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Accident Analysis and Prevention 37 (2005) 775–786

ACCIDENT ANALYSIS & PREVENTION

www.elsevier.com/locate/aap

Comprehensive analysis of vehicle–pedestrian crashes at intersections in Florida

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Received 6 January 2005; accepted 23 March 2005

Abstract

This study analyzes vehicle–pedestrian crashes at intersections in Florida over 4 years, 1999–2002. The study identifies the group of drivers and pedestrians, and traffic and environmental characteristics that are correlated with high pedestrian crashes using log-linear models. The study also estimates the likelihood of pedestrian injury severity when pedestrians are involved in crashes using an ordered probit model. To better reflect pedestrian crash risk, a logical measure of exposure is developed using the information on individual walking trips in the household travel survey. Lastly, the impact of average traffic volume on pedestrian crashes is examined. As a result of the analysis, it was found that pedestrian and driver demographic factors, and road geometric, traffic and environment conditions are closely related to the frequency and injury severity of pedestrian crashes. Higher average traffic volume at intersections increases the number of pedestrian crashes; however, the rate of increase is steeper at lower values of average traffic volume. Based on the findings in the analysis, some countermeasures are recommended to improve pedestrian safety.

Keywords: Pedestrian; Crash frequency; Injury severity; Exposure; Intersection

1. Introduction

As population and traffic volume increase, the conflicts between pedestrians and vehicles on roads are more frequent and consequently, vehicle–pedestrian crashes have become a major concern in improving traffic safety. According to the National Highway Traffic Safety Administration (2004), approximately 4700 pedestrians were killed and 70,000 pedestrians were injured in the United States in the year 2003. Although the number of pedestrian victims has continuously decreased over the last 16 years (1988–2003), actual pedestrian crash risk may not have been reduced considering the fact that the number of pedestrian trips has been reduced as more people own and drive cars. In particular, the current intersection design guidelines mainly focus on the operation and safety of vehicles rather than pedestrian safety (Pietrucha and Opiela, 1993).

For the improvement of pedestrian safety at intersections, understanding the effects of crash-related factors on pedestrian crashes can help develop more effective countermeasures as the types of pedestrian crashes vary with these factors (Stutts et al., 1996). Thus, the past studies on frequency and injury severity of pedestrian crashes have generally focused on the effects of pedestrian and driver characteristics, vehicle characteristics and conditions, and road geometric and traffic characteristics of intersections.

A number of studies identified that there exists strong relationship between demographic factors of pedestrians (particularly age) and crash risk. For example, Zegeer et al. (1993) observed high fatality of older pedestrians in daytime, on weekdays, and in winter. They also found that since older pedestrians reacted slowly with reduced vision and wore dark clothing at nighttime, dark lighting conditions were more hazardous to older pedestrians. Fontaine and Gourlet (1997) found that children and the elderly were the most vulnerable to pedestrian crashes among age groups. Oxley et al. (1997) found that when cars approached closely, older pedestrians crossed more frequently and adopted unsafe road crossing

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0001-4575/$ – see front matter
doi:10.1016/j.aap.2005.03.019

strategy (e.g. slow walking speed, delay in reaction). Similarly, Tarawneh (2001) observed that old pedestrians walked slower than younger pedestrians and their level of exposure to vehicle traffic increased. Al-Ghamdi (2002) found that the fatality rate of the old-age pedestrian group (age 60 and over) was the highest whereas the fatality rate of the young-age pedestrian group (age 20–29) was the lowest. These results suggest that old pedestrians are most likely to be involved in a crash and also severely injured when they are involved in a crash.

Some studies claimed that a pedestrian's alcohol use is also an important factor affecting pedestrian crashes. Miles-Doan (1996) suggested that alcohol-impaired pedestrians were more involved in pedestrian crashes and their odds of dying relative to surviving were higher than non-alcohol-impaired pedestrians. Öström and Eriksson (2001) found that intoxicated pedestrians were more severely injured and suffered more head injuries than non-intoxicated pedestrians. Some studies considered the combined effect of pedestrian age, gender and alcohol use on crash risk. For example, Holubowycz (1995) reported that young and middle-age intoxicated males are high-risk pedestrian groups.

Vehicle characteristics and conditions such as vehicle speed, vehicle types, and vehicle movement are also closely associated with pedestrian crashes. For instance, Anderson et al. (1997) observed that when the speed limit was reduced, the number of fatal pedestrian crashes was also reduced. Some researchers compared the injury severity of pedestrian crashes caused by different vehicle types and vehicle movement. Lefler and Gabler (2004) found that the pedestrian fatality rate when struck by light trucks and vans (LTV) was two to three times greater than the fatality rate when struck by passenger cars since LTVs have higher bumpers and more blunt frontal profiles. Preusser et al. (2003) found that turning vehicles often caused pedestrian crashes because drivers failed to yield the right of way to pedestrians at intersections.

A few studies examined the effect of road geometric and traffic characteristics on pedestrian crash risk. Given that median not only blocks vehicle interactions in different directions but also provides safe refuge area for pedestrians, Bowman et al. (1994) demonstrated that different types of median have different effects on pedestrian crashes. LaScala et al. (2000) observed that injuries in pedestrian crashes were greater in the areas with higher population density, average daily traffic, and number of cross-streets per kilometer roadway through a spatial analysis using a geographic information system. On the other hand, Garber and Lienau (1996) reported contradicting results that fatality rate of pedestrian crashes in rural areas with lower population density was higher than the fatality rate in urban areas. Similarly, Zajac and Ivan (2003) found that pedestrian injury severity was higher in village and downtown fringe areas than downtown and low-to-medium density commercial areas.

In spite of significant research efforts in the past studies, there still remain some unanswered questions: (1) do we need to analyze pedestrian crashes at driver's fault and pedestrian crashes at pedestrian's fault separately since their causal factors may be different? (2) Does higher frequency of pedestrian crashes actually reflect higher crash risk by pedestrians? As daSilva et al. (2003) suggested, due to lack of information on walking patterns by different age groups, most studies on pedestrian crashes could not properly reflect risk by age groups. (3) Are there any other important road geometric and traffic characteristics affecting pedestrian crashes, such as average traffic volume at intersections, that we are unable to identify since they are not readily available in typical crash reports?

Thus, this study has three objectives: (1) to investigate the relationship between frequency/injury severity of pedestrian crashes at intersections and various driver, pedestrian, traffic, and environmental characteristics; (2) to explore exposure of pedestrian walking on the roads for estimating the risk of pedestrian crashes; and (3) to examine the effect of average traffic volume at intersections on the occurrence of pedestrian crashes.

