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Pedestrian Safety Prediction Methodology

**Douglas W. Harwood
Darren J. Torbic
David K. Gilmore
Courtney D. Bokenkroger
Joanna M. Dunn
Midwest Research Institute
Kansas City, MO**

**Charles V. Zegeer
Raghavan Srinivasan
Daniel Carter
Craig Raborn
University of North Carolina, Highway Safety Research Center
Chapel Hill, NC**

**Craig Lyon
Bhagwant Persaud
Persaud and Lyon, Inc.
Etobicoke, ON, Canada**

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CHAPTER 1.

INTRODUCTION

BACKGROUND

Based on limited available research, there is believed to be a strong, but unquantified, relationship between pedestrian/motor vehicle crashes and site specific characteristics. Models are currently not available that can help predict pedestrian crashes based on site-specific conditions and operational characteristics of a roadway.

A coordinated effort is underway to develop a *Highway Safety Manual* (HSM) for use in making quantitative estimates of the safety performance of specific highway types and quantitative estimates of proposed improvements to specific highway types. The highway types being addressed in the first edition of the HSM are rural two-lane highways, rural multilane highways, and urban and suburban arterials. Explicit consideration of pedestrian safety on urban and suburban arterials is considered critical to implementation of the first edition of the HSM.

An HSM methodology to make safety predictions for urban and suburban arterials was developed in Phases I and II of NCHRP Project 17-26 for potential publication as HSM Chapter 10. The Project 17-26 database is most suited for modeling motor vehicle crashes on roadway segments and at intersections. Models were also developed in Phases I and II of Project 17-26 that estimate pedestrian safety based on average pedestrian crash frequency for roadway segments and intersections. However, these models are not sensitive to site-specific conditions that influence pedestrian crashes. Thus, the models in the current draft of HSM Chapter 10 will *not* address the needs for determining site-specific pedestrian safety effects or for evaluating the site-specific effects of proposed projects intended to improve pedestrian safety.

There is a need to include more comprehensive pedestrian safety prediction models for urban and suburban arterials in the first edition of the HSM. The research presented in this report has been conducted to develop improved pedestrian safety prediction models for use in the HSM.

RESEARCH OBJECTIVES AND SCOPE

The objective of the work under Phase III of the contract for Project 17-26, as presented in this report, is to develop a methodology for quantifying the pedestrian safety effects related to existing site characteristics and/or proposed improvements on urban and suburban arterials.

The scope of this new work is similar to the scope of the work in Phases I and II of Project 17-26, except that the new work specifically addresses pedestrian safety. The pedestrian safety prediction methodology has been developed to function as part of the overall safety prediction methodology for urban and suburban arterials being developed in Project 17-26. Thus, the comprehensive methodology will combine predicted values for nonpedestrian crashes based

on the methodology developed in Phases I and II of Project 17-26 and predicted values for pedestrian crashes based on the methodology presented in this report.

The scope of the Phase III pedestrian safety methodology includes signalized intersections and roadway segments between intersections, but does not include unsignalized intersections. Pedestrian safety at unsignalized intersections will be addressed with the methodology developed in Phases I and II.

The end product of the Phase III work will be prepared in a form compatible with the urban and suburban arterial safety prediction methodology and appropriate for incorporation in the *Highway Safety Manual*.

ORGANIZATION OF THIS REPORT

This report presents an overview of the work conducted in Phase III of this research. The remainder of this report is organized as follows. Chapter 2 summarizes results of completed and ongoing research in pedestrian safety. Chapter 3 describes the pedestrian safety databases assembled for use in the research. Chapter 4 presents results of pedestrian safety modeling. Chapter 5 summarizes the recommended pedestrian safety prediction methodology for application in HSM Chapter 12. Chapter 6 presents the conclusions and recommendations of this research. Chapter 7 presents a list of references cited in this report. Appendix A presents a fourth draft of HSM Chapter 12 incorporating the pedestrian safety prediction methodology (formerly designed as HSM Chapter 10).

CHAPTER 2.

LITERATURE REVIEW

A review of completed and ongoing research has been conducted to identify current knowledge or methodologies that may be appropriate for predicting pedestrian safety effects related to roadway geometrics and other factors. The review of literature and research in progress addressed the following issues:

- Current knowledge based on completed research concerning pedestrian safety and its relationship to pedestrian exposure and to geometric design, traffic control, and other features that can be modified by highway agencies
- Ongoing research on pedestrian safety relationships
- Safety modeling approaches that have been applied to pedestrian safety in completed or ongoing work
- Other safety modeling approaches, including approaches that are being used in the development of other portions of the HSM, whether or not those modeling approaches have been applied to pedestrian safety

Key sources that have been consulted in the literature review include:

- The AASHTO *Guide for Planning, Design, and Operation of Pedestrian Facilities (1)*, which was written, in part, by the University of North Carolina (UNC) Highway Safety Research Center (HSRC) in NCHRP Project 15-20, and was revised and edited by Midwest Research Institute (MRI) in NCHRP Project 20-7(161)
- The *Guide for Reducing Collisions Involving Pedestrians (2)* written by HSRC in NCHRP Report 500, Volume 10
- The evaluation of safety differences between marked and unmarked crosswalks at intersections performed by HSRC for FHWA (3)
- The evaluation of the safety differences between roadways with and without sidewalks performed by HSRC (4)
- The synthesis on pedestrian safety at channelized right turns (5) prepared by MRI in NCHRP Project 3-72
- The draft material on pedestrian safety prepared by iTRANS Consulting, Inc., for the interim report of NCHRP Project 17-27 (6) and for eventual use in Parts A and D of the HSM

FHWA's *Pedestrian and Bicycle Crash Analysis Tools (7)* (PBCAT) has been used as a source of ideas for the HSM methodology, as has a recent paper by Lyon and Persaud (8) entitled

Pedestrian Collision Models for Urban Intersections. Another recent paper by Lyon et al. (9) has proposed an “index of pedestrian activity” for use in safety modeling.

The results of the literature review are presented below in sections that address the effect of intersection characteristics on pedestrian safety, the effect of roadway segment characteristics on pedestrian safety, predictive models for pedestrian crashes, estimating pedestrian exposure data from count periods less than 24 hours, and estimating pedestrian volumes from land use characteristics.

EFFECT OF INTERSECTION CHARACTERISTICS ON PEDESTRIAN SAFETY

Research included in this section of the literature review is focused on the pedestrian safety effect of various intersection characteristics. Many pedestrian safety studies use non-crash-based measures of effectiveness, such as:

- Changes in pedestrian behavior (e.g., increased use of pedestrian pushbuttons, increased use of crosswalks, decreased crossings on red signal, etc.)
- Changes in motorist behavior (e.g., increased number of yields, reduction in speed, etc.)
- Other surrogate safety measures (e.g., conflicts, avoidance maneuvers, etc.)

In contrast to these measures of safety, this literature review is limited to those studies that focused on pedestrian crashes as the unit of analysis. The following discussion combines literature reviewed in this research and literature reviewed for the Project 17-27 interim report (6). The effects of the following intersection characteristics on pedestrian safety are addressed:

- Pedestrian volume
- Traffic volume
- Crossing width
- Raised pedestrian crosswalks
- Crosswalk marking
- Crosswalk illumination
- Median refuge islands
- Raised intersections
- Bus stop location
- Pedestrian-related signing
- Pedestrian signal type
- Pedestrian signal timing
- Right-turn-on-red
- One-way streets

Pedestrian Volume

Pedestrian volume, also called pedestrian exposure, has been found by several studies to be one of the most influential factors in predicting pedestrian crashes. Zegeer et al. (10) studied pedestrian crashes at 1,297 signalized intersections in 15 cities. They collected data on 2,081 crashes over a three to six year period. The analysis found that the volume of pedestrians crossing at an intersection was the most influential variable in explaining the variation in pedestrian crashes. The frequency of pedestrian crashes generally increased with increasing pedestrian volume. Intersections with less than 1,200 pedestrians per day experienced an average of 0.178 pedestrian accidents per intersection per year, while intersections with 1,200 pedestrians per day or more experienced an average of 0.553 pedestrian accidents per intersection per year, and intersections 3,500 pedestrians per day or more experienced 1.002 pedestrian accidents per intersection per year.

Brude and Larsson (11) studied the effect of pedestrian and traffic volumes on pedestrian crashes at intersections in Swedish municipalities. The analysis included crash data from 285 intersections (121 signalized, 155 unsignalized, and 9 roundabouts). Each site had 100 or more pedestrian crossings per day. They found pedestrian volume to have a significant and positive relationship to pedestrian crashes in a single predictive model that covered all intersection types.

Lyon and Persaud (8) developed pedestrian crash prediction models for urban 3-leg and 4-leg signalized and unsignalized intersections in Toronto. They included 684 4-legged signalized intersections averaging 7.72 pedestrian crashes over 11 years, 263 3-legged signalized intersections averaging 4.05 pedestrian crashes over 11 years, and 122 3-legged stop controlled intersections averaging 1.3 crashes over 11 years. Pedestrian volume was found to have a significant and positive relationship to pedestrian crashes for all intersection types. Additionally, models that included pedestrian volumes had a better fit than those without pedestrian volumes.

Zegeer et al. (3) compared the safety aspects of marked and unmarked crosswalks at uncontrolled locations under various traffic and roadway conditions. They studied 1000 marked crosswalks and 1000 matched (comparison) unmarked crosswalks (about 80 percent of these sites were at intersections). They analyzed 229 pedestrian crashes that occurred over an average of five years. Pedestrian volume was found to have a significant and positive relationship to pedestrian crashes in predictive models developed for both marked and unmarked crosswalks.

Traffic Volume

Traffic volume has also been found to be a major contributing factor to pedestrian crashes. Zegeer et al. (10) found that traffic volume was the second most important factor in explaining pedestrian crashes. The analysis showed that, for a specific pedestrian volume level, the frequency of pedestrian accidents per intersection per year generally increased as the motor vehicle traffic volume increased. Studies by Brude and Larsson (11) and Zegeer et al. (3) also found that the number of incoming vehicles per day at intersections was a significant and positive variable in predicting pedestrian crashes.

The above studies used data on average daily traffic (ADT), which is generally collected on a regular basis for most major roads in developed areas. Some studies also included turning vehicle movements. Leden (12) compared pedestrian crashes with left-turning traffic at semi-protected left-turn schemes with pedestrian crashes with right-turning vehicles. He found that an increase in left-turn volume was associated with a larger increase in pedestrian crashes compared to a similar increase in right-turn volumes. Lyon and Persaud (8) include left-turning traffic volume in predictive models for pedestrian crashes. They found that the proportion of left-turning traffic to total traffic had a significant and positive relationship to pedestrian crashes for signalized intersections. For stop-controlled intersections, left-turning traffic volume was found to be more important than total entering volume and was included as a solitary factor (not as a proportion).

Crossing Width

The recent report for NCHRP Project 17-27 (6) found only a few studies that used crash data to analyze the effect of narrowing the crossing width by curb extensions or other means; many other studies have used other measures such as vehicle speeds and pedestrian/vehicle interactions to evaluate the effect of crossing width on pedestrian safety. Project 17-27 found two studies that used crashes in their evaluation of road narrowing.

