. The 85th speed percentile is utilized because Oregon DOT suggests utilizing the 85th speed percentile to set speed limits that increase user compliance (ODOT, 2014). The median and average speeds are approximately 22 mph, see tables in the Appendix A.

To determine if there was a violation of the crosswalk law, the diagrams presented in Fig. 1 were followed as well as the text of the law ORS 811.028. A detailed set of instructions was developed to ensure consistency among data processors and data recorders. Oregon laws ORS 811.028 is violated when the driver does not stop for a pedestrian as shown in Fig. 1; ODOT recommends that a vehicle stops 30 feet before the crosswalk in multilane arterials. To study if vehicles that comply with the law were also complying with the 30 feet recommendation, the stopping distance of compliant vehicles was also recorded. In addition, Oregon law states that pedestrians must exercise due care and walk safely (ORS 811.005).

Summarizing, the following conditions were required to have a valid pedestrian-vehicle event and to standardize the data processing:

i The vehicle crossed CW1 and CW2, i.e. the vehicle did not turn left at College St.
ii If a driver had a compliance event at CW1 then any posterior non-compliance event at CW2 was not included in the dataset.
iii The vehicle did not exit from a mid-block location, i.e. gas station or building between College St. and Lincoln St.
iv A pedestrian entered CW1 or CW2 when an approaching vehicle was at least 122 feet away.
v The pedestrian correctly utilized the crosswalk and followed the law, i.e. no partial or full jaywalking.

Conditions (i) and (ii) are necessary to separate any interaction effect between CW1 and CW2. Condition (iii) is necessary to estimate the impact of speed and upstream traffic conditions on compliance rates. Conditions (iv) and (v) are necessary to study only events where the pedestrians fully comply with Oregon law, i.e. the pedestrian is walking safely and exercising due care; the focus of this study is on *driver* behavior, hence we are excluding a few events where pedestrians may have been aggressive or jaywalked.

After applying conditions (i)–(v) several driver-pedestrian interactions were removed from the dataset. A total of 73 ORS 811.028 non-compliance events were observed after the data was analyzed, processed, and filtered as described in this section; 43 drivers complied with the law and stopped for pedestrians between 0 and 30 feet from the crosswalk. There were 6 observations where the drivers stopped at a distance that exceeded 30 feet. The ratio of compliant over non-compliant events was approximately the same for both crosswalks. The reader is reminded that there is no "Stop Here for Pedestrians" in-street sign or line marked on the pavement before either CW1 or CW2. In all the modeling results presented in the next section, 116 observations were utilized to estimate the coefficients.

3. Modeling results

Assuming that pedestrians comply with the law and exercise due care, this research aims to answer two questions: (1) What are the factors that affect driver non-compliance? and (2) What are the factors that affect driver stopping distance? To answers these research questions two models are developed: (1) a binary logistic regression model where the dependent variable is compliance i.e. whether a vehicle followed ORS 811.028 law and (2) an ordered logistic regression model where the dependent variable is stopping distance. Probit models were also developed but the logit model presented better results in terms of fit. The literature review indicates that speed is an important variable to explain drivers' non-compliance. This study tests whether more detailed traffic and trajectory variables can be used to explain drivers' non-compliance, i.e. the null hypothesis states that detailed trajectory and traffic variables do not explain drivers' non-compliance or that their estimated coefficients are zero.

Table 1 presents a data dictionary of the independent variables utilized in both models. Only events that comply with conditions (i)–(v) detailed in the previous section were included in the models. The acronym CIA stands for "Crosswalk Influence Area" and is defined as the area, adjacent to the curb and with a different texture, that let visually impaired pedestrians quickly identify the presence of a crosswalk.

From the video it was not possible to accurately determine drivers' personal characteristics, such as gender or age group; data processors had a 5% or higher rate of disagreement or more than 5% of observations that were classified as "unable to accurately determine gender/age group". Hence, driver demographic variables are not included in the models. Some contributing factors associated with drivers' risk of accident, i.e. driver under the influence

Table 1
Data Dictionary for Binary Logistic and Ordered Logistic Regression Models.