2. Frequency and injury severity of pedestrian crashes

This study analyzed pedestrian crashes that have occurred at intersections in Florida over 4 years (1999–2002) using the crash information compiled in Florida Traffic Crash Records Database (Florida Department of Highway Safety and Motor Vehicles, 2002). Approximately 7000 pedestrian crashes occurred at intersections or are influenced by intersections. The crashes at mid-block crosswalks and unmarked locations are not included in this study. Five percent of these crashes were fatal crashes. The study considered the variables associated with the characteristics of pedestrians, drivers and vehicles that are involved in crashes, and traffic/road geometry and environmental conditions at the time of crashes as shown in Table 1. Continuous variables (e.g. pedestrians' and drivers' age, vehicle speed) were classified into several categories based on the classification used in the past studies and the authors' subjective judgment. The number of lanes was classified into 1, 2, and 3 or more lanes.

This study develops two types of models to analyze frequency and injury severity of pedestrian crashes. In the analysis of crash frequency, log-linear models were used to identify the relationship between crash frequency and the crash-related variables. This analysis identifies which factors, or the combination of factors, mainly contribute to the occurrence of pedestrian crashes. In the analysis of crash injury severity, an ordered probit model was used to identify the factors causing higher injury severity of pedestrians who are involved in crashes. The following two subsections illustrate the methodology and discuss the results of model estimates.

2.1. Frequency analysis

The analysis of crash frequency identifies the group of drivers/pedestrians and various traffic and environmental

Table 1
Description of variables

Type	Variables	Categories
Pedestrian characteristics	Pedestrians' age	Children (∼14 year old) Very young (15–19 year old) Young (20–24 year old) Middle 1 (25–44 year old) Middle 2 (45–64 year old) Old (65–79 year old) Very old (80 year old and over)
	Pedestrians' gender	Male Female
	Pedestrians' alcohol/drug use	No alcohol/drug use Alcohol and/or drug use
Driver characteristics	Drivers' age	Very young (15–19 year old) Young (20–24 year old) Middle 1 (25–44 year old) Middle 2 (45–64 year old) Old (65–79 year old) Very old (80 year old and over)
	Drivers' gender	Male Female
	Drivers' alcohol/drug use	No alcohol/drug use Alcohol and/or drug use
Vehicle characteristics	Vehicle type	Passenger car Bus, truck, van
	Vehicle speed	Low (0–29 mph) Medium (30–39 mph) High (40 mph and over)
Traffic/road geometric characteristics	Traffic control	No traffic control Traffic signal Other traffic control (Stop, yield, etc.)
	Divided/undivided	Divided Undivided
	Number of lanes	1 lane 2 lanes 3 lanes and over
Environmental characteristics	Lighting	Daylight, dusk, dawn Dark
	Weather	Clear Adverse
	Location	Urban areas Rural areas

conditions that are most involved in pedestrian crashes as causers. The analysis does not estimate risk of each driver and pedestrian group in the form of crash rates. The reason for not being able to consider crash rates is that it is difficult to estimate exposure of some factors and the combination of multiple factors used for modeling. For instance, we cannot accurately measure the proportion of intoxicated drivers/pedestrians in total population of drivers/pedestrians, or the proportion of middle-age male drivers during dark lighting on a divided 3-lane road at signalized intersections in urban areas. To correctly identify factors affecting frequency of pedestrian crashes, it is more appropriate to classify crashes into different types based on actual causes of crashes. Since both drivers and pedestrians make errors leading to crashes, pedestrian crashes are classified into the following two types: (1) crashes at driver's fault and (2) crashes at pedestrian's fault. The premise of this classification is that crashes at driver's fault are more associated with driver characteristics whereas crashes at pedestrian's fault are more associated with pedestrian characteristics. In this study, if the drivers who were involved in pedestrian crashes were cited for moving violation, the crashes were classified as crashes at driver's fault. Otherwise, the crashes were classified as crashes at pedestrian's fault. The data show that the percentage of crashes at pedestrian's fault is substantially higher (80%) than the percentage of crashes at driver's fault (20%).

The two log-linear models were developed for the two types of crashes. The following describes general structure of a log-linear model and the method of calculating odds multipliers (i.e. likelihood of crash occurrence relative to a reference) based on the model estimates. If the two factors affecting pedestrian crashes (categorical variables x and y) are considered, the functional specification of a second-order log-linear model including main effects and the interaction between the two factors is as follows:

$$\ln(F_{ij}) = \theta + \lambda_{x(i)} + \lambda_{y(j)} + \lambda_{xy(ij)} \qquad (1)$$

where F_{ij} is the expected number of pedestrian crashes when $x = i$ and $y = j$, θ a constant, $\lambda_{x(i)}$ the effect of the ith level of a factor x, $\lambda_{y(j)}$ the effect of the jth level of a factor y, and $\lambda_{xy(ij)}$ the interaction between the ith level of a factor x and the jth level of a factor y.

For instance, to estimate the odds of the ith level of a factor x relative to the base level ($i = 1$) of the same factor with respect to interaction with the jth level of a factor y, odds multipliers are calculated using the following equation:

$$\begin{aligned}\ln\left(\frac{F_{ij}}{F_{1j}}\right) &= \ln\left(F_{ij}\right) - \ln\left(F_{1j}\right) = \left(\theta+\lambda_{x(i)}+\lambda_{y(j)}+\lambda_{xy(ij)}\right) \\ &\quad - \left(\theta + \lambda_{x(1)} + \lambda_{y(j)} + \lambda_{xy(1j)}\right) \\ \frac{F_{ij}}{F_{1j}} &= \exp\left(\lambda_{x(i)} + \lambda_{xy(ij)} - \lambda_{x(1)} - \lambda_{xy(1j)}\right) \\ &= \exp\left(\lambda_{x(i)} - \lambda_{x(1)}\right)\exp\left(\lambda_{xy(ij)} - \lambda_{xy(1j)}\right).\end{aligned} \qquad (2)$$

If only main effects are considered (i.e. a first-order log-linear model), the interaction terms no longer exist and odds multipliers are $\exp(\lambda_{x(i)} - \lambda_{x(1)})$. Tables 2 and 3 show the estimated parameters of the log-linear models for crashes at driver's fault and crashes at pedestrian's fault, respectively. Positive estimates indicate higher number of crashes relative to the base case and negative estimates indicate lower number of crashes relative to the base case. Initially a Poisson distribution of the crash frequency was assumed but did not produce a good fit indicating a possible over-dispersion.