The first study that addressed the effect of crossing width was a summary of pedestrian research in the United Kingdom. Davies (13) reported results from Nottingham (by Thompson and Heyden, 1991) where curb extensions were extended 8.2 ft [2.5 m] into the street and included “substantial lengths of guardrail,” (assumed to be protective railing for pedestrians). The authors reported a reduction in average pedestrian crashes from 4.7 to 1 per year after the treatment. Insufficient information was available to determine an AMF from this study.

The second study that addressed the relationship between crossing width and pedestrian safety was a 2004 review that examined two studies from Denmark and Norway (14). The studies do not state if the intersections studied had 3- or 4-legs. Both were simple before-after studies not controlling for any confounding factors and therefore both of these studies have been rated as low quality. Accordingly, the standard error has been adjusted by a factor of 3. The result of a meta-analysis of these two studies is provided in Table 1, and is highly uncertain. As a general note related to NCHRP Project 17-27 (6), standard errors of the results were adjusted depending on the quality of the study. For studies considered high quality, the adjustment factor was close to 1.0. For studies rated as low quality, the adjustment factor was 2 or higher.

A 2004 synthesis of pedestrian safety research examined other studies on reducing crossing speed (15). However, the studies cited in that synthesis used vehicle speeds and pedestrian/vehicle conflicts as measures of effectiveness instead of crashes.

TABLE 1. Effects on Crashes of Road Narrowing and Curb Extensions at Intersections (6, 14).

Treatment/element	Setting	Intersection type and volume	Crash type and severity	Index of effectiveness ($t_{adjusted}$)	Estimate of Std. Error (s)
Widen sidewalks at intersections	Not reported	Not reported	All types, injury	1.116	1.260

Due to the design of the crash-based studies that have been reviewed, it is uncertain whether crossing width has a significant impact on pedestrian safety.

Raised Pedestrian Crosswalks

Elvik and Vaa (14) recently performed a meta-analysis of four international studies that evaluated raised pedestrian crosswalks. Three of these studies have been rated as low quality, and one study (15) was rated as medium-low quality. Standard errors have been adjusted by a factor of 3 in the three low quality studies and by a factor of 2.2 in the medium-low quality study. Intersection types and volumes were not reported by Elvik and Vaa. The resulting indices of effectiveness are presented in Table 2. Based on these values, raised pedestrian crosswalks appear to reduce accidents. The effects may be overstated, as none of the studies have controlled for regression-to-the-mean or long-term trends in accident frequency. Standard errors are very large.

TABLE 2. Effects on Crashes of Raised Pedestrian Crossings at Intersections (6, 14).

Treatment/element	Setting	Intersection type and volume	Crash type and severity	Index of effectiveness ($t_{adjusted}$)	Estimate of Std. Error (s)
Raised pedestrian crosswalks	Not reported	Not reported	All types, injury	0.642	0.543
Raised pedestrian crosswalks	Not reported	Not reported	Pedestrian, injury	0.545	0.937
Raised pedestrian crosswalks	Not reported	Not reported	Vehicle, all severities	0.697	0.667

Based on these studies, raised crosswalks appear to reduce pedestrian crashes.

Crosswalk Marking

A 2004 review of pedestrian safety research by Campbell et. Al. (15) reviewed 13 crash-based studies on crosswalk markings, including the study by Zegeer et al. for FHWA (3) that is considered the most comprehensive crash-based study on this topic. The 13 studies had conflicting findings, partly because of the different methodologies and data limitations which existed in some of the studies. The Zegeer et al. study (3) found that: "...on two-lane roads, the presence of a marked crosswalk alone at an uncontrolled location was association with no

difference in pedestrian crash rate, compared to an unmarked crosswalk. Further, on multilane roads with traffic volumes above 12,000 vehicles per day, having a marked crosswalk alone (without other substantial improvements) was associated with a higher pedestrian crash rate (after controlling for other site factors) compared to an unmarked crosswalk.”

Crosswalk Illumination

The 2004 review (15) covered two crash-based studies on crosswalk illumination. The first study was conducted in two parts—a pilot test and a follow-on test (16). In both stages, crashes were counted before and after the installation of sodium floodlights at the pedestrian crossing. The results of their tests, showing a significant decrease in nighttime pedestrian crashes, are shown in Table 3.

TABLE 3. Crash Effects of Providing Sodium Floodlights at Pedestrian Crossings (Perth, Australia) (16).

	Pedestrian crashes			Crashes involving vehicles alone		
	Day	Night	Total	Day	Night	Total
Pilot Test (6 crossings)						
5 years before	19 (1)	7 (1)	26 (2)	5	1	6
5 years after	21 (1)	2	23 (1)	9	0	9
Follow-on Test (57 additional crossings)						
2 years before	57 (2)	32 (1)	89 (3)	19	2	21
2 years after	58 (2)	13 (1)	71 (3)	18 (1)	1	19 (1)

Fatalities are shown in parentheses.

The second study by Polus and Katz (17) conducted a crash analysis on sites before and after a combination of illumination and signing was installed at 99 test sites. Thirty-nine unilluminated control sites were also used. The results of the study, showing a decrease in crashes after illumination, are shown in Table 4.

TABLE 4. Effects of Crosswalk Illumination on Pedestrian Crashes (Israel) (17).

	Number of night crashes	
	Before	After
Illuminated sites	28	16
Unilluminated sites	10	16

Since daylight crashes remained relatively unchanged, and factors such as pedestrian and vehicle volume and weather remained unchanged, the decrease in nighttime crashes was attributed to the illumination effect.

The consensus from these two studies indicates that crosswalk lighting serves to decrease pedestrian crashes.

Median Refuge Islands

The Project 17-27 interim report (6) reviewed two crash-based studies that examined the effect of median refuge islands on pedestrian safety. Zegeer et al. (3) studied 2,000 crossing sites in 30 cities; all sites were in urban or suburban areas and included primarily arterial and collector streets. Streets covered a range of speed limits, typically 25 to 40 mph [40 to 64 km/h]. Sites were selected within a variety of area types (i.e., residential, downtown, commercial, urban fringe, etc.). Zegeer et al. found that the presence of a raised median or refuge island was associated with a significantly lower rate of pedestrian crashes on multi-lane roads (compared to no median or refuge island). This was true at marked as well as unmarked crosswalks. All sample sites used in the study were uncontrolled crossings at intersection (i.e., no traffic signals or STOP-control on intersection approach of interest) or mid-block locations. The presence of painted (not raised) medians or islands and two-way-left-turn lanes provided no significant reduction in pedestrian crash rate on multi-lane roads. The study collected and controlled for pedestrian and vehicle exposure, along with other site variables in the analysis.

The purpose of a study by Lalani (18) was to compare personal injury crashes before and after installation of “Double-D” shaped refuge islands at 120 sites, including intersection and mid-block, marked, and unmarked locations in London, England. These islands were installed in conjunction with other roadway improvements, such as anti-skid surfacing, illuminated bollards, bus lanes, and crosshatch markings. This study found that refuges reduced vehicle crash frequency but increased pedestrian accident frequency at intersections. Lalani also determined that:

- At intersections, vehicular accident frequency was significantly reduced only when the refuge islands were reinforced with hatch markings to channelize motor traffic;
- At midblock locations, vehicular accidents were only reduced where the islands had internally illuminated bollards; and
- Pedestrian accidents were only reduced at sites where the refuge islands were constructed on roads next to high pedestrian generators. (It is unclear if Lalani is referring to intersection or midblock or both.)

It is possible that the results of the Lalani study (i.e., the increase in pedestrian crashes after installation of refuge islands) may be a manifestation of the fact that more pedestrians are drawn to use the crossing after a refuge island is installed. A study of all of the pedestrian crashes along a road section (with corresponding pedestrian exposure) and controlling for pedestrian exposure at the crossings would allow for quantifying this effect.

Based on these two crash-based studies, it is uncertain whether a median refuge island significantly impacts pedestrian safety.

Raised Intersections

The Project 17-27 interim report (6) mentioned only one study that examined the effect of raised intersections on pedestrian crashes. This study by Schull et al. used a simple before-after design and did not control for the potential effects of confounding factors. Details on traffic control at the intersections were not provided. The study was rated as low quality, and the results were inconclusive concerning the safety effectiveness of raised intersections.

Bus Stop Location

In their predictive crash model, Zegeer et al. (10) found that sites nearer to bus routes had more crashes and that the difference was small but significant. Neither the 2004 review (15) nor the Project 17-27 interim report (6) included any crash-based studies concerning the effect of bus stop location on pedestrian safety.

Pedestrian-Related Signing

Neither the 2004 review (15) nor the Project 17-27 interim report (6) included any crash-based studies concerning the effect of pedestrian-related signs on pedestrian safety.

Pedestrian Signal Type

Pedestrian signal indications can be configured in several ways. The walk indications may be solid or flashing. There may also be a countdown displayed with the signal. The Project 17-27 interim report (6) did not find any studies that related the type of pedestrian signal to pedestrian crashes.

Pedestrian Signal Timing

The design of pedestrian signals can involve timing schemes such as concurrent (standard) timing, exclusive phase (also called scramble timing), and other special timing sequences. The Project 17-27 interim report (6) reviewed a study from Israel by Zaidel and Hocherman (19) that analyzed 1,310 pedestrian crashes at 320 signalized intersections. Higher rates of pedestrian crashes were found at intersections with higher pedestrian and vehicle volumes, as well as at more complex intersections (i.e., the most legs or potential points of conflict). The type of signal timing provided for pedestrians had only a slight effect on pedestrian crashes and no effect on vehicle injury crashes, especially where vehicle volumes were low (less than 18,000 ADT). Intersections with exclusive phases for pedestrians had fewer crashes where vehicle and pedestrian volumes were higher. These results concur with the results of Zegeer et al. (20, 21).

A 1984 study by Robertson and Carter (22) found pedestrian signal indications can have different effects on pedestrian crashes, depending on the type of intersection. Robertson and Carter found that pedestrian signal indications reduce pedestrian crashes at some intersections, have little or no effect at others, and may actually increase crashes at yet other sites. The presence of pedestrian signals in itself did not have a statistically significant effect on pedestrian and vehicle delay, but the signal timing scheme had a major influence on delay. The authors suggested further study to identify the types of intersections where pedestrian signals would be most effective. AMFs could not be derived from the study results.

Zegeer et al. (10) studied the effect of pedestrian signal timing at 1,297 intersections. The analysis specifically focused on pedestrian signal designs, including sites with concurrent (standard) timing, sites with exclusive timing, and sites with no pedestrian signal. After adjusting for pedestrian volume, traffic volume, and street operation, Zegeer et al. found that exclusive timing resulted in significantly lower mean crashes per year than concurrent pedestrian signal or no pedestrian signal.

The findings from these studies indicate that the type of pedestrian signal can have an effect on pedestrian crashes, especially at intersections with high pedestrian and vehicle volumes.

Right-Turn-On-Red Operation at Signalized Intersections

The Project 17-27 interim report (6) reviews two crash-based studies that examine the effect of right-turn-on-red (RTOR) on pedestrian crashes. A study by Preusser et al. (23) examined sites in four states and found that there was a small effect of increasing right turn crashes after RTOR went into effect. This study was conducted during the mid-1970s, at which time a number of states in the eastern portion of the U.S. adopted the “permissive” type of RTOR that was already common in the western U.S. The “Western” approach to RTOR allows this maneuver at all locations that are not otherwise marked by a prohibitory sign. Of course, motorists are expected to stop and yield to pedestrians, bicyclists, and oncoming vehicles prior to making a Western RTOR. Preusser et al. evaluated several of the eastern locations and found statistically significant increases in pedestrian crashes with right-turning vehicles after RTOR was introduced. Comparison of computerized accident data from the periods before and after implementation of RTOR rule showed the following increases in accident rates:

- 43 percent for pedestrians in New York State
- 107 percent for pedestrians in Wisconsin
- 57 percent for pedestrians in Ohio
- 82 percent for pedestrians in New Orleans

It should be noted that these percentages are increases in very small numbers, since RTOR-pedestrian crashes are very rare.