Dependent Variables	Type	Description
Compliance	Binary	1 if a vehicle complied with ORS 811.028, 0 otherwise
Stopping distance	Ordinal	Distance between stopped vehicle and crosswalk: 0 if vehicle did NOT stop, 1 = if stopped 0–10' from crosswalk, 2 = if stopped 10–20', 3 = if stopped 20–30', 4 = if stopped 30–40'.
Pedestrian Variables		
Pedestrian Speed	Continuous	Pedestrian crossing speed between curbs (feet per second)
Ped Direction	Binary	1 if Eastbound
Ped Lane	Binary	Ped location when the non-compliance took place, 1 = left lane, 2 = center lane, 3 = right lane. It was modeled as a dummy variable.
Disturbance	Binary	1 if the pedestrian had to stop or speed up significantly
CIA Time	Continuous	Pedestrian time (seconds) at the CIA (crosswalk influence area) before crossing
Peds in CIA	Integer	Number of pedestrians in CIA when the event took place
Driver/vehicle Variables		
Origin I-405	Binary	Vehicle comes from I-405
Origin SW 4th Ave.	Binary	Vehicle comes from SW 4th
Vehicle Type	Binary	Binary variables to distinguish passenger cars, light duty truck, van, medium-duty truck, and transit buses
Lincoln Red Light	Binary	1 if the vehicle stopped at the red light at SW Lincoln
Vehicle Speed	Continuous	Vehicle speed when pedestrian enters the crosswalk
Speed1	Continuous	Vehicle speed at SA1
Speed2	Continuous	Vehicle speed at SA2
Speed Change	Continuous	Difference: Speed2–Speed1
Platoon1	Binary	1 if the vehicle is part of a platoon at SA1
Platoon2	Binary	1 if the vehicle is part of a platoon at SA2
Vehicle Headway	Continuous	Time between vehicles when pedestrian enters the crosswalk
Ups. Headway1	Continuous	Time between vehicle and (next) upstream vehicle at SA1
Ups. Headway2	Continuous	Time between vehicle and (next) upstream vehicle at SA2
Ups. Headway Change	Continuous	Difference: Ups. Headway2 – Ups. Headway1
Dow. Headway1	Continuous	Time between vehicle and (next) downstream vehicle at SA1
Dow. Headway2	Continuous	Time between vehicle and (next) downstream vehicle at SA2
Dow. Headway Change	Continuous	Difference: Dow. Headway2 – Dow. Headway1
Lane Change	Binary	1 if the vehicle changed lanes between Lincoln and College
Left Turn Waiting	Binary	1 if there is another vehicle waiting to turn left at College
Vehicle Lane	Binary	A binary variable for each lane; lane that the vehicle used to enter the crosswalk
Distance	Continuous	Distance from crosswalk
Adjacent Stopped	Binary	1 if a vehicle in an adjacent lane stops for a pedestrian
Roadway and Crosswalk Variables		
Crosswalk	Binary	1 if non-compliance took place at CW1
Num. Vehicles	Integer	Number of vehicles between Lincoln St. and College St.
Num. Bicycles	Integer	Number of bicycles between Lincoln St. and College St.
Num. Peds.	Integer	Number of pedestrians in the crosswalk plus CIAs
Num. Peds. in CIA	Integer	Number of pedestrians in the CIAs
Visual Obstruction	Binary	1 if there was a visual obstruction (i.e. another vehicle) in the line of sight between the driver and the pedestrian when the pedestrian entered the crosswalk

of alcohol, were not observable either. Likewise, attitudes towards risk taking and/or aggressive personality characteristics are not observable unless the driver manifested them in a crosswalk non-compliance action. In Table 1, any reference to "vehicle/driver" or "pedestrian" are in relation to the vehicle or pedestrian that were involved in a compliance or non-compliance event. Unless stated otherwise, the timing of any data point is when the pedestrian entered the crosswalk.

4. Binary logistic regression results

This subsection presents the results of a model where the dependent variable is compliance i.e. whether a vehicle followed ORS 811 law; the independent variables are all the variables listed in Table 1. The data collection process selected only events where the drivers had the option to safely stop and comply with the pedestrian law. Hence, a binary logistic regression model where the dependent variable is to comply (Y = 1) or not comply (Y = 0) is warranted. Binary logistic and probit models were explored; the results were conceptually similar but logitic models results were slightly superior in term of the Akaike Information Criterion or AIC.