Table 2
Estimated parameters of pedestrian crashes at driver's fault

Parameter	Estimate	S.E.
Constant	−4.3884	0.3206
Drivers' age		
Very young (15–19)	0.7284	0.2192
Young (20–24)	0.9392	0.2140
Middle 1 (25–44)	2.1799	0.1989
Middle 2 (45–64)	1.6940	0.2037
Old (65–79)	0.8974	0.2153
Very old (80∼)[a]	0	0
Drivers' sex		
Male	0.7046	0.1075
Female[a]	0	0
Vehicle type		
Passenger car	1.1981	0.1094
Van, truck, bus[a]	0	0
Traffic control		
No traffic control	−0.8357	0.2103
Traffic signal	−0.9764	0.2113
Other traffic control[a]	0	0
Location		
Urban areas	1.0062	0.1575
Rural areas[a]	0	0
Traffic control–location interaction		
No traffic control–urban areas	−0.2687	0.2648
Traffic signal–urban areas	0.7794	0.2524
Other control–urban areas	0	0
No traffic control–rural areas	0	0
Traffic signal–rural areas	0	0
Other control–rural areas	0	0
Drivers' alcohol/drug use		
No alcohol and drug	2.0834	0.2266
Alcohol and/or drug[a]	0	0
Lighting		
Daylight, dawn, dusk	−0.4151	0.3176
Dark[a]	0	0
Alcohol–lighting interaction		
No alcohol–daylight	1.8559	0.338
No alcohol–dark	0	0
Alcohol–daylight	0	0
Alcohol–dark	0	0
Pearson chi-square	486.1	
Degrees of freedom	560	
p-Value	0.989	
Number of observations	1168	

[a] Base case to calculate odds multipliers.

Therefore, the final models were calibrated using a negative binomial distribution, which showed a very good fit.

In case of crashes at driver's fault, the results showed that middle-age (25–64) and male drivers are more involved in crashes as causers than other driver groups. When only main effects are considered, it appears that crashes occur more frequently at the intersections with other traffic control (e.g. stop signs, yield signs, etc.) in urban areas when non-intoxicated drivers are driving passenger cars at night. Some results are reasonable from a practical sense as there are more middle-age drivers who drive passenger cars, there are more intersections in urban areas, and drivers tend to make more misjudgment at night due to their reduced vision. However, it should be noted that due to over-representation of 25–64-year-old drivers in total population of drivers (approximately 70% according to Highway Statistics 2003 (FHWA, 2004)), the result does not imply that middle-age drivers are the most

Table 3
Estimated parameters for pedestrian crashes at pedestrian's fault

Parameter	Estimate	Standard error
Constant	−1.8557	0.1889
Pedestrians' age		
Children (∼14)	1.6779	0.1531
Very young (15–19)	1.0867	0.1613
Young (20–24)	0.7725	0.1666
Middle 1 (25–44)	2.3792	0.1536
Middle 2 (45–64)	1.9239	0.1550
Old (65–79)	0.9925	0.1615
Very Old (80∼)[a]	0	0
Pedestrians' sex		
Male	0.6235	0.0723
Female[a]	0	0
Divide		
Divided	−0.4466	0.0753
Undivided[a]	0	0
Number of lanes		
1 lane	−4.1076	0.1804
2 lanes	−0.6803	0.0790
3 lanes and over[a]	0	0
Traffic control		
No traffic control	0.0150	0.1308
Traffic signal	−0.4030	0.1370
Other traffic control[a]	0	0
Location		
Urban areas	0.7523	0.1210
Rural areas[a]	0	0
Location–traffic control interaction		
No traffic control–urban areas	−0.2293	0.1733
Traffic signal–urban areas	0.2700	0.1765
Other control–urban areas	0	0
No Traffic control–rural areas	0	0
Traffic signal–rural areas	0	0
Other control–rural areas	0	0
Pedestrian's alcohol/drug use		
No alcohol and drug	1.0348	0.1054
Alcohol and/or drug[a]	0	0
Lighting		
Daylight, dawn, dusk	−1.1162	0.1404
Dark[a]	0	0
Alcohol–lighting interaction		
No alcohol–daylight	2.2127	0.1649
No alcohol–dark	0	0
Alcohol-daylight	0	0
Alcohol–dark	0	0
Pearson chi-square	1812.5	
Degrees of freedom	1997	
p-Value	0.999	
Number of observations	3340	

[a] Base case to calculate odds multipliers.

dangerous driver group. The result should be interpreted in a way that middle-age drivers are more involved in pedestrian crashes as causers than any other driver groups. On the other hand, given that the proportions of total licensed male drivers (50.26%) and female drivers (49.74%) in Florida are almost equal (FHWA, 2004), the result indicate that male drivers are more likely to cause pedestrian crashes than female drivers and we can speculate that male drivers may be more risk-taking than female drivers. In the case of crashes at pedestrian's fault, the crashes occur more frequently under the similar conditions to crashes at driver's fault, but also at the undivided and wide (i.e. more number of lanes) intersections. The results also seem logical since pedestrians, particularly older pedestrians, have difficulty in walking a longer crosswalk without a median and they are more exposed to approaching vehicles.

However, more investigation is needed to explain some counter-intuitive results of main effects: (1) more crashes occurred at the intersections with traffic control (other than traffic signal) than the intersections without traffic control and (2) more crashes occurred when drivers are not intoxicated than when drivers are intoxicated. Thus, the interactions of alcohol/drug use–lighting and traffic control–location were considered. To better understand the relative impact of factors on the expected number of crashes, the odds multipliers were calculated using Eq. (2) as shown in Table 4.

From the interaction of alcohol/drug use–lighting, it was observed that the odds multiplier of the expected number of crashes for drivers' alcohol/drug use was higher when drivers were intoxicated than when they were not intoxicated in dark lighting. The same trend was observed for pedestrians' alcohol/drug use. These results suggest that drivers' and pedestrians' alcohol/drug uses lead to more pedestrian crashes at night. Thus, drinking and walking at night is equally problematic as drinking and driving.