A second part of the Preusser et al. study involved analysis of actual police crash reports. From this analysis, the authors were able to identify a common crash scenario involving RTOR.

Often, a driver who is stopped prior to turning right focuses on traffic coming from the left in order to identify a gap adequate to permit his right turn. Consequently, the motorist does not see a pedestrian on his right and a conflict occurs when the turn is initiated. The Preusser team found that RTOR accidents account for 1 to 3 percent of all pedestrian and bicycle accidents.

A study by Clark et al. (24) examined the effects of RTOR on pedestrian safety in South Carolina and Alabama. In South Carolina, crashes at signalized intersections involving right-turning vehicles for two years before and three years after the RTOR law was implemented were compared with accidents in the same period that did not involve right-turning vehicles. A similar comparison in Alabama covered three years before and five years after RTOR was instituted.

Results showed a statistically significant increase during the after period in South Carolina for right-turning property damage crashes than for crashes not involving right turns. This was not true in Alabama. There was no statistically significant difference in the rate of change in fatal or injury crashes in either state when comparing right-turning vehicles to non-right-turning vehicles. Furthermore, there was no evidence of increased pedestrian crashes resulting from RTOR in either South Carolina or Alabama. Considering both the South Carolina and Alabama results, Project 17-27 recommended an AMF of 1.067 for RTOR. Previous analysis in the current research found that this AMF only marginally involved pedestrian crashes (25).

The Project 17-27 interim report (6) also cited a 2003 study that examined the scope of the problem in Canada and the U.S. and found that RTOR-related pedestrian crashes made up less than 1 percent of all reported crashes and that the crashes that did occur were not usually severe.

The studies on RTOR have shown mixed results with respect to the effect of RTOR on pedestrian crashes, but it is clear that RTOR-related pedestrian crashes are rare.

One-Way Streets

The 2004 review (15) cited a 1978 Canadian study that studied streets in the city core and found that there were fewer crashes on one-way streets than two-way streets. These crashes were estimated to comprise about 10 percent of the total crashes in the city. The 2004 review also cites a 1973 study that examined 253 pedestrian crashes over a five-year period in New York City. The results showed the benefit to pedestrian safety of the simplified operation of one-way streets. In their predictive crash model, Zegeer et al. (3) found that there is no statistically significant difference in pedestrian crash risk between one-way and two-way streets, after controlling for other significant traffic and roadway factors.

The consensus of these studies indicates that one-way streets have a higher level of pedestrian safety versus two-way streets. However, the effect of pedestrian exposure on these findings has not been studied; consideration of pedestrian exposure would be needed to more accurately define the effect of one-way streets on pedestrian safety.

EFFECT OF ROADWAY SEGMENT CHARACTERISTICS ON PEDESTRIAN SAFETY

Research included in this section of the literature review is focused on the effect of roadway segment characteristics on pedestrian safety. Many studies have used non-crash-based measures of effectiveness, such as:

- Changes in pedestrian behavior (e.g., increased use of crosswalks, types of crossing behaviors, etc.)
- Changes in motorist behavior (e.g., increased number of yields, reduction in speed, etc.)
- Other surrogate safety measures (e.g., conflicts, avoidance maneuvers, etc.)

In contrast to these measures of safety, this literature review is limited to those studies that focused on pedestrian crashes as the unit of analysis. Many of the studies cited in this literature review are quoted from the interim report of NCHRP 17-27 (6), which consisted of draft chapters for the upcoming HSM. The effects of the following roadway characteristics on pedestrian safety are addressed:

- Sidewalks
- Midblock raised pedestrian crossings
- Illuminated crosswalk signs
- Pedestrian overpasses and underpasses
- Medians and pedestrian refuges
- Traffic calming
- Other factors without crash-based studies

Sidewalks

The Project 17-27 interim report (6) reviewed a 2002 study by McMahon et al. (26) that examined “walking along roadway” pedestrian crashes. The study used a case control methodology and applied conditional and binary logistic models to determine the effects of various roadway features and socioeconomic and other census data on the likelihood that a site is a pedestrian crash site. A total of 47 crash sites were found, which were matched with 94 comparison sites (i.e., one nearby and one far-away matched comparison site for each crash site) for analysis purposes. Comparison sites were selected which were similar to the crash sites in terms of number of lanes, traffic volume, roadway and shoulder width, vehicle speeds, area type, etc. Nearby comparison sites were selected within the same neighborhood and/or within approximately 1 mi [1.6 km] of the crash site. Far-away sites were matched sites that were selected in neighborhoods or areas on the other side of the county.

Physical roadway features found to be associated with a significantly higher likelihood of having a “walking along roadway” pedestrian crash included lack of a walkable area and the absence of a sidewalk augmented by higher traffic volume and higher speed limits. Using “risk

ratio” and controlling for other roadway factors, the likelihood of a site with a sidewalk or wide shoulder (of 4 ft [1.2 m] or wider) having a “walking along roadway” pedestrian crash was 88.2 percent lower than a site without a sidewalk or wide shoulder at the sites studied. Increased pedestrian crash risk existed for higher speed limits and for higher traffic volumes. The authors stated that these results “should not be interpreted to mean that installing sidewalks would necessarily reduce the likelihood of pedestrian/motor vehicle crashes by 88.2 percent in all situations. However, the presence of a sidewalk clearly has a strong beneficial effect of reducing the risk of a “walking along roadway” pedestrian/motor vehicle crash.” AMFs were not developed from the results.

A 1983 study by Tobey (27) examined roadway segment characteristics. This study investigated the relative risks of sidewalks and other traffic and roadway characteristics, using two different measures of pedestrian exposure: pedestrian volume (P) and pedestrian volume multiplied by vehicle volume (P×V). The percent of pedestrian crashes divided by the percent of pedestrian exposure was defined as the “hazard score” for each site, and “hazard scores” were compared for sites with various traffic and roadway characteristics. If the percent of pedestrian crashes was greater than the percent of pedestrian exposure, then the “hazard score” was greater than 1.0, or a pedestrian crash risk greater than average. Where the percent of crashes was less than the percent of exposure, the “hazard score” was computed as the percentage of exposure divided by the percent of crashes and assigned a negative sign (i.e., a negative sign represents a safer than average condition).

Sites with no sidewalks or pathways had the highest “hazard scores,” with values of +2.6 (using P as the exposure measure) and +2.2 (using P×V as the exposure measure). This is compared to “hazard scores” of +1.2 and +1.1 (using exposure measures of P and P×V, respectively) for sites with a sidewalk on one side of the road only. Sites with sidewalks on both sides of the road had “hazard scores” of -1.2 (using exposure measures of P and P×V), which represents a safer condition than having sidewalks on one side or no sidewalks at all.

These studies indicate that sidewalks and walkways can reduce pedestrian crashes, especially “walking along roadway” crashes.

Midblock Raised Pedestrian Crossings

The Project 17-27 interim report (6) addresses four studies related to raised pedestrian crossings that are cited in the AASHTO *Guide for the Planning, Design, and Operation of Pedestrian Facilities (1)*. These studies contain a total of ten estimates of effect. None of the studies have controlled for regression-to-the-mean or long-term trends in accident occurrence. For raised pedestrian crosswalks, 8 estimates have been rated as low quality and 2 as medium low quality. Thus, a high quality quantification of safety is not available for this measure.

The safety effects of raised pedestrian crosswalks in Table 5 refer to pedestrian crashes or crashes involving motor vehicles only. The latter category includes all crashes that involve one or more motor vehicles, but not a pedestrian. It cannot be ruled out that the summary estimates presented in Table 5 are confounded by uncontrolled regression-to-the-mean and uncontrolled

long-term trends in crash occurrence. Standard errors have been adjusted by a factor of 3 for each low quality estimate of effect and a factor of 2.2 for each medium low quality estimate of effect.

TABLE 5. Effects on Injury Crashes of Raised Pedestrian Crosswalks (6).

Data summarized	Crash type and severity	Index of effectiveness ($t_{adjusted}$)	Estimate of Std. Error (s)
All studies (10 estimates)	All crashes, injury	0.642	0.543
All studies (5 estimates)	Pedestrian crashes, injury	0.545	0.937
All studies (5 estimates)	Vehicle crashes, injury	0.697	0.667

These studies indicate that raised pedestrian crosswalks seem to reduce pedestrian crashes. However, the lack of control on potentially confounding factors and large standard errors introduces a high degree of uncertainty on quantifying the effect of raised crosswalks.

Illuminated Crosswalk Signs

The 2004 review (15) of pedestrian safety research cited a study that evaluated 20 locations in Tokyo, Japan (28) with illuminated crosswalk signs. An analysis was conducted on crashes occurring before and after the installation of the illuminated crosswalk signs. The results showed that within 656 ft [200 m] on either side of the crosswalk, pedestrian crashes increased by 4.8 percent and other unrelated crashes increased by 2.4 percent. Within 164 ft [50 m], both crash types increased by 11.4 percent. The researchers concluded that the illuminated crosswalk signs showed no benefit to pedestrian crashes, but it is unclear whether the study accounted for factors such as annual volume increase.

Pedestrian Overpasses and Underpasses

The 2004 review (15) found one before-after study that examined pedestrian crashes at 31 locations in Tokyo, Japan, where pedestrian overpasses had been installed (28). The results (see Table 6) show the crashes occurring 6 months before and 6 months after installation. There was a reduction seen in the occurrence of crashes related to pedestrian crossing events, as well as a greater reduction of daytime pedestrian crashes over nighttime pedestrian crashes.

TABLE 6. Comparison of Crashes Before and After Installation of Pedestrian Overpasses (Tokyo, Japan) (28).

Type of crash	656-ft section			328-ft section		
	Before	After	Reduction	Before	After	Reduction
Related Crashes	2.16	0.32	85%	1.81	0.16	91%
Nonrelated Crashes	2.26	2.77	23%	1.65	1.87	-14%
Total	4.42	3.09	30%	3.46	2.03	41%

The limited number of crash-based studies on the effect of pedestrian overpasses and underpasses does not provide definitive results. The Tokyo study indicates that overpasses can reduce pedestrian crashes, but it can be assumed that the safety effect is directly related to the level of usage of the overpasses by pedestrians, which can vary widely.

Medians and Pedestrian Refuges

The Project 17-27 interim report (6) reviewed a 2002 study by Zegeer et al. (3) whose primary goal was to examine the safety effects of marked versus unmarked crosswalks. One thousand crosswalks of each type were included from 30 U.S. cities. Predictive models based on five years of crash data showed that raised medians were associated with a 46 percent reduction in pedestrian crashes on marked crosswalks and a 39 percent reduction on unmarked crosswalks, for multi-lane roads with ADTs greater than 15,000 vehicles per day.