A model specification was selected dropping variables that were not significant and utilizing a backwards stepwise selection proce-

Table 2
Final Compliance Model.

Variable	Coeff.	Std.Err.	t-value	P-value	Signif.
Intercept	−3.882	0.878	−4.422	9.78E-06	***
Speed Change	−0.187	0.050	−3.740	1.84E-04	***
Down. Headway Change	0.151	0.047	3.223	1.27E-03	**
Disturbance	4.006	1.331	3.011	2.61E-03	**
Peds in CIA	0.701	0.296	2.365	1.80E-02	*
Origin SW 4th Ave.	1.431	0.610	2.347	1.89E-02	*
Lincoln Red Light	1.315	0.630	2.088	3.68E-02	*
SUV-Pickup	−1.177	0.670	−1.690	9.10E-02	.
Adjacent Stopped	1.013	0.611	1.658	9.73E-02	.

Codes significance: "." when p < 0.10; "*" when p < 0.05; "***"when p < 0.01; "****"when p < 0.001.

dure based on variable significance and AIC values. Different model specifications were tested, e.g. including all the speeds and headways vs. including speeds and headways differences or combining differences and actual measurements. The final model is shown in Table 2. The independent variables are sorted by P-value, from lowest to highest. If variables from the model are removed one at the time, ceteris paribus, it is possible to get a sense of the contribution of each variable to the explanatory power of the model. Table 3

Table 3
Compliance Model – Ceteris Paribus Log-likelihood Change.

Variable	ΔLL
Speed Change	10.01
Down. Headway Change	6.56
Disturbance	5.54
Origin SW 4th Ave	3.06
Peds in CIA	2.71
Lincoln Red Light	2.37
SUV-Pickup	1.57
Adjacent Stopped	1.48

Table 4
Final Compliance Model with only College Variables – i.e. measured near College Street.

Variable	Coeff.	Std.Err.	t-value	P-value	Signif.
(intercept)	−1.305	0.907	−1.438	1.50E-01	
Num. Peds. in CIA	0.828	0.292	2.837	4.55E-03	**
Disturbance	2.722	1.099	2.478	1.32E-02	*
Speed2	−0.084	0.034	−2.463	1.38E-02	*
Visual Obstruction	1.031	0.519	1.989	4.68E-02	*
Dow. Headway2	0.071	0.042	1.704	8.85E-02	.

Codes significance: "." when $p < 0.10$; "*" when $p < 0.05$; "***"when $p < 0.01$.

shows the change in log-likelihood value and variables are sorted in terms of their explanatory power. The ordering in Table 3 is almost the same as the ordering in Table 2 except for the variables "Peds in CIA" and "Origin SW 4th Ave" that swapped positions.

The results presented in Tables 2 and 3 show that "Speed Change", whether the driver speeds up or slows down is by far the strongest predictor of the pedestrian law compliance. Drivers that increase their speed between speed areas 1 and 2 (SA1 and SA2) are less likely to comply with the crosswalk law. The reader is reminded that SA2 is approximately 122 feet before a crosswalk, hence, the speed change variable does not include the segment where the driver or vehicle are typically decelerating as they approach the crosswalk. In the models, "Speed Change", was a variable that prevailed over the actual speed at SA2 or the speed of the vehicle when the pedestrian entered the crosswalk.

The second variable in terms of importance, "Down. Headway Change", indicates that when the headway between the vehicle (that is part of the pedestrian-driver interaction event) and the vehicle ahead (downstream) increases, then the vehicle is more likely to comply with the pedestrian law. Hence, if the platoon of vehicles become more compact, the driver is less likely to comply with the pedestrian law. "Down. Headway Change" was a variable that prevailed over the actual headway at SA2 or when the pedestrian entered the crosswalk.

The third variable, "Disturbance", indicates that a driver is more likely to stop if the pedestrian suddenly reduces or increases his/her walking speed. Disturbance is a function of the comparison of the pedestrian speed when the vehicle is located 60 feet or more and when the vehicle is located 60 feet or less. If the pedestrian speed changed by more than 50% (plus or minus) then it was coded that the pedestrian was "disturbed". This variable was coded 1 when the pedestrian looking at the oncoming vehicle decided to stop or significantly increase walking speed to avoid a potential crash. Perhaps drivers more easily notice a significant change in pedestrian speed and observing this "pedestrian anxiety or distress" leads to higher compliance of the law.