From the interaction of traffic control–location, the effects of traffic control on the expected number of pedestrian crashes were found to be different between urban and rural areas. First, for crashes at driver's fault, it was found that the odds multipliers were higher at the intersections with traf-

Table 4
Comparison of odds multipliers between two types of pedestrian crashes

Variables	Crashes at driver's fault	Crashes at pedestrian's fault
Age		
Very old (80∼)	1	1
Children (∼14)	–	5.35
Very young (15–19)	2.07	2.96
Young (20–24)	2.56	2.17
Middle 1 (25–44)	8.85	10.80
Middle 2 (45–64)	5.44	6.85
Old (65–79)	2.45	2.70
Sex		
Female	1	1
Male	2.02	1.87
Vehicle type		
Van, truck, bus	1	–
Passenger car	2.74	–
Divide		
Undivided	–	1
Divided	–	0.64
Number of lanes		
3 lanes and over	–	1
2 lanes	–	0.51
1 lane	–	0.02

	Traffic control	Location			
		Urban areas	Rural areas	Urban areas	Rural areas
Traffic control–location interaction	No traffic control	1	1	1	1
	Traffic signal	2.48	0.39	1.11	0.81
	Other traffic control	3.02	1.06	0.52	0.77

	Lighting	Alcohol use			
		No alcohol	Alcohol	No alcohol	Alcohol
Alcohol use–lighting interaction	Daylight, dawn, dusk	1	1	1	1
	Dark	0.23	1.51	0.33	3.05

fic control than the intersections without traffic control in urban areas whereas the odds multiplier was significantly lower at the intersections with traffic signals than the intersections without traffic signals in rural areas as shown in Table 4. This result suggests that drivers tend to drive more carefully when they approach traffic signals than stop or yield signs in rural areas and pedestrian crashes occur less frequently at rural signalized intersections. Second, for crashes at pedestrian's fault, it was found that the odds multiplier was higher at signalized intersections but lower at the intersections with other control in urban areas whereas the odds multipliers were relatively lower at the intersections with traffic control than the intersections without traffic control in rural areas. The low odds multipliers of both types of pedestrian crashes at signalized intersections in rural areas indicate that the installation of traffic signals in rural areas may provide significant reduction of pedestrian crashes.

The odds multipliers of variables were compared between crashes at driver's fault and crashes at pedestrian's fault to identify the difference in causal factors as shown in Table 4. Middle-age males are more involved in pedestrian crashes as both drivers and pedestrians. In particular, high odds multiplier for children (age of younger than 14) in crashes at pedestrian's fault suggests that many pedestrian crashes occurred due to children's carelessness and misjudgment.

In comparison of traffic control–location interaction, the frequencies of crashes were consistently lower at signalized intersections in rural areas for both types of crashes but the different trend was observed in urban areas. The frequency of crashes at driver's fault was higher at the intersections with traffic control than the intersections without traffic control whereas the frequency of crashes at pedestrian's fault was only higher at signalized intersection. The results reflect that pedestrian crashes occur more frequently in urban areas when drivers violate traffic signals or signs while pedestrians observe them. On the other hand, the frequency of crashes at pedestrians' fault only increases at the signalized intersections but decreases at the intersections controlled by traffic signs. This may be because pedestrians tend to be more careful at the intersections controlled by traffic signs than traffic signals.

In comparison of alcohol use–lighting interaction, the impacts of alcohol use on chances of nighttime crashes were higher for crashes at pedestrian's fault than crashes at driver's fault. This result indicates that the intoxicated pedestrians are more involved in pedestrian crashes as causers than the intoxicated drivers at night.

2.2. Injury severity analysis

The analysis of crash injury severity examines the likelihood of pedestrian injuries and fatalities when pedestrians are involved in crashes. In the crash database, the severity of pedestrians' injury is classified into one of the following five categories: (1) no injury, (2) possible injury, (3) non-incapacitating evident injury, (4) incapacitating injury, and (5) fatal injury.

This study uses an ordered probit model since the model can account for the ordinal nature of injury severity categories. The functional specification of an ordered probit model is as follows:

$$y_i^* = \beta' x_i + \varepsilon_i \tag{3}$$

where y_i^* is the predicted injury by a pedestrian i, β' a row vector of unknown parameters, x_i a vector of explanatory variables, and ε_i the random error term that follows normal distribution. The injury level is classified based on the predicted injury using the following criteria (μ_1, μ_2 and μ_3 are the thresholds estimated by the model):

$$y_i = \begin{cases} 0 & \text{if } y_i{}^* \le 0 \quad \text{(no injury)} \\ 1 & \text{if } 0 < y_i{}^* \le \mu_1 \quad \text{(possible injury)} \\ 2 & \text{if } \mu_1 < y_i{}^* \le \mu_2 \quad \text{(non-incapactating evident injury)} \\ 3 & \text{if } \mu_2 < y_i{}^* \le \mu_3 \quad \text{(incapacitating evident injury)} \\ 4 & \text{if } y_i{}^* > \mu_3 \quad \text{(fatal injury).} \end{cases}$$

Most factors used in the frequency analysis were also used as explanatory variables in this analysis. In addition to these variables, the speed of vehicles and weather at the time of crashes were included as they have close relationship with the impact of collision. Since this analysis focuses on the severity of pedestrians' injury after the crash occurrence, all pedestrian crashes were analyzed regardless of causes (driver's fault or pedestrian's fault). The ordered probit models were estimated using the LIMDEP software (Greene, 1998). The results of the models show that older pedestrians are more likely to sustain higher injury than younger pedestrians as indicated by generally increasing parameter values as pedestrians are older as shown in Table 5. In particular, the likelihood of injury severity was significantly higher for the old and very old pedestrians (age 65 and over) whereas the likelihood of injury severity was lower for the young and very young pedestrians (age 15–24) who are most physically healthy. This result reflects that as people age, their physical strength is weakened and the impact of crashes on their bodies is likely to be more severe. The result also indicates that each pedestrian age group tends to cross intersections at different speeds and consequently the impact of crashes is different. It was also found that female pedestrians had higher injury severity than male pedestrians as indicated by higher parameter value that is marginally significant.