Two studies on the effects of pedestrian refuge islands were also reviewed in the Project 17-27 report (6). Bacquire et al. (29) conducted a before-after analysis of raised pedestrian refuge islands. The analysis considered pedestrian and vehicle crashes at 28 sites from 3 years before to 3 years after installation. Although pedestrian crashes that were related to refuge islands were reduced by 73 percent, there was an increase in total crashes by 136 percent. The possibility that treatment sites were selected on the basis of crash history introduced potential regression-to-the-mean bias. The authors concluded that overall safety was not helped by the installation of raised pedestrian refuge islands.

Cairney (30) reviewed a 1994 Australian Geoplan study which found that none of the four types of refuge islands examined was found to be very effective from a safety perspective. In fact, three types caused large increases in the adjusted pedestrian crash rate (the calculation of and adjustments made to the pedestrian crash rate were not reported), while only one type resulted in a slight reduction (2 percent reduction). However, according to Cairney, "...it seems inherently unlikely that pedestrian refuges did not reduce crashes. The method used in the Geoplan study compared crashes occurring at the site of the facility, before and after. Where pedestrian refuges are provided, it would be expected that pedestrians would be attracted to cross at this point—pedestrians who would otherwise have crossed some distance along the road, so that pedestrian flow is greatly increased at the refuge. A study of the crash history of the whole street where pedestrian refuges have been installed would therefore be necessary to determine whether there had been a reduction in pedestrian crashes."

A study by Bowman and Vecellio (31) that examined the safety effects of median types involved an analysis of 32,894 vehicular crashes and 1,012 pedestrian crashes that occurred in three U.S. cities (Atlanta, Georgia; Phoenix, Arizona; and Los Angeles/Pasadena, California). The median types which were compared were: (a) raised, (b) flush or two-way-left-turn-lane (TWLTL), and (c) no existing median (undivided). A variety of statistical tests were used, including t-tests, analysis of variance, and the Scheffe multiple comparison test. The authors did not have pedestrian volume data, but used area type (CBD and suburban areas) and land use as surrogate measures for pedestrian activity and developed pedestrian crash prediction models separately for the two area types.

The results of this analysis provide strong evidence that having some area of refuge (either a raised median or TWLTL) on an arterial CBD or suburban street provides a considerably safer condition for pedestrians than having an undivided road (i.e., with no refuge for pedestrians in the middle of the street). Furthermore, while this study found that suburban arterial streets with raised-curb medians had lower pedestrian crash rates, as compared to TWLTL medians, this difference was not statistically significant. This may be a clear indication that some refuge area (in the middle of wide streets) is more beneficial to pedestrian safety when crossing streets than having no refuge area. However, the safety benefits for a raised median vs. a TWLTL were not quantified. Based on the study results, Bowman and Vecellio recommended that in CBD areas, whenever possible, divided cross-sections should be used due to their lower crash rates for pedestrians and motor vehicles.

Cairney (30) also presented the results of the following studies related to medians:

- A study by Moore and McLean reports early research in New South Wales by Johnson in 1962 and Leong in 1970. These studies found that providing narrow medians reduced vehicle-to-vehicle crashes but had no effect on pedestrian crashes. The author did not report the sample size of the studies, the type of statistical analysis, or whether data variables such as pedestrian exposure were collected and controlled for in the analyses. Crash data were not reported.
- A 1986 study by Scriven in Adelaide, South Australia, found that medians were effective in reducing pedestrian crashes. On arterial roads, pedestrian crash rates were directly related to median width. Roads with the narrowest medians (4 ft [1.2 m]) had pedestrian crash rates that were four times higher than routes with the widest medians (10 ft [3.0 m]).
- A 1994 study by Claessen and Jones found that replacing a 6-ft [1.8-m] painted median with a wide raised median reduced pedestrian crashes by 23 percent. According to Cairney, this conclusion was consistent with Scriven's finding that pedestrian crash rates for roads with 10-ft [3.0-m] medians were 33 percent lower than for roads with 4-ft [1.2-m] painted medians.

Overall, these studies indicate that medians and pedestrian refuges serve to reduce pedestrian crashes. The emphasis on safety effectiveness indicates that raised medians are better than nonraised, and wider medians and refuges are better than narrow ones.

Traffic Calming

Although past studies indicate that traffic calming may cause a decrease in total crashes, no crash-based studies were found to determine any significant effect of traffic calming on pedestrian crashes.

Other Factors Without Crash-Based Studies

No crash-based studies were found for the following roadway segment (midblock) factors:

- Pedestrian-activated flashing yellow beacon
- Overhead electronic LED signs (animated eyes)
- In-pavement lighting

EXISTING PREDICTIVE MODELS FOR PEDESTRIAN CRASHES

This section reviews existing predictive models for pedestrian crashes that have been developed in previous work. The first portion of this section presents the provisional approach for estimating the frequency of vehicle-pedestrian crashes in the HSM methodology already developed as part of this research. This provisional approach is being replaced with the pedestrian safety prediction methodology presented in this report. The second portion of this section reviews four previous pedestrian modeling efforts reported in the literature.

Current Approach to Estimating Pedestrian Safety in the HSM Methodology

Separate pedestrian safety estimation procedures are used for intersections and roadway segments. Each set of procedures is presented below (25).

Intersections

Safety predictions for a particular intersection are developed as a combination of base models, calibration factors, and accident modification factors (AMFs) using the following general approach:

$$N_{int} = (N_{bi} + N_{pedi} + N_{bikei}) C_i \quad (1)$$

$$N_{bi} = N_{bibase} (AMF_{1i} AMF_{2i} AMF_{3i} AMF_{4i} AMF_{5i}) \quad (2)$$

where:	N_{int}	=	predicted number of total intersection-related accidents per year after application of accident modification factors
	N_{bi}	=	predicted number of total intersection-related accidents per year (excluding vehicle-pedestrian and vehicle-bicycle collisions)
	N_{bibase}	=	predicted number of total intersection-related accidents per year for nominal or base conditions (excluding vehicle-pedestrian and vehicle-bicycle collisions)
	N_{pedi}	=	predicted number of vehicle-pedestrian collisions per year
	N_{bikei}	=	predicted number of vehicle-bicycle collisions per year

- C_i = calibration factor for at-grade intersections developed for use for a particular geographical area
- $AMF_{1i} \dots AMF_{5i}$ = accident modification factors for intersections

Four types of intersections on arterial roadways are considered:

- Three-leg intersections with STOP control on the minor-road approach (3ST)
- Three-leg signalized intersections (3SG)
- Four-leg intersections with STOP control on the minor-road approaches (4ST)
- Four-leg signalized intersections (4SG)

Specific procedures for estimating N_{bi} are presented in the HSM methodology. The number of vehicle-pedestrian collisions per year for an intersection is estimated from N_{bi} as:

$$N_{pedi} = N_{bi} f_{pedi} \quad (3)$$

where: f_{pedi} = pedestrian safety adjustment factor

Table 7 presents the values of f_{pedi} for use in Equation (3). All vehicle-pedestrian collisions are considered to be fatal-and-injury accidents. These adjustment factors are based upon average proportions of pedestrian crashes to total crashes, for the given intersection type.

TABLE 7. Pedestrian Safety Adjustment Factors for Intersections (25).

Intersection type	Pedestrian safety adjustment factor (f_{pedi})
3ST	0.008
3SG	0.005
4ST	0.016
4SG	0.017

NOTE: These factors apply to the methodology for predicting total accidents (all severity levels combined). All pedestrian collisions resulting from this adjustment factor should be treated as fatal-and-injury accidents and none as property-damage-only accidents.

Roadway Segments

Safety predictions for a particular roadway segment are developed as a combination of base models, calibration factors, and AMFs using the following general approach:

$$N_{rs} = (N_{br} + N_{pedr} + N_{biker}) C_r \quad (4)$$

$$N_{br} = N_{brbase} (AMF_{1r} AMF_{2r} AMF_{3r}) \quad (5)$$

where: N_{rs} = predicted number of total roadway segment accidents per year
 N_{br} = predicted number of roadway segment accidents per year excluding vehicle-pedestrian and vehicle-bicycle collisions
 N_{brbase} = predicted number of total roadway segment accidents per year for nominal or base conditions excluding vehicle-pedestrian and vehicle-bicycle collisions
 N_{pedr} = predicted number of vehicle-pedestrian collisions per year
 N_{biker} = predicted number of vehicle-bicycle collisions per year
 $AMF_{1r} \dots AMF_{3r}$ = accident modification factors for roadway segments
 C_r = calibration factor for roadway segments developed for use for a particular geographical area

Five types of roadway segments are considered:

- Two-lane undivided arterials (2U)
- Three-lane arterials including a center TWLTL (3T)
- Four-lane undivided arterials (4U)
- Four-lane divided arterials (i.e., including a raised or depressed median) (4D)
- Five-lane arterials including a center TWLTL (5T)

Specific procedures for estimating N_{br} are presented in the HSM methodology. The number of vehicle-pedestrian collisions per year for a roadway segment is estimated from N_{br} as:

$$N_{pedr} = N_{br} f_{pedr} \quad (6)$$

where: f_{pedr} = pedestrian safety adjustment factor

Table 8 presents the values of f_{pedr} for use in Equation (6). All vehicle-pedestrian collisions are considered to be fatal-and-injury accidents. These adjustment factors are based upon average proportions of pedestrian crashes to total crashes, for the given roadway type. In applying Table 8, roadways with traffic speeds or posted speed limits of 48 km (30 mph) or less should be considered low speed; roadways with traffic speeds or posted speed limits greater than 48 km (30 mph) should be considered intermediate or high speed. The original version of Table 8 in the first and second drafts of the HSM chapter used the column headings “urban” and “suburban;” these column headings have been changed in the third and fourth drafts of the HSM Chapter to “low speed” and “intermediate or high speed,” because the use of the terms “urban” and “suburban” was confusing to some reviewers.

TABLE 8. Pedestrian Safety Adjustment Factors for Roadway Segments in Urban and Suburban Areas (25).

Road type	Pedestrian safety adjustment factor (f_{pedr})	
	Low speed	Intermediate or high speed
2U	0.031	0.003
3T	0.030	0.002
4U	0.044	0.008
4D	0.018	0.006
5T	0.036	0.004

Note: These factors apply to the methodology for predicting total accidents (all severity levels combined). All pedestrian collisions resulting from this adjustment factor should be treated as fatal-and-injury accidents and none as property-damage-only accidents.

Predictive Models From the Literature

Four studies have previously developed predictive models of pedestrian crashes (3,8,11,12). Three of these studies (3,8,12) estimated negative binomial regression models that used the following functional form:

$$N_{ped} = \exp(\beta_0 + \beta_1 ADT + \beta_2 PedVol + \beta_x X_3 + \dots + \beta_n X_n) \quad (7)$$

where $\beta_0 \dots \beta_n$ are coefficients to be estimated. N_{ped} is the expected number of pedestrian crashes, ADT is the annual average daily traffic (i.e., vehicular volume), PedVol is the annual average daily pedestrian volume, and $X_3 \dots X_n$ represent other site characteristics such as proportion of left-turn volume, number of lanes, speed limit, presence/absence of a crosswalk, and presence/absence of a median.