The fourth variable, "Peds in CIA", indicates that a driver is more likely to stop if there is a group of pedestrians entering the crosswalk or about to enter the crosswalk. It is likely that more pedestrians are easier to see and/or that drivers feel more compelled to yield when there are more pedestrians involved in the events.

The fifth variable, "Origin SW 4th Ave.", indicates that a driver is more likely to stop if the pedestrian origin is SW 4th Ave. If this variable is removed, then the variable "Origin I-405" with a negative sign enters the model (all other variables remain). This indicates that drivers that are coming from freeway Interstate 405 may not have enough time to adjust to the new "urban" and pedestrian environment. There are no speed limit or pedestrian signs before the crosswalks. In addition, three lanes of traffic may provide clues about a "vehicle" dominant environment. Previous research efforts have indicated that drivers who have driven at high speeds for a prolonged period are more likely to underestimate their travel-

ing speed, this phenomenon is usually called "speed adaptation" (NCHRPS, 2011).

The sixth variable, "Lincoln Red Light", reinforces this interpretation. Vehicles that are stopped at the upstream traffic light are more likely to comply with the crosswalk law. It is possible that the red traffic light indication is giving the drivers more time to adjust to urban driving conditions and the presence of pedestrians ahead.

The seventh variable, "SUV-Pickup", indicates that drivers of larger vehicles are less likely to comply with the crosswalk law. However, vehicle size is not likely to be the direct factor affecting non-compliance; as a counterexample, public transportation (bus) drivers always complied with the law and stopped far away from the crosswalk. The final and eight variable, "Adjacent Stopped", indicates that drivers are more likely to comply with the law if another driver has already complied. This result agrees with previous research efforts, e.g. (Schroeder and Rouphail, 2011) but in this case in a multilane one-way street.

To more easily compare the results to previous studies, the results of a model constrained to have only variables that are measured between the Speed Area 2 (SA2, approximately 122 feet from the crosswalk) and the crosswalk are shown in Table 4. As expected, vehicle speed, headway, number of pedestrians in the CIA, and pedestrian disturbance are significant variables and their signs are intuitive and have the same interpretation as before. In addition, a variable "Visual Obstruction" is significant.

When comparing AIC values for the model in Table 2 (AIC = 107.33) and the model in Table 4 (AIC = 122.65) it is possible to observe a clear loss of information and predictive value. The relative likelihood of the Model in Table 4 is 0.05%, i.e. the second model is 0.05% as probable to minimize information loss when compared to the Model presented in Table 2. We can safely conclude that the addition of trajectory and upstream traffic variables (stopping at a traffic light, vehicle origin, speed upstream, headway upstream) are providing highly variable information to predict the compliance of the law.

Summarizing, the model results reject the null hypothesis since the estimated coefficients for speed change and downstream headway change were not only highly significant but also the most important variables in terms of *p*-values and explanatory power. Also, in terms of AIC, a model with detailed traffic and trajectory variables clearly outperforms a model that includes only traffic speed or headway information near the crosswalk. Previous research efforts have indicated that approaching speed is a key factor to predict driver behavior; the presented research results do not contradict this finding. Approaching speed is indeed a significant and important factor but the same can be said about other traffic and trajectory variables that measure headway/speed change, vehicle origin, and number of previous stops. However, the results suggest that speed and headway change are perhaps more important than speed/headway measured at only one point along the trajectory of the vehicle.

Table 5
Final Distance Model.

Variable	Coeff.	Std.Err.	t-value	P-value	Signif.
Speed Change	−0.115	0.037	−3.121	1.80E-03	**
Down. Headway Change	0.104	0.036	2.919	3.51E-03	**
Disturbance	2.114	0.764	2.767	5.66E-03	**
Origin SW 4th Ave	1.275	0.510	2.501	1.24E-02	*
Visual Obstruction	1.153	0.480	2.407	1.61E-02	*
Peds in CIA	0.476	0.241	1.976	4.82E-02	*
SUV-Pickup	−1.110	0.607	−1.827	6.77E-02	.
Lincoln Red Light	0.917	0.530	1.729	8.37E-02	.