Table 5
Estimated parameters of pedestrian injury severity

Variables	Parameter	t-statistics
Constant	−0.423	−1.324
Dummies for pedestrians' age		
1 = very young (15–19), 0 = otherwise	−0.047	−0.703
1 = young (20–24), 0 = otherwise	−0.050	−0.666
1 = middle 1 (25–44), 0 = otherwise	−0.032	−0.627
1 = middle 2 (45–64), 0 = otherwise	0.172	3.293
1 = old (65–79), 0 = otherwise	0.337	5.356
1 = very old (80 and over), 0 = otherwise	0.488	5.949
Pedestrians' sex (1 = female, 0 = male)	0.064	1.885
Pedestrians' alcohol/drug use (1 = intoxicated pedestrians, 0 = non-intoxicated drivers)	0.217	4.106
Vehicle speed	0.474	19.738
Vehicle type (1 = van, truck, bus, 0 = passenger cars)	0.096	2.648
Weather (1 = adverse conditions, 0 = clear)	0.106	2.639
Lighting (1 = dark, 0 = daylight, dawn, dusk)	0.219	5.778
Traffic control (1 = presence of traffic control, 0 = no traffic control)	−0.113	−2.978
Location (1 = rural areas, 0 = urban areas)	0.122	3.357
Thresholds		
α_1	1.421	36.095
α_2	2.562	60.523
α_3	3.909	69.925
Log likelihood at convergence[a]	−5367.3	
Number of observations	4351	

[a] Maximized value of the log-likelihood function.

Alcohol/drug use by pedestrians also increased the severity of pedestrians' injury since alcohol and drug impaired pedestrians' perception and made high impact with vehicles inevitable.

The results also showed that the higher speed of vehicles that collided with pedestrians increased the severity of pedestrians' injury due to higher impact of crashes. High likelihood of injury of pedestrians struck by high-speed vehicles was also found in the past studies (Anderson et al., 1997; Gårder, 2004). Environmental conditions such as adverse weather and dark lighting were also found to contribute to higher pedestrian injury severity. This may be because adverse weather (in particular, heavy rain in Florida) and dark lighting severely reduce both drivers' and pedestrians' sight and in turn their reaction times to avoid crashes increase. Consequently, these conditions increase braking distance of vehicles and lead to higher impact at the time of crashes. Also, vans, buses, and trucks tended to cause higher injury severity than passenger cars due to larger area of impacts on pedestrians as consistent with the findings in the past studies (Al-Ghamdi, 2002; Lefler and Gabler, 2004).

In comparing crashes in different locations, the severity of pedestrian' injury was higher in rural areas than urban areas although the frequency of crashes was lower in rural areas as shown in the previous section. This may be because (1) there are relatively fewer medical facilities in rural areas and pedestrian victims are less likely to receive timely treatment leading to higher fatality rate; and/or (2) average speed is generally higher in rural areas (average posted speed limits were higher in rural areas than urban areas) and consequently the impact of collision increases. On the other hand, compact building layout in urban areas increases a driver's awareness of pedestrian activity (Zajac and Ivan, 2003) and reduces vehicle speeds resulting in lower impact of collision. For a similar reason, the severity of pedestrians' injury was higher at the intersections without traffic control. In the absence of traffic control, drivers tend to drive faster and increase the impact of crashes when they collide with pedestrians.

In summary, the results of the ordered probit model suggest that pedestrian injury severity caused by crashes is closely related to the following factors (the associated variables in parentheses): (1) pedestrians' physical condition (age and alcohol/drug use), (2) the speed of vehicles (speed at the time of crashes, location of crashes, and the presence of traffic control), (3) drivers' and pedestrians' perception and reaction (weather, lighting), and (4) the area of impacts (vehicle type).

3. Exposure of pedestrian crashes

Despite statistically significant results in the previous sections, it is still uncertain whether the model estimates properly reflect the risk of pedestrian crashes in the absence of exposure measures. In fact, crash risk from a pedestrian's perspective is more influenced by pedestrian volume than vehicle volume (Gårder, 2004). In this regard, population has been often used as exposure to calculate pedestrian crash rate in the form of the number of crashes per capita. Using the classification of ages in Florida in Census 2000 (U.S. Census Bureau, 2004), the number of pedestrian crashes per capita in Florida by age is shown in Fig. 1. The figure shows that in spite of high frequency of pedestrian crashes for middle-age people (age 35–44) (Fig. 1a), the number of crashes per capita is higher for younger people (age 10–19) (Fig. 1c).

However, the number of crashes per capita only shows what types of people have crashes, but do not show the relationship between crashes and the amount of trips these people make (Ampt, 1995). In fact, we do not know how many pedestrians in the total population of each age group crossed intersections (exposure of risk) and what proportion of the pedestrians was actually involved in crashes. More specifically, the population of age groups does not reflect different walking travel patterns by different age groups. For instance, since older people spend more time on walking and make more frequent walking trips during weekdays than middle-age people, it is expected that their exposure to pedestrian crashes is higher although their population is lower (Fig. 1b). Thus, similar to vehicle-kilometers of travel that are frequently used as exposure to vehicle–vehicle crashes, the frequency and length of walking trips by pedestrians are important in the determination of exposure to vehicle–pedestrian crashes. Clearly, we