Collectively, the following conclusions can be made from these four studies:

1. Most of the studies that have tried to predict pedestrian crashes have been conducted at intersections. Even the sample in the Zegeer et al. (3) study that looked at both intersections and nonintersection locations consisted mostly of intersections (more than 80 percent).
2. As expected, increase in total traffic volumes and pedestrian volumes lead to higher pedestrian crashes. However, the coefficient for pedestrian volumes in most of these models is significantly less than 1.0. This implies that the relationship between pedestrian volumes and pedestrian crashes is nonlinear (e.g., a 50 percent increase in pedestrian volumes will lead to a less than 50 percent increase in pedestrian crashes, all other things being equal).
3. Based on the work by Lyon and Persaud (8), it is clear that the amount of turning traffic plays an important role in vehicle-pedestrian crashes. In fact, at 3-leg intersections with minor-road STOP control in Toronto, left-turn volumes were

found to be more important than total volumes in predicting the number of pedestrian crashes. However, it is also likely that many jurisdictions do not have resources to collect turning volume information on a regular basis.

4. Except for Zegeer et al. (3), most of the work has focused on trying to relate just pedestrian/vehicle volumes with pedestrian crashes. Zegeer et al. (3) included information on other site characteristics and found median type, number lanes, and marked/unmarked crosswalks to be associated with pedestrian crashes.
5. Due to the limited frequency of pedestrian crashes, a large sample of sites with many years of data is needed to estimate such models. For example, Lyon and Persaud (8) utilized 122 intersections in the three-leg STOP-controlled group (the smallest intersection group) and compiled 11 years of data at these locations. Zegeer et al. (3) collected data from 2,000 locations.

ESTIMATING PEDESTRIAN EXPOSURE DATA FROM COUNT PERIODS OF LESS THAN 24 HOURS

The availability and use of pedestrian exposure data are important in the development of pedestrian crash models in this study. Pedestrian exposure at an intersection may be represented by such measures as pedestrian crossings per hour or estimated pedestrian volume related to the number of pedestrians crossing the street within the intersection (or on the approach legs of interest). On roadway segments, the pedestrian exposure may include the number of pedestrians who cross the street along the segment, such as for use in modeling pedestrian crashes involving street crossings. The number of pedestrians walking along the roadway may be the most appropriate pedestrian exposure measure, however, for modeling crashes involving pedestrians “walking along the road” on roadway segments.

The challenge in obtaining such pedestrian exposure data is that few public agencies routinely collect pedestrian exposure data on a large number of sites, and thus, most (if not all) of the pedestrian exposure data which is needed for this study must be assumed to be collected by the project team at the selected sample sites. The collection of pedestrian exposure can be quite labor-intensive for an assumed sample of hundreds or thousands of sites, as will be needed for modeling purposes in this study. Therefore, practical and cost-efficient data collection strategies must be selected.

A methodology for estimating daily pedestrian volumes at intersections was developed and utilized by Zegeer et al. (3) The methodology involved using 24-hour pedestrian counts from one city (Seattle) to develop estimated hourly pedestrian percentages for various area types (i.e., CBD, urban fringe, and residential). Counts of 11 hours were collected at multiple sites in several other cities to assist in determining hourly pedestrian volume distributions. Then, one-hour pedestrian volume counts were collected at each of the 2,000 crossing sites, and hourly adjustment factors were used to compute estimated daily pedestrian volumes.

It was found, for example, that the 12-hour period from 7:00 a.m. to 7:00 p.m. represented 86 percent of the daily pedestrian crossing volume. Hourly pedestrian adjustment factors were developed for intersections in each of the three area types. For example, in CBD

areas, the pedestrian volume between 10:00 a.m. and 11:00 a.m. represented approximately 8.2 percent of the daily pedestrian crossing volume. Thus, a pedestrian count of 100 during that 10:00 to 11:00 a.m. period was expanded to an estimated daily pedestrian volume of 1,220 (100 divided by 0.082).

It is recognized that this is a rough estimate of pedestrian exposure and that pedestrian activity may vary from day-to-day, by season, weather condition, etc. Pedestrian counts, therefore, should typically be collected on week days during relatively good weather conditions for use in developing pedestrian volumes. In fact, motor-vehicle ADT volume data are often the result of short-term counts with expansion factors applied. Using this type of methodology for estimating pedestrian exposure in this study will allow for collecting a much greater sample of total sites for use in the modeling.

Only a few highway agencies have extensive records of pedestrian volume data at intersections or roadway segments. This lack of pedestrian volume data may be an impediment to applying an HSM safety prediction methodology that uses pedestrian volume as an input variable. The HSM methodology is intended primarily for application in the project development process. Extensive data collection activities are typically undertaken during project development activities, so it seems reasonable to expect that the data collection could include pedestrian volumes. However, because pedestrian counts may not be a routine part of current data collection protocols, it also seems desirable to provide guidelines as part of the HSM methodology for HSM users to estimate pedestrian volumes.

ESTIMATING PEDESTRIAN VOLUMES FROM LAND USE CHARACTERISTICS

Transportation planners have been considering methods for estimating pedestrian volumes from land use characteristics. The following discussion reviews two related promising tools for estimating pedestrian volumes from land use characteristics. Further development of these tools would require resources beyond those available in this research, but tools like those would be reviewed below might eventually be considered for incorporation in the HSM.

Space Syntax

Raford and Ragland (32) observed a fairly significant correlation between predicted and observed pedestrian volumes ($R^2 = 0.7712$, $p < 0.001$) using a collection of modeling tools and simulation techniques called Space Syntax to analyze pedestrian movement and predict pedestrian volume in Oakland, CA. Street layout and connectivity generate “movement potentials” which are compared to sampled pedestrian counts at key locations and land use indicators such as population and employment density. The resulting correlations can be extrapolated to predict pedestrian volumes on a street-by-street level for the study area, which might include an entire city.

The Space Syntax method first requires an axial line map for the analysis area. Raford and Ragland incorporated a total of 7000 street segments from Oakland. An “integration” value

for each segment is then developed using Space Syntax, generally based on the number of street segments accessible within 3 links. Population density and other demographic characteristics, including median household income, age, and race, were then applied to the Space Syntax model. The above description admittedly oversimplifies the Space Syntax algorithm that calculates “Integration.” That algorithm is explained in more detail in two papers: “The Common Language of Space: a way of looking at the social, economic, and environmental functioning of cities on a common basis.” Hillier, Bill, no date, available online at <http://www.spacesyntax.org/publications/commonlang.html>; and “Spatial Distribution of Urban Traffic: civilizing urban traffic.” Croxford, Ben, et al., May 1995, available online at <http://www.bartlett.ucl.ac.uk/web/ben/copenhagen.html>.

Pedestrian Flow Modeling

Clifton et al. (33) have adapted the origin-destination-based demand model to standardize a modeling protocol for estimating pedestrian volumes on streets and sidewalks. The description for this model is based on conversations with the lead author, a presentation by a coauthor, and references to the model by Burnier and Clifton (34). In two case studies, the difference between pedestrian counts estimated by the model and those observed by actual pedestrian counts were within 4 percent on any given link in the modeled network. The model uses 14 trip purposes to differentiate among activities. Block-face detail is used for land use, networks, and trip making. Accessibility to activities influences the number of walking trips in the model. The barrier effects of streets (i.e., width, volume, speed, signals, etc.) are also used to influence accessibility and the distribution of trips.

Stochastic path finding defines a distribution of walking routes from origins to destinations. Pedestrian trip generation characteristics (origins and destinations) for the Pedestrian Flow Model were derived from the 1996 NYMTC Household Survey, which included 11,000 households and projects a total of 59.3 million daily trips from 89,605 trip records. A total of 12,274 walking trips were recorded, estimating 9 million daily walking trips.

Necessary input data includes sources readily available for most communities:

- Census TIGER line files for streets
- Census Block Group population and housing characteristics
- Census Journey to Work data
- Parcel-level property data and land uses
- Aerial imagery, such as ortho-photography

Easy access to data sources and the ability to apply limited manual interpretation and adjustments to the data as the model is developed increase the viability of the Pedestrian Flow Model. Detailed data can be assembled from available sources with reasonable effort. The model is sensitive to real-world factors that affect pedestrian travel such as land use, sidewalk network connectivity and quality, and barrier effects of streets. In addition outputs from the model can be used to evaluate pedestrian crash exposure and risk, and can inform development of safety priorities.

In addition to the two models discussed above, other methods for estimating pedestrian travel have been tried and applied in various settings. These methods include sketch planning techniques that predict pedestrian travel using simple calculations and rules of thumb about travel behavior; development and application of expansion factors to sample pedestrian counts; and developing estimates based on comparisons to similar locations. Each has limitations that render them excessively inaccurate for application to pedestrian crash risk assessment—primarily the lack of reliable street segment-level estimates. The two models discussed here are more promising for pedestrian crash risk assessment because they provide individual street segment-level estimates that have been accurate to within 4 percent of actual counts.

Literature Review of Land Use Features Associated With Crash Risk

Table 9 summarizes factors that literature indicates to be associated with increased or decreased pedestrian crash risk (i.e., with increased or decreased pedestrian crash frequencies). The sources in the literature on which Table 9 is based are discussed below.

Identification of areas with increased pedestrian crash risk has generally relied on roadway characteristics, including geometry, traffic volumes, number of lanes, etc. Land use variables, however, have usually not been included, or are highly generalized when included. In a comprehensive analysis of pedestrian crashes at intersections, for example, Lee and Abdel-Aty (35) examined pedestrian and driver characteristics (age, gender, alcohol use), vehicle characteristics (type, speed), traffic/road geometric characteristics (traffic control device, divided/undivided, and number of lanes), and environmental characteristics (lighting, weather, and location). Of these, the location variable is the only land use-related variable, but it only indicates whether the location was urban or rural. The pedestrian characteristics variables of age and alcohol use might be proxies for adjacent or nearby land use variables, but spatial analysis examining the relationship between the distribution of pedestrians with those characteristics and the presence of the characteristics in adjacent land uses would be necessary before these variables could be replaced by land use variables. A statistically significant relationship between crashes involving pedestrians with certain demographic characteristics and those same crashes occurring in areas where those demographic characteristics are significantly present might indicate that the demographic land use variable would also correlate to pedestrian crash risk. LaScala et al (36) discuss methods of spatial analysis applied to variables that correlate to pedestrian injury crashes, and Austin et al. (37) presents a novel application of spatial statistics to land uses and expected pedestrian behavior.

More detailed land use variables that may have significant correlation to pedestrian crash risk are available. These variables are discussed below.

Epidemiological studies have long suggested additional correlations to various land use, demographic, or geographic characteristics. In addition, a limited number of recent planning or transportation studies have examined multiple variables and developed coefficients for numerous land use, demographic, or geographic variables that correlate with increased pedestrian crash frequencies.

TABLE 9. Land Use Variables Associated With Pedestrian Crash Risk.