Codes significance: "." when p < 0.10; "*" when p < 0.05; "***"when p < 0.01.

4.1. Ordered logistic regression results

This subsection presents the results of an ordered logistic regression model where the dependent variable is stopping distance from the crosswalk. Ordinal logistic regression models are suitable in this case because the dependent variable is categorical of an ordered nature. Stopping distances were grouped into several groups: (1) negative, i.e. vehicles that do not stop, (2) vehicles stopped between 0 and 10 feet from the crosswalk, (3) vehicles stopped between 10 and 20 feet from the crosswalk, (4) vehicles stopped between 20 and 30 feet from the crosswalk, and (5) vehicles stopped at a distance longer than 30 feet. A nested model where the first choice was whether to comply with the law and the second choice within "comply" was stopping distance was not supported by the data, hence, in this section only the results of the ordered logistic model are reported.

The independent variables are all the variables listed in Table 1. A model specification was selected dropping variables that were not significant and utilizing a backwards stepwise selection procedure (based on the Akaike Information Criterion or AIC). The final model is shown in Table 5. Most variables are significant at the p < 0.05 level, with the remainder being significant at the p < 0.10 level. The model also passed the test of parallel lines.

Most of the variables that were significant in the compliance model are also significant in this model and can be interpreted in a similar way: speed change, Down. Headway Change, Disturbance, Origin SW 4th Ave, Peds in CIA, SUV-Pickup, and Lincoln Red Light. The model results indicate that the variables that are useful to predict compliance are also useful to predict stopping distance. In the final model shown in Table 5 it is possible to see that only one variable, "Adjacent Stopped", was dropped from the model shown in Table 2. Only one variable "Visual Obstruction" was added to the model. The positive value of "Visual Obstruction" indicates that if there is a visual obstruction (another vehicle) in the line of sight between the driver and the pedestrian (when the pedestrian entered the crosswalk) then the driver is more likely to stop farther away from the crosswalk. This variable is correlated with presence of traffic on adjacent lanes, one possible interpretation is that the presence of adjacent traffic tend to make drivers more alert and/or ready to stop.

5. Conclusions and discussion

This paper examines traffic and trajectory factors that explain whether a driver complies with the Oregon pedestrian law. Data from detailed video records (several cameras at different heights) were utilized to analyze driver and vehicle trajectories up to 200 m (650 feet) upstream of a crosswalk with a high record of pedestrian law violations. The modeling results indicate that speed and headway changes as well as driving trajectory before reaching the crosswalk are the most significant variables to predict crosswalk law compliance and stopping distance.

Novel results indicate that vehicle origin and stopping at upstream traffic lights affect compliance rates. Drivers that are coming from a freeway or do not stop at an upstream traffic light are more likely to be less compliant and stop closer to the crosswalk. In addition, changes in vehicle speed and headways are the most significant variables to predict pedestrian crosswalk law compliance and stopping behavior. This is the first research effort to analyze crosswalk stopping distance; it is notable that the variables that explain crosswalk compliance rates are also useful to explain stopping distance. Results also indicate that drivers are more likely to comply with the pedestrian law if the pedestrian stopped while crossing or had to speed up in response to approaching vehicles. Drivers of SUV/pickups tend to comply less than smaller passenger vehicles.

Pedestrians, even if they are acting lawfully as assumed in this research, are highly vulnerable while crossing a crosswalk with approaching oncoming traffic. At locations with high non-compliance rates efforts must be made to increase pedestrian safety and stopping distance. It has been argued that the psychological comfort of pedestrians should be given more consideration because of the greater vulnerability of pedestrians at crosswalks (Hubbard et al., 2007). Enforcement and education campaigns, as the campaigns executed by PBOT, can be useful to lower non-compliance rates and increase stopping distances. In addition, in some cases, engineering measures may also be necessary.