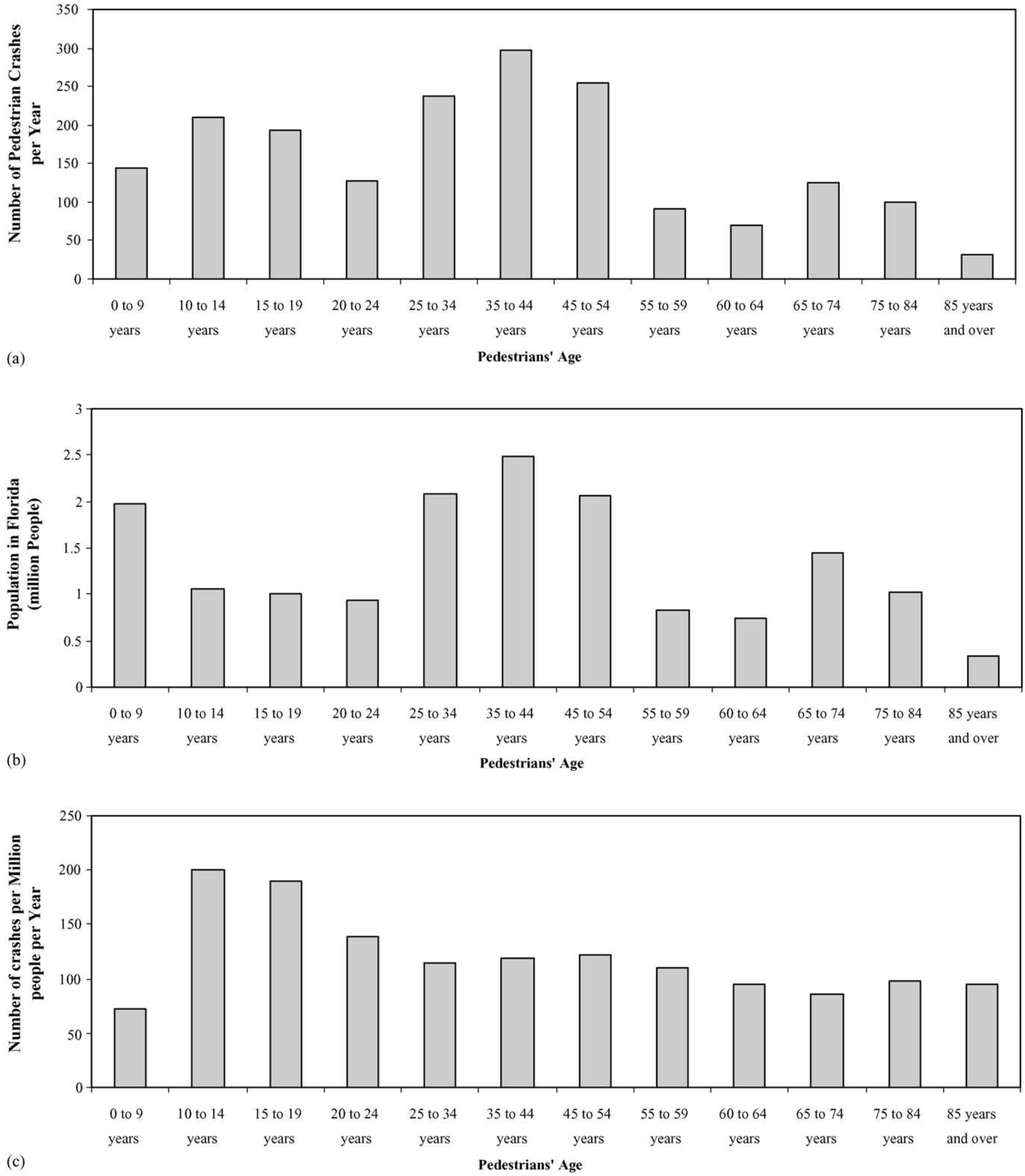


Fig. 1. Number of crashes, population and number of crashes per capita by age. (a) Number of pedestrian crashes by age. (b) Population in Florida by age. (c) Number of pedestrian crashes per capita by age.

need to estimate more accurate pedestrian exposure to calculate pedestrian crash rates.

In this regard, Keall's pioneering work (1995) developed better measures of pedestrian exposure to risk of crashes using the New Zealand travel survey data. He used the number of walking trips, the time spent walking on streets, and number of roads crossed by each pedestrian age group as exposure measures. Similarly, Baltes (1998) estimated exposure to pedestrian risk by age in terms of total distance of walk in kilometers using the Nationwide Personal Transportation Survey. However, if exposure by age is estimated, total distance may not reflect actual "duration" of walking trips due to different walk speed by different age groups. For example, the duration of older pedestrians' walking trips is generally longer than that of younger pedestrians' walking trips even for the same trip distance. However, if exposure by gender or by some other traffic and environmental factors is considered, there may be no difference in walking speed among different groups and travel distance can represent exposure.

Similar to the previous works, this study used the travel survey data for U.S. households (U.S. Department of Transportation, 2004) to estimate pedestrian exposure. Since this study analyzes pedestrian crashes in Florida, only responses from the residents in Florida were extracted from the National Household Travel Survey (NHTS) database. The NHTS database contains the total number of daily walking trips, duration (travel time), distance, and purpose of each walking trip by each household member during a 13-month period (April 2001–April 2002). Although trip distance is included in the survey, the study did not use trip distance as an exposure measure because of the difference in walk speed by age group as explained earlier. Also from the authors' point of view, it appears that the distance included in the survey is relatively less accurate than travel time as people tend to remember travel time better than distance in their daily lives.

In this study, pedestrian exposure is defined as the sum of the durations of individual walking trips as follows:

$$\mathrm{EXP}_j = \sum_i \sum_j D_{ij} \qquad (4)$$

where EXP_j is the exposure of pedestrian j to crash risk and D_{ij} the duration of walking trip i by pedestrian j. Since the travel survey does not show the details of pedestrian movements (e.g. crossing intersections, walking along the intersections, etc.), it is uncertain whether all walking trips occur on the road. However, given that walk is often considered as an alternative mode to automobiles for short-distance work and shopping trips, it is expected that most walking trips do occur on the road. Thus, it is reasonable to assume that the proposed exposure measures represent the frequency of the events that pedestrians are exposed to crash risk on the road.

Since the travel survey was conducted for only sample of households, the number of sample walking trips needed to be expanded to estimate representative walking patterns of whole population in Florida. For this purpose, specific weights were applied to account for non-response and under-representative person groups in the survey (U.S. Department of Transportation, 2004). The weights were determined based on the national-level distribution of personal characteristics such as age, gender, education, income, etc.

Fig. 2 shows the distributions of the frequency and total duration of walking trips by different pedestrian age groups and pedestrian crash rate defined as the number of crashes divided by total duration of walking trips in hour. It was found that the frequency of walking trips was highest for young pedestrians (age 25–34) (Fig. 2a) whereas the total duration of walking trips was highest for old pedestrians (age 65–74) (Fig. 2b) as shown in solid lines. This clearly reflects that young people are physically more active than old people and they are willing to walk more frequently. However, since old pedestrians walk slower, their duration of walking trip is longer than young pedestrians.