Land use variable (nongeometric roadway factor)	Pedestrian crash risk	Source
Unemployment (less than 1.75% of population)	Increases	McMahon (26)
Employment (number of employed)	Increases	Burnier and Clifton (34)
Employment	Decreases*	Greenwald and Boarnet (40)
Age of housing stock	Increases	McMahon (26)
Single-parent households	Increases	McMahon (26)
Population density	Increases	LaScala (36, 38)
Population density	Increases	Burnier and Clifton(34)
Population density	Decreases*	Saelens et al. (39)
Proportion of children (age 0-15)	Decreases	LaScala (36, 38)
Percent children	Decreases	Burnier and Clifton (34)
Percent children (age 0-16)	Decreases*	Greenwald and Boarnet (40)
Proportion of population age 16-29	Increases	LaScala (36, 38)
Proportion of population age 55+	Decreases	LaScala (36, 38)
Age (scaled)	Decreases*	Greenwald and Boarnet (40)
Gender (proportion of males)	Increases	LaScala (36, 38)
Education (% high school or higher)	Decreases	LaScala (36, 38)
Education (% attended some college)	Decreases	Burnier and Clifton (34)
Proximity to alcohol availability	Increases	LaScala (36, 38)
Density of restaurants	Increases	LaScala (36, 38)
Number of households in census tract	Decreases	Burnier and Clifton (34)
Income (in \$1000s)	Decreases	Burnier and Clifton (34)
Race (percentage of nonwhite)	Increases	Burnier and Clifton (34)
Vehicle ownership	Increases	Burnier and Clifton (34)
Car ownership	Decreases*	Greenwald and Boarnet (36, 38)
Density of roads	Increases	Burnier and Clifton (34)
Percent parkland	Increases	Burnier and Clifton (34)
Commercial accessibility	Decreases	Burnier and Clifton (34)
Transit accessibility	Increases	Burnier and Clifton (34)
Transit usage (number of users within area)	Increases	Hess (41); Vernez-Moudon (42)
Mixed use	Increases	Burnier and Clifton (34)
Land use mixture	Decreases*	Saelens et al. (39)
Grocery store proximity (1/4 mile)	Decreases	Hess (41); Vernez-Moudon (42)
Retail land use proximity (1/4 mile; 100K sq ft)	Increases	Hess (41); Vernez-Moudon (42)

* Saelens et al. (39) and Greenwald and Boarnet (40) examined levels of walking associated with the land use variable, so their research looks at the denominator of the pedestrian crash risk (number of pedestrians). Increasing the denominator lowers the risk, so these variables are identified as decreasing risk, although there is conflicting research about whether pedestrian safety actually increases or decreases with higher volumes. This table presents the variable as described in the source paper. In some instances, the variable description has been modified to match other research or to clarify differences in variables. A meta-analysis of the results of the various reported studies would allow more accurate evaluation and comparison by adjusting all results to a comparable scale.

In an examination of geographic correlates of pedestrian injury crashes, LaScala et al. (38) showed that pedestrian injury rates were spatially related to population density, age composition of the local population, unemployment, gender, and education. Availability of alcohol through bars was also directly related to pedestrian injury crashes.

McMahon et al. (26) found that nongeometric roadway factors are associated with a significantly higher likelihood of being a crash site. Factors that were associated included high levels of unemployment, older housing stock, lower proportions of families within households, and more single-parent households.

Burnier and Clifton (34) showed significant effects of land use on pedestrian crashes, as well as on pedestrian exposure. Urban downtown areas with high population density and high-

density roadway networks were found to have lower pedestrian crash risk. The model included thirteen variables, shown in Table 9.

Saelens et al. (39) identify a number of land uses that correlate to increased levels of walking. Evidence suggested that more walking occurs in neighborhoods with higher population density, increased sidewalk connectivity, and mixtures of land uses. They also note that land use variables appear to add to variance accounted for beyond demographic predictors of walking. Greenwald and Boarnet (40) examine the built environment as a determinant of walking behavior. They found increased walking occurring in census tracts with higher percentages of younger residents, and decreased levels of walking in tracts with more older residents, higher rates of car ownership, and more employed household members.

In addition, there are numerous epidemiological studies that show some level of association between land use or demographic variables and an increased crash risk. These often focus on narrow population segments; a few have been summarized in Table 9 along with those identified as part of the more comprehensive studies discussed above. At least 22 variables have been associated in various studies with an increased risk of pedestrian crashes.

Table 9 shows some contradictions for some variables. For example, in separate studies employment levels and unemployment levels were each shown to increase crash risk. In one study, grocery store proximity decreased crash risk, while proximity to retail land use increased risk. These contradictions may be explained by methodology between studies, differences in study areas, or different definitions of the associated variable. In general, however, Table 9 shows that there are many potential land use, demographic, or geographic variables that warrant consideration in development of predictive models for pedestrian crash risk.

In addition, most comprehensive studies, including LaScala et al. (38) and Burnier and Clifton (34), provide beta values for the coefficients because the variables are in different units or on different scales. As a result, Table 9 cannot present the relative strength of each variable because the scale of each variable is different. For example, population density may be presented on a scale, while education is typically presented with only two or three divisions that encompass the entire population. As described in a footnote above, a meta-analysis would allow effective comparison of relative significance of each variable.

Another limitation of much of the existing research associating land use, demographic, or geographic variables with increased risk of pedestrian crashes is that the research does not identify whether the variable affects risk by changing the numerator of risk (number of crashes) or the denominator (volume). In many instances, which element of risk is affected may be intuitive, but probably not in all cases; however, knowing which element of risk is affected by the variable may not be necessary for developing predictive models of pedestrian crash risk. In some instances, though, knowing whether risk has increased because there are likely to be more pedestrians or whether there may be more actual crashes (perhaps for behavioral reasons associated with a population using a particular land use) may affect the predictive model.

Studies have also examined land use variables and correlation to pedestrian crashes among some population groups. Roberts et al. (43) showed high levels of curb parking increases

the risk of child pedestrian injury. Von Kries et al. (44) associated neighborhoods with more playgrounds with decreased risk of child pedestrian injury, although the studies listed in Table 9 associate parks with an increased risk of pedestrian injuries in the general population. In an even narrower study, Agran et al. (45) found household crowding in the Hispanic population, inability of a parent to read well, and level of poverty were associated with an increased risk of pedestrian injuries for Hispanic children. Agran et al. also found that single parent households, car ownership, and level of education did not increase rate of injury among Hispanic children.

Overall, the research indicates a complex relationship between land use, demographic, and geographic characteristics that is not yet well understood. Inclusion of these variables may improve models developed to predict pedestrian crashes.

Closure

A number of recent research projects have proposed apparently similar multivariate equations to estimate pedestrian volume, with encouraging results. Using a GIS-based statistical analysis process, called “Space Syntax,” Rford and Ragland (32) have observed fairly significant correlations between predicted and observed pedestrian volumes in Oakland, CA ($R^2 = 0.7712$) (2003) and Boston, MA ($R^2 = 0.81$) (2005). Other applications of the same basic process have attained R^2 values of 0.84 by Hillier (46) and 0.749 by Hillier (47). Using linear regression modeling, Pulugurtha et al. (48) developed pedestrian volume estimates that attained a 2.2 percent difference from observed values. Clifton et al. (33) adapted the origin-destination based demand model to develop estimates of pedestrian counts that were within 4 percent of actual counts. Other pedestrian research projects have included volume estimation models without adequate evaluation or testing of their predictive value (33, 49, 50, 51).

The “Space Syntax” approach, discussed above, develops a type of measure called “Integration” that generally describes the level of pedestrian travel possible within a specified number of intersections, called “Radius-3” or “Radius-5.” The equation used by the Space Syntax software is embedded in an add-on program called “Confeego” for the MapInfo GIS software system. Rford and Ragland (32) also include a series of land use variables in their equations.

CHAPTER 3.

PEDESTRIAN SAFETY DATABASES

This chapter describes the pedestrian safety databases assembled for use in this research from the City of Toronto, the City of Charlotte, and two metropolitan areas in Minnesota.

SIGNALIZED INTERSECTIONS IN TORONTO

The City of Toronto, Ontario, Canada, has over 1,500 signalized intersections in its jurisdiction. The City has collected both vehicle and pedestrian volume data at most of these intersections which creates a rich database for pedestrian safety research. Intersections meeting the following criteria were included in this study:

- signalized control
- not the terminal of a freeway ramp
- no one-way intersection legs
- no turn restrictions

For each site, the research team obtained data elements on intersection characteristics, signal data, vehicle and pedestrian volumes, and vehicle-pedestrian crashes.

Intersection Characteristics

Table 10 summarizes the data elements that were available for signalized intersections in Toronto. Most of these variables were available in an existing City database. The research team supplemented the existing data through a review of aerial photographs to obtain data on the presence of median refuge islands and to verify data on the number of lanes on each intersection leg.

Vehicle and Pedestrian Volumes

Vehicle and pedestrian volume data were available for each intersection leg, but no vehicle turning movement counts were available.

The expansion factor for pedestrian volumes discussed above were based initially on a 1985 FHWA study by Zegeer et al. (10). As part of that study, there was a need to develop pedestrian volume expansion factors to adjust short-term pedestrian counts to pedestrian ADTs. Since cities typically do not collect pedestrian volumes on a 24-hr basis, the only available counts were a large sample of pedestrian volume counts taken in Seattle, Washington, which were summarized by hour of the day and also by area type (e.g., CBD, fringe, and residential). The 1985 study used those data to compute pedestrian volume adjustment factors to allow for expanding shorter counts to approximate pedestrian volumes on a 24-hr basis. This pedestrian

ADT expansion methodology was further refined, checked, and used in a 2005 FHWA study by Zegeer et al. (3). These adjustment factors are given and explained in detail on page 67 of the 2005 FHWA report.

Vehicle-Pedestrian Collision Data

Data for vehicle-pedestrian collisions at the signalized intersections in Toronto were available from City records for seven years from 1999 through 2005. Hard-copy police reports were reviewed for many of these collisions to verify their location relative to the intersection in question. Vehicle-pedestrian collisions were attributed to the intersection if they occurred within 76 m (250 ft) of the intersection and were related to the operation of the intersection.

TABLE 10. Summary of Available Data Elements for Signalized Intersections in Toronto and Charlotte.

Data element	Available in Toronto Database	Available in Charlotte Database
INTERSECTION-LEVEL DATA		
Number of intersection legs	X	X
Intersection/skew angle	X	X
Presence of lighting		X
INTERSECTION-LEG-LEVEL DATA		
Number of through lanes	X	X
Number of left-turn lanes	X	X
Number of right-turn lanes	X	X
Right-turn treatment		X
Presence of marked pedestrian crosswalks	X	X
Presence of median	X	X
Presence of curb parking		X
Presence of sidewalks (left and right)		X
Presence and type of pedestrian signal	X	X
Type of left-turn phasing		X
Curb return radius		X
One-way vs. two-way traffic operation	X	X
Posted speed limit		X
Presence and type of turn restrictions	X	X
VOLUME DATA		
Average daily traffic volume by leg	X	X
Vehicle turning movement counts by leg		X
Pedestrian crossing volume by leg	X	X

SIGNALIZED INTERSECTIONS IN CHARLOTTE

The City of Charlotte has approximately 600 signalized intersections in its jurisdiction. Given that Charlotte Department of Transportation (CDOT) collects vehicle and pedestrian counts at these intersections on a regular basis, many of these intersections were suitable for this study. Intersections meeting the following criteria were included in this study:

- signalized control

- not the terminal of a freeway ramp
- no one-way intersection legs
- no turn restrictions
- not equipped with automated enforcement

For each site, the research team collected data on the intersection characteristics, signal data, vehicle and pedestrian volumes, and vehicle-pedestrian crashes.

Intersection Characteristics

Geometric and physical characteristics of an intersection can affect pedestrian safety. Some characteristics are particular to the whole intersection, whereas some are leg specific and can be different for different legs of an intersection. Table 10 summarizes the data that were available for signalized intersections in Charlotte. Most of these data were collected by examining high-resolution aerial photography and signal plans provided by CDOT. The streetlight data were obtained in a GIS format from the local power company and spatially joined to the intersections to determine how many were within 30 m (100 ft). The presence and type of turn restrictions were determined by brief field visits to each intersection.