This research effort has several limitations. It has focused only on pedestrians who fully comply with the law, i.e. not aggressive; future research efforts may consider how drivers' trajectory and behavior are affected by the level of pedestrian aggressiveness. Future research efforts should also consider the comparison of crosswalks with high and low non-compliance rates and the analysis of more crosswalks in different environments. It is also increasing important to study the impact of distracted drivers and pedestrians on compliance rates. Future research efforts can also study interaction effects among crosswalks, for example how compliance at one crosswalk may affect compliance at downstream crosswalks.

The focus of this paper is not on the effectiveness of a particular treatment or specific design recommendations, however, based on the model results it is highly likely that measures that can be taken to reduce vehicle speeds are very likely to improve compliance rates. Additional signage, especially for drivers coming from freeway Interstate 405, may also result in higher compliance rates. Dynamic speed signs, displaying approaching vehicle speeds may be useful to inform drivers as well as pedestrians, however, some research have shown that the positive impact of dynamic speed displays may wear off over time (Ardeshiri and Jeihani, 2014). Forcing vehicles to stop at the upstream intersection, e.g. flashing red light, can provide a valuable visual and normative cue about appropriate driving speeds and solve the problem of speed adaptation especially for drivers coming from Freeway I-405. Treatments like rectangular rapid flashing beacons (RRFBs) have shown to increase yield rates substantially (Shurbutt et al., 2009). Changing the type of crosswalk, e.g. a raised crosswalk, may increase visibility and awareness (Zegeer et al., 2001). A more radical approach would involve changes in the cross-section of the street, e.g. street narrowing or even a road diet from 3 to 2 lanes; appropriate signage plus a road diet after crossing Lincoln street (one block upstream from the crosswalks) would signal drivers that they are entering an urban area with heavy pedestrian traffic.

The results of this research suggest that treatments or driver notifications (Habibovic and Davidsson, 2012) that discourage accelerating – speeding up – towards the crosswalk would be most useful to increase compliance. Previous studies have shown the potential positive payback of reducing traffic speeds to posted speed limits (Carsten and Tate, 2005). Assuming non-aggressive

pedestrian behavior, it can be speculated that connected vehicles with intelligent speed adaptation, i.e. reduction of speeds when entering more urban or pedestrian areas, and/or automated detection of pedestrians may greatly increase pedestrian safety and comfort levels.

Acknowledgements

Appendix A.

See

Table A1
Descriptive Statistics – Significant continuous/integer variables.

Variable	Min.	15th P.	Avg.	Med.	85th P.	Max.
Speed1 (mph)	10.60	15.80	22.47	22.00	29.13	38.40
Speed2 (mph)	2.20	13.60	21.69	21.80	28.30	43.60
Speed Change (mph)	−18.10	−8.55	−0.78	−0.40	5.95	21.90
Dow. Headway1 (sec.)	0.71	3.12	11.88	12.36	20.00	25.09
Dow. Headway2 (sec.)	1.10	2.47	12.70	15.78	20.00	20.00
Dow. Headway Change (sec.)	−16.80	−6.98	−0.83	0.00	2.34	18.02
Peds in CIA	0	0	0.97	1	2	5

Table A2
Descriptive Statistics – Significant (bold) and related binary variables.

Variable	Avg.
Disturbance	0.07
Origin SW 4th Ave.	0.46
Origin I-405	0.30
Origin other (Lincoln)	0.24
Lincoln red light	0.34
Adjacent stopped	0.30
SUV-Pickup	0.22
Cars	0.70
Other vehicle	0.08

Table A3
Correlations – Significant variables.

Variable	Speed Change (mph)	Dow. Headway Change (s)	Peds in CIA	Origin SW 4th Ave.	SUV-Pickup	Lincoln red light	Adjacent stopped
Speed Change (mph)	1	0.00	−0.24	0.03	0.15	0.07	−0.02
Dow. Headway Change (s.)	0.00	1	−0.04	−0.12	−0.14	−0.26	0.17
Peds in CIA	−0.24	−0.04	1	−0.06	0.14	−0.09	0.30
Origin SW 4th Ave.	0.03	−0.12	−0.06	1	0.02	0.17	−0.15
SUV-Pickup	0.15	−0.14	0.14	0.02	1	−0.03	−0.09
Lincoln red light	0.07	−0.26	−0.09	0.17	−0.03	1	−0.05
Adjacent stopped	−0.02	0.17	0.30	−0.15	−0.09	−0.05	1

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