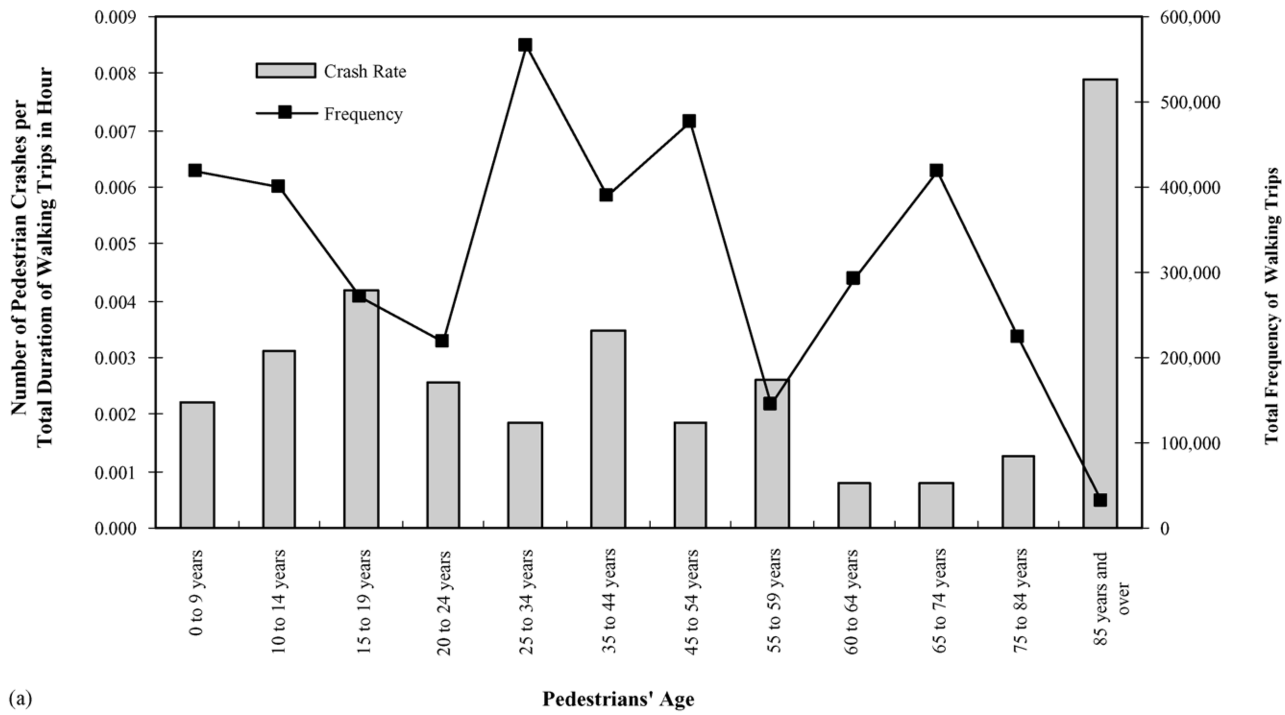
It was also observed that the distribution of the proposed pedestrian crash rate by age was different from the distribution of the number of crashes per capita by age (Fig. 1c). It can be seen that the crash rate was highest for very old pedestrians (age 85 and over) unlike the number of crash per capita that is highest for very young pedestrians (age 10–14). This implies that the number of crashes per capita underestimates high crash risk by very old pedestrians. There were also large differences across crash rates for middle-age pedestrians (age 25–59) whereas the number of crashes per capita was almost the same for the same age group. This suggests that certain middle-age group walks in different patterns and their crash risk is relatively higher.

Although only pedestrians' age was considered in this analysis, the suggested exposure can also be classified by many other factors such as pedestrians' gender, time of walking trips (daytime/nighttime), purpose of walking trips, etc. The findings of this analysis suggest the need of more detailed information on pedestrian travel behavior and understanding its impact on pedestrian exposure to crash risk.

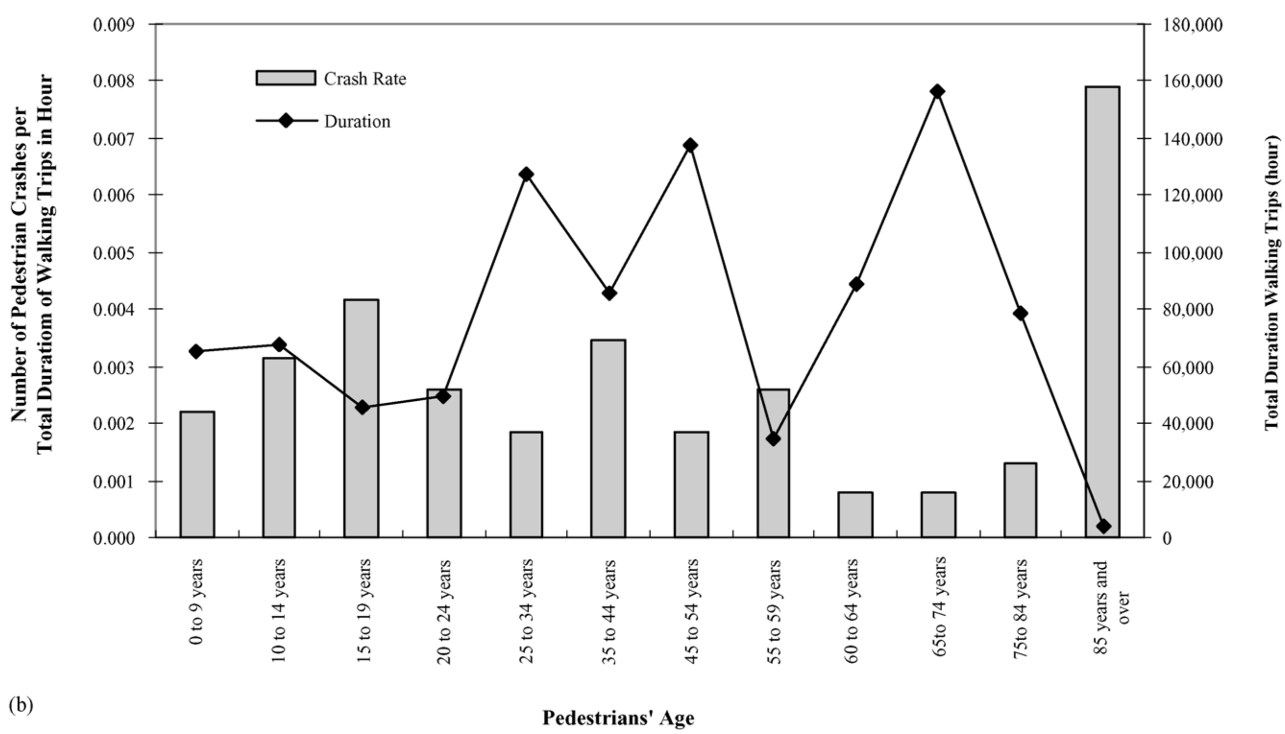
4. Effects of average traffic volume at intersections

It should be noted that all the possible factors affecting pedestrian crashes were not considered in this study, since the factors were limited to only the information included in the crash database. In other words, there may exist more important factors affecting crashes but they could not be captured in the earlier analysis due to lack of data. Thus, this study obtains average traffic volume at intersections that is not typically available in crash reports and investigates its effect on pedestrian crashes. Traffic volume normally reflects the typical traffic condition at each intersection. Traffic volume was measured in the form of average annual daily traffic (AADT) on major roads of the intersections.

In this study, the number of pedestrian crashes and traffic volume at 1563 signalized intersections were ob-



(a)



(b)

Fig. 2. Pedestrian crash rates by age. (a) Comparison between pedestrian crash rates and frequency of walking trips. (b) Comparison between pedestrian crash rates and duration of walking trips.