Vehicle and Pedestrian Volume

The main source for vehicle and pedestrian volume data was the set of turning movement data supplied by CDOT. The city conducts 12-hour turning movement counts (7:00am – 7:00pm) of most intersections on a regular basis (approximately once every two or three years). The turning movement count broke down the movements on each leg to through, right, left, and pedestrian.

Vehicle Annual Average Daily Traffic (AADT) was calculated from an expansion of the 12-hour count. CDOT supplied a specific expansion factor for each intersection count. Years for which there was no count were filled by extrapolation. Percentage of right and left turns were calculated by dividing the number of turning vehicles by the total vehicles on the leg.

For intersections with no turning movement counts available, traffic volume data were obtained from the Metropolitan Planning Organization (MPO). The MPO regional network contained volumes on most major streets. The volumes were estimations based on vehicle trip generation and distribution. Approximately 3 percent of intersections had no turning movement count and relied on MPO traffic volume data.

Pedestrian daily volumes were also calculated from an expansion of the 12-hour count. There was no expansion factor for pedestrian volumes available from CDOT. Based on past research, the team used an expansion factor of 1.16 to convert a 12-hour pedestrian volume to a daily volume. Pedestrian volumes were not available for sites relying on MPO traffic volume data, and these sites were excluded from subsequent analyses.

The expansion factor for pedestrian volumes discussed above were based initially on a 1985 FHWA study by Zegeer et al. (10). As part of that study, there was a need to develop pedestrian volume expansion factors to adjust short-term pedestrian counts to pedestrian ADTs.

Since cities typically do not collect pedestrian volumes on a 24-hr basis, the only available counts were a large sample of pedestrian volume counts taken in Seattle, Washington, which were summarized by hour of the day and also by area type (e.g., CBD, fringe, and residential). The 1985 study used those data to compute pedestrian volume adjustment factors to allow for expanding shorter counts to approximate pedestrian volumes in a 24-hr basis. This pedestrian ADT expansion methodology was further refined, checked, and used in a 2005 FHWA study by Zegeer et al. (3). These adjustment factors are given and explained in detail on page 67 of the 2005 FHWA report.

Vehicle-Pedestrian Collision Data

Pedestrian crash data were obtained from CDOT in a GIS format. Crash data were available for a period of nine years from 1997 to 2005. Crashes had been manually geocoded by city staff. For most years, if a crash occurred within 30 m (100 ft) of an intersection, the crash was placed at the intersection (in GIS terms, the crash was said to be “snapped” to the intersection point). If a crash occurred farther than 30 m (100 ft) from an intersection, it was placed on the appropriate road segment.

Given this rough method of determining whether a crash was intersection-related, the team desired more accuracy. To this goal, crashes were matched to the records in the state pedestrian crash database. North Carolina has a detailed pedestrian and bicycle crash database that includes information such as crash typing, which gives further description of the pre-crash actions of each party. The state database was used to determine with more accuracy whether or not the crash was intersection-related. Unfortunately, crashes could not be matched by a unique identifier, so they had to be matched based on date and location (street names). Some crashes could not be matched to the state record in this manner. In these cases, the city specification of whether the crash was intersection-related was kept as the final rule.

Land Use and Demographic Characteristics

Data on land use and demographic characteristics of the area surrounding each intersection in Charlotte was assembled through analysis of planning data available in GIS format. The available data elements included:

- presence of bus stops within 300 m (1,000 ft) of the intersection
- presence of schools (either public or private) within 300 m (1,000 ft) of the intersection
- presence of parks within 300 m (1,000 ft) of the intersection
- number of alcohol sales establishments within 300 m (1,000 ft) of the intersection
- average per capita income of all census block groups within 300 m (1,000 ft) of the intersection
- number of square feet of buildings on commercial land parcels partially or entirely within 0.8 km (0.5 mi) of the intersection
- number of commercial structures on commercial land parcels within 0.8 km (0.5 mi) of the intersection

- number of commercial land parcels within 300 m (1,000 ft) of the intersection

ROADWAY SEGMENTS IN MINNESOTA

A database of vehicle-pedestrian collisions for roadway segments in Minnesota was available from the research performed in Phases I and II of this project (25). The database assembled for Phases I and II consisted of five years of crash data (1998-2002), including data for vehicle-pedestrian collisions. The roadway segment crash database includes all vehicle-pedestrian collisions on the roadway segments of interest that did not occur at an intersection and were not related to the operation of an intersection.

Table 11 presents the list of roadway segment characteristics included in the database developed for Phases I and II of the research. For the roadway segments located in the Minneapolis-St. Paul and St. Cloud metropolitan areas, the database from Phases I and II was expanded to include eight years (1998-2005) of vehicle-pedestrian collision data. The following land use and demographic variables were added to these data through a combination of on-line database and field reviews:

- Type of development (commercial/residential/mixed)
- Presence and location of schools within three blocks of the roadway segment
- Presence of school crossings within the roadway segment or at adjacent intersections
- Location and traffic control for school crossings
- Presence and location of parks within three blocks of the roadway segment
- Type of park facilities
- Number of alcohol sales establishments within roadway segment
- Number of bus stops within roadway segment or at adjacent intersections

TABLE 11. Site Characteristics Data Obtained for Roadway Segments on Urban and Suburban Arterials in Minnesota (25).

Data element	Description of data element	Primary source
Beginning landmark	Name of intersecting street or other landmark at beginning of block	Highway agency data or field review
Beginning milepost	Milepost or log mileage at beginning of block to tie field locations to accident data	Highway agency data
Bicycle route (marked)	Presence of bicycle route marked by signs	Field or videolog review
Bicycle facilities	Presence of bicycle facilities including sidepath, marked bicycle lane, or wide curb lane	Field or videolog review
Driveway locations	Location of driveway (side of road and distance from beginning of block)	Aerial photograph and field review
Driveway types	Each driveway was classified into one of seven categories (see accompanying text)	Aerial photograph and field review
Ending landmark	Name of intersecting street or other landmark at end of block	Highway agency data or field review

TABLE 11. Site Characteristics Data Obtained for Roadway Segments on Urban and Suburban Arterials in Minnesota (25) (Continued)

Data element	Description of data element	Primary source
Ending milepost	Milepost or log mileage at end of block to tie field locations to accident data	Highway agency data
Grade	Roadway grade within block (level, moderate, or steep)	Field or videolog review
Horizontal curve length	Length of horizontal curve (mi) computed from beginning and ending locations	Computed
Horizontal curve location	Distance of beginning and end of horizontal curve from beginning of block (mi)	Aerial photographs
Horizontal curve radius	Radius of horizontal curve (ft) measured on aerial photograph	Aerial photographs
Intersections	A basic data set was collected for the intersections at each end of each block including number of legs, side of road (for three-leg intersections), traffic control device, and type of pedestrian facilities (if any). This data set is less extensive than the data collected for the full intersection study sites.	Field or videolog review
Lane width	Width of through lanes (ft) not including gutters. Measured at first block in a series of consecutive blocks and points of change. Lane width is averaged over multiple lanes where present.	Field measurement
Length of site	Length of site (mi) from beginning landmark to end landmark. Measured from center of intersection where intersections are site boundaries.	Highway agency data
Lighting	Presence of street lighting (none, intersection only, or continuous lighting along street) and presence of other ambient lighting	Field review
Median opening location	Distance of median opening from beginning of block (mi). Applicable to divided streets only.	Aerial photograph or field review
Median opening type	Type of median opening (conventional/directional)	Aerial photograph or field review
Median type	Presence and type of median (none, raised, depressed, flush)	Field or videolog review
On-street parking	Presence and type of on-street parking (none, parallel parking, angle parking)	Field or videolog review
Pedestrian crosswalk (midblock)	Location and type of midblock crosswalk (if any)	Field or videolog review
Roadside hazard rating	Rating on 1 to 7 scale (see accompanying text)	Field or videolog review
Roadway type	Number of through lanes and divided undivided (2U, 3T, 4U, 4D, or 5T) as defined in Chapter 2 of this report.	Field or videolog review
Route number or street name	Route number or street name for arterial used to tie field locations to accident data	Highway agency data

TABLE 11. Site Characteristics Data Obtained for Roadway Segments on Urban and Suburban Arterials in Minnesota (25) (Continued)

Data element	Description of data element	Primary source
Shoulder type	Type of shoulder (paved, gravel, turf, composite) and presence/absence of curb. Determined separately for each side of the road.	Field or videolog review
Shoulder width	Width of shoulder (ft). Determined separately for each side of the road. Entered as zero for curbed sections.	Field measurement
Sidewalks	Presence/absence of sidewalk. Determined separately for each site of the road.	Field or videolog review
Speed limit	Posted speed limit (mph) or speed limit applicable under state law	Field or videolog review
Traffic volume	ADTs for each year of study period. Interpolated between count years when not available for every year.	Highway agency data

The major limitation of the Minnesota roadway segment data is that it includes traffic volume, but not pedestrian volume data.

DESCRIPTIVE STATISTICS FOR AVAILABLE DATABASES

Signalized Intersections

Table 12 summarizes the number of intersections, number of vehicle-pedestrian collisions, and exposure measures in the available databases for signalized intersections in Toronto and Charlotte. Data are tabulated separately for three-leg signalized (3SG) intersections and four-leg signalized (4SG) intersections.

Table 13 summarizes descriptive statistics for four key variables in the databases for intersections in Toronto and Charlotte. The key variables summarized in the table are:

- major-road ADT (veh/day)
- minor-road ADT (veh/day)
- total pedestrian volume crossing all intersection legs (pedestrians/day)
- maximum number of lanes crossed by pedestrians at intersection considering presence of refuge islands

Roadway Segments

Table 14 summarizes the number and length of roadway segments, number of vehicle-pedestrian collisions, and exposure measures in the available database for roadway segments in Minnesota. Data are tabulated separately for five types of roadway segments:

- two-lane undivided arterials (2U)
- three-lane arterials including a center two-way left-turn lane (TWLTL) (3T)
- four-lane undivided arterials (4U)
- four-lane divided arterials (i.e., including a raised or depressed median) (4D)
- five-lane arterials including a center TWLTL (5T)

TABLE 12. Number of Intersections, Number of Vehicle-Pedestrian Collisions, and Exposure Measures for Signalized Intersections in Toronto and Charlotte.

Intersection type	Number of intersections	Number of vehicle-pedestrian collisions	Average study period duration (years)	Total entering vehicles (100 millions)	Total crossing pedestrians (100 millions)	Vehicle-pedestrian collisions		
						per intersection per year	per 100 million entering vehicles	per 100 million crossing pedestrians
TORONTO								
3SG	366	681	6.72	209.5	7.8	0.28	3.25	87.5
4SG	1,166	4,530	6.89	1,223.0	53.5	0.56	3.70	84.7
CHARLOTTE								
3SG	84	47	8.02	65.1	0.1	0.07	0.72	597.3
4SG	267	294	8.28	262.0	1.4	0.13	1.12	204.7

TABLE 13. Descriptive Statistics for Key Data Elements at Signalized Intersections in Toronto and Charlotte.