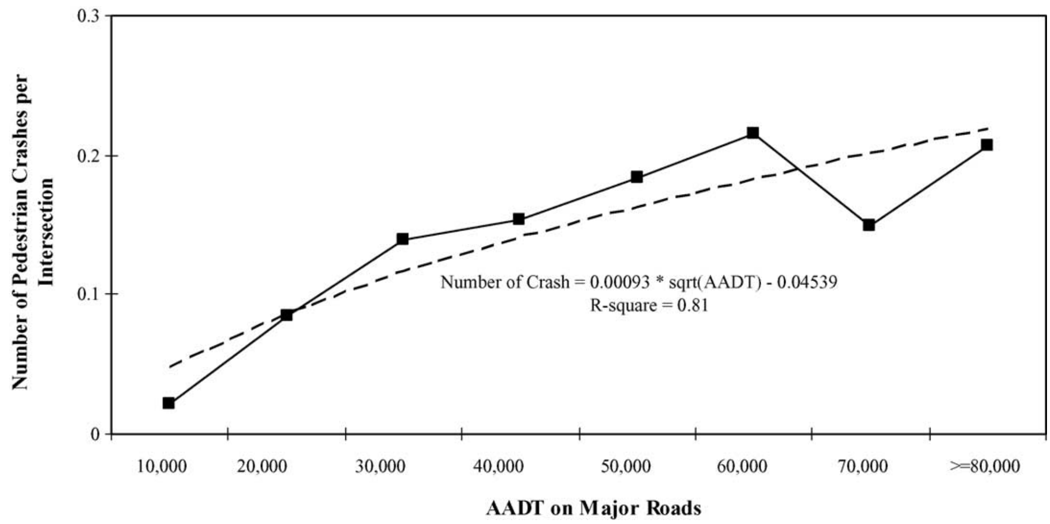


Fig. 3. Relationship between pedestrian crashes and AADT on major roads.

tained from the following six counties in Florida: Brevard, City of Orlando, Dade, Hillsborough, Orange, and Seminole. Among a total of 40,870 crashes in 3 years (1999–2001) that have occurred at these intersections, 219 crashes were pedestrian crashes. The average number of pedestrian crashes per intersection (defined as frequency) was calculated and compared to AADT on major roads.

Fig. 3 shows that the frequency of pedestrian crashes generally increases with AADT. This indicates that pedestrian crashes are more likely to occur at intersections with higher traffic volume that increases the potential conflicts between pedestrians and vehicles. However, it appears that the rate of increase gradually decreases as AADT increases. The figure illustrates that the rate of increase in the average number of pedestrian crashes per intersection increases rapidly up till an AADT value of around 30,000, then the rate of increase is milder for AADT values between 30,000 and 60,000. Above 60,000 there seems to be no apparent trend, suggesting that the rate is almost uniform. This implies that when traffic volume is very high, the traffic condition is likely to be congested (i.e. vehicles are moving slowly) and the likelihood of conflicts with pedestrians will not proportionally increase as in low-volume conditions. The relationship in Fig. 3 can be fit to the following non-linear regression model:

$$\text{number of pedestrian crashes} = 0.00093 \times (\text{AADT})^{0.5} - 0.04539 \quad (R^2 = 0.81). \quad (5)$$

This trend is consistent with the previous British and European models showing a relationship that the number of pedestrian crashes are approximately proportional to the square root of vehicle volume.

5. Conclusions and recommendations

This study analyzed vehicle-pedestrian crashes in Florida from different perspectives. First, the study identified the groups of drivers and pedestrians, and traffic and environmental characteristics that are correlated to pedestrian crashes using a log-linear models. It was found that middle-age male drivers and pedestrians were correlated to more pedestrian crashes than the other age and gender groups, the passenger cars were correlated to more crashes than trucks, vans and buses, and more crashes occurred on undivided roads with more number of lanes than divided roads with less number of lanes. It was also found that intoxicated drivers and pedestrians were correlated to more crashes at nighttime than daytime and the absence of traffic signals were correlated to more crashes than the presence of traffic signals in rural areas. Some differences were observed between crashes at driver's fault and crashes at pedestrian's fault—for example, intoxicated pedestrians were correlated to more crashes than intoxicated drivers at night and drivers were correlated to more crashes than pedestrians at the intersections with traffic control in urban areas.

Second, the study also identified factors affecting injuries and fatalities of pedestrians who are involved in crashes using an ordered probit model. It was found that when pedestrians involved in crashes are old or intoxicated, vehicles collide with pedestrians at high speed, drivers and pedestrians have reduced vision and reaction due to adverse weather and dark lighting, and vehicles involved in crashes are larger than passenger cars in size, injury severity of pedestrians is likely to be higher.

Third, the study developed a logical expression of pedestrian exposure to crash risk using the individual walking trip data collected from the household travel survey.

The proposed exposure (total duration of walking trips) reflects different walking patterns by different age groups of pedestrians. The results of the analysis suggest that the number of pedestrian crashes per total duration of walking trips (in hours) by age captures the high crash risk of very old pedestrians that was underestimated in the number of pedestrian crashes per capita.

Finally, the study investigated the effects of average traffic volume at intersections (that is not readily available in crash reports) on pedestrian crashes. It appears that higher average traffic volume at intersections increases the number of pedestrian crashes per intersection due to increased chances of conflicts between pedestrians and vehicles; however, the rate of increase is steeper at lower AADT values.

Based on these findings, several countermeasures of pedestrian crashes are recommended. For example, more intensive driver education and restrictive traffic regulation (e.g. higher penalty on speed limit violation, drinking and driving, etc.) should be targeted for middle-age male drivers. As the analysis suggested, intoxicated pedestrians were also involved in many nighttime crashes and thus the public should be more aware of the problems with drinking and walking at night. In terms of traffic facilities, more traffic signals should be installed in particularly rural areas to reduce pedestrian crashes. Street lighting also needs to be improved to aid drivers' and pedestrians' reduced vision in adverse weather and dark lighting.

In future work, to investigate the effectiveness of these countermeasures in reducing pedestrian crashes, more refined measures of pedestrian crash risk considering exposure of pedestrian walking should be developed. To accurately estimate exposure with the limited samples of personal trip data, the data should be collected from a number of representative groups of pedestrians based on proportions of age, gender, race, education, etc. in the total population. Also, it is recommended that additional factors such as intersection characteristics be considered to examine their potential effect on pedestrian crashes at intersections.

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