Variable	3SG intersections					4SG intersections				
	Mean	Median	Standard deviation	Minimum value	Maximum value	Mean	Median	Standard deviation	Minimum value	Maximum value
TORONTO										
Major-road ADT (veh/day)	30,055	29,032	11,902	811	74,226	30,138	28,820	12,024	6,576	80,187
Minor-road ADT (veh/day)	6,562	4,709	6,599	152	51,412	11,570	8,726	9,299	164	49,100
Total pedestrian volume crossing all intersection legs (pedestrians/day)	867	309	1,291	0	12,548	1,823	898	3,210	1	34,129
Maximum number of lanes crossed by pedestrians at intersection considering presence of refuge islands	–	5	–	2	9	–	5	–	2	9
CHARLOTTE										
Major-road ADT (veh/day)	22,959	23,363	8,160	6,173	44,157	24,369	22,932	11,944	5,764	73,235
Minor-road ADT (veh/day)	7,025	5,219	5,215	79	21,695	8,096	6,162	6,866	371	43,481
Total pedestrian volume crossing all intersection legs (pedestrians/day)	32	17	55	0	398	178	51	556	0	6,002
Maximum number of lanes crossed by pedestrians at intersection considering presence of refuge islands	–	4	–	2	6	–	4	–	2	9

TABLE 14. Number and Length of Roadway Segments, Number of Vehicle-Pedestrian Collisions, and Exposure Measures for Minnesota Database.

Roadway segment type	Number of segments	Total length of segments (mi)	Number of vehicle-pedestrian collisions	Average study period duration (years)	Average vehicle ADT (veh/day)	Total veh-mi of travel (100 millions)	Vehicle-pedestrian collisions per mi per year	Vehicle-pedestrian collisions per 100 million veh-mi
2U	486	63.1	34	8	10,725	19.76	0.067	1.72
3T	169	18.7	15	8	13,462	7.35	0.100	2.04
4U	548	53.7	95	8	15,900	24.93	0.221	3.81
4D	273	41.8	45	8	28,932	35.31	0.135	1.27
5T	39	6.2	12	8	16,608	3.01	0.242	3.99

CHAPTER 4.

PEDESTRIAN SAFETY MODELING

This chapter presents the results for pedestrian safety modeling conducted with the available databases.

MODELS FOR SIGNALIZED INTERSECTIONS IN TORONTO

Candidate models in the following eight functional forms were considered:

$$N_{ped} = \exp(a + b \ln ADT_{maj} + c \ln ADT_{min} + d \ln PedVol) \quad (8)$$

$$N_{ped} = \exp(b \ln ADT_{maj} + c \ln ADT_{min} + d \ln PedVol) \quad (9)$$

$$N_{ped} = \exp(a + b \ln ADT_{maj} + c \ln ADT_{min} + d PedVol) \quad (10)$$

$$N_{ped} = \exp(b \ln ADT_{maj} + c \ln ADT_{min} + d PedVol) \quad (11)$$

$$N_{ped} = \exp\left(a + b \ln ADT_{tot} + c \ln \left(\frac{ADT_{min}}{ADT_{maj}}\right) + d PedVol\right) \quad (12)$$

$$N_{ped} = \exp\left(b \ln ADT_{tot} + c \ln \left(\frac{ADT_{min}}{ADT_{maj}}\right) + d PedVol\right) \quad (13)$$

$$N_{ped} = \exp\left(a + b \ln ADT_{tot} + c \ln \left(\frac{ADT_{min}}{ADT_{maj}}\right) + d \ln PedVol\right) \quad (14)$$

$$N_{ped} = \exp\left(b \ln ADT_{tot} + c \ln \left(\frac{ADT_{min}}{ADT_{maj}}\right) + d \ln PedVol\right) \quad (15)$$

where: N_{ped} = predicted number of vehicle-pedestrian collisions per year
 ADT_{maj} = average daily traffic volume (veh/day) for the major road
 ADT_{min} = average daily traffic volume (veh/day) for the minor road
 ADT_{tot} = $ADT_{maj} + ADT_{min}$

PedVol = sum of the daily pedestrian volumes crossing all intersection legs
(pedestrians/day)
a,b,c,d = regression coefficients

Table 15 illustrates the results obtained when the eight candidate model functional forms were applied to the data for three- and four-leg signalized intersections in Toronto. The models in which major-road ADT, minor-road ADT, and pedestrian volume were considered separately, as in Equations (8) through (11), generally showed that for three-leg signalized intersections, major-road ADT has an inverse effect on vehicle-pedestrian collisions and minor-road ADT and pedestrian volume both have direct effects. For four-leg signalized intersections, minor-road ADT and pedestrian volume have direct effects, while major-road ADT in most cases had an inverse effect on vehicle-pedestrian collisions. The statistical significance of the coefficients for pedestrian volume and minor-road ADT were always high; the relationship of major-road ADT to vehicle-pedestrian collisions was statistically significant, but was generally less strong (i.e., had a lower significance level) than did pedestrian volume or minor-road ADT. It seems natural that both vehicle and pedestrian volumes are related to the frequency of vehicle-pedestrian collisions and that, of these variables, pedestrian volume should have the strongest relationship.

The inverse relationship of major-road ADT to vehicle-pedestrian collisions was investigated further. It was found that, while major-road ADT had an inverse effect on vehicle-pedestrian collisions, the ratio of minor-road to major-road ADT had a direct effect. In other words, when the minor-road ADT is relatively small compared to the major-road ADT, there are relatively few pedestrian-related collisions. However, when the minor-road ADT is larger (e.g., approaching a magnitude to the major-road ADT), there are generally a substantial number of vehicle-pedestrian collisions. Thus, the functional forms shown in Equations (12) through (15), which incorporate the ratio of minor- to major-road ADT, tend to fit the data the best and exhibit direct relationships between all three independent variables and the frequency of vehicle-pedestrian collisions.

Equation (14) provides the most satisfactory model from among the alternative functional forms considered based on the goodness of fit of the models and the consistency of the observed effects of the independent variables with the expected effects. Table 16 presents the modeling results for the functional form shown in Equation (14). The goodness-of-fit measure, R_{LR}^2 , for these models is known as the likelihood ratio R^2 value. This value represents the extent to which the model explains more of the variation in the dependent variable (i.e., vehicle-pedestrian collisions) than an intercept-only model. Thus, the meaning of R_{LR}^2 differs from the meaning of R^2 for an ordinary least squares regression model which represents the proportion of the variation in the dependent variable which is explained by the model.

Several additional geometric design and traffic control variables were considered for addition to the models shown in Table 16. These additional variables are:

- maximum number of lanes crossed by a pedestrian on any intersection leg
- number of intersection legs with refuge islands

- maximum number of traffic lanes crossed by a pedestrian in any crossing maneuver at the intersection (considering presence of refuge islands)
- number of intersection legs with marked crosswalks
- presence of a skewed intersection leg

The only one of these independent variables that was statistically significant with an effect in the expected direction was the maximum number of lanes crossed by a pedestrian on any intersection leg (considering presence of refuge islands).

The resulting model incorporating maximum number of lanes crossed has the following functional form:

$$N_{\text{ped}} = \exp \left(a + b \ln \text{ADT}_{\text{tot}} + c \ln \left(\frac{\text{ADT}_{\text{min}}}{\text{ADT}_{\text{maj}}} \right) + d \ln \text{PedVol} + e n_{\text{lanesx}} \right) \quad (16)$$

where: n_{lanesx} = maximum number of lanes crossed by a pedestrian in any crossing maneuver at the intersection (considering presence of refuge islands)

Table 17 presents the results for models in the form shown in Equation (16). The model in this form is very appropriate for potential application in the HSM. The model for 4SG intersections had a better fit than the model for 3SG intersections. All of the coefficients for the 4SG model are statistically significant at the 90 percent confidence level. The goodness-of-fit measure, R_{LR}^2 , has a value of 0.46, indicating that the model explains substantially more of the variance in vehicle-pedestrian collision frequency than an intercept-only model. The results for this model indicate that the frequency of vehicle-pedestrian collisions increases with increasing pedestrian volume and with increasing total traffic volume. Vehicle-pedestrian collision frequencies also increase with the ratio of minor- to major-road traffic volume. As noted earlier, the frequency of vehicle-pedestrian collisions is highest when the minor- and major-road traffic volumes are nearly equal and is lowest when the minor-road traffic volume is much less than the major-road traffic volume.

The model for 4SG intersections also includes a statistically significant effect of the maximum number of traffic lanes that must be crossed by a pedestrian in any crossing maneuver at the intersection. This variable has been defined to include both through and turning lanes that must be crossed by a pedestrian and to consider the presence of refuge islands along the crossing path. If the crossing path is broken by an island that provides a suitable refuge for the pedestrian such that the crossing may be accomplished in two (or more) stages, then the number of lanes crossed in each stage is considered separately.

The model for 3SG intersections also has coefficients that are statistically significant at the 90 percent confidence level and has a goodness-of-fit measure, R_{LR}^2 equal to 0.23. While the goodness of fit is not as strong as for the 4SG-intersection model, the goodness of fit is still substantially better than an intercept-only model. The primary drawback of the model for 3SG intersections is that the coefficient for the total traffic volume term, while statistically significant, has a negative value. It appears counterintuitive to indicate that vehicle-pedestrian collisions would decrease as vehicle volumes increase.

TABLE 15. Models in Various Functional Forms for Vehicle-Pedestrian Collisions at Toronto Intersections.

Functional form in Equation	Regression coefficient (standard error)				Over-dispersion parameter (k)	R ² _{LR}
	a	b	c	d		
THREE-LEG SIGNALIZED INTERSECTIONS (3SG)^a						
(8)	-5.94 (1.45)	<i>-0.06 (0.12)</i>	0.20 (0.07)	0.5402 (0.0581)	0.50	0.25
(9)	-	<i>-0.51 (0.06)</i>	<i>0.10 (0.06)</i>	0.4738 (0.0566)	0.57	0.21
(10)	<i>-2.11 (1.46)</i>	<i>-0.12 (0.13)</i>	0.20 (0.07)	0.0003 (0.0001)	0.70	0.13
(11)	-	<i>-0.29 (0.05)</i>	0.16 (0.07)	0.0003 (0.0001)	0.71	0.13
(12)	<i>0.58 (1.80)</i>	<i>-0.16 (0.17)</i>	0.28 (0.07)	0.0003 (0.0001)	0.66	0.15
(13)	-	<i>-0.11 (0.01)</i>	0.28 (0.07)	0.0003 (0.0001)	0.66	0.15
(14)	<i>-3.84 (1.78)</i>	<i>-0.04 (0.16)</i>	0.25 (0.07)	0.5197 (0.0579)	0.48	0.26
(15)	-	<i>-0.38 (0.04)</i>	0.28 (0.07)	0.4804 (0.0548)	0.49	0.25
FOUR-LEG SIGNALIZED INTERSECTIONS (4SG)^b						
(8)	<i>-8.57 (0.57)</i>	0.11 (0.06)	0.37 (0.03)	0.4795 (0.0230)	0.22	0.48
(9)	-	<i>-0.66 (0.03)</i>	0.37 (0.03)	0.3868 (0.0237)	0.31	0.38
(10)	<i>-5.38 (0.62)</i>	<i>-0.03 (0.06)</i>	0.52 (0.03)	0.0001 (0.0000)	0.38	0.32
(11)	-	<i>-0.53 (0.03)</i>	0.51 (0.03)	0.0001 (0.0000)	0.43	0.27
(12)	<i>-5.71 (0.65)</i>	0.51 (0.06)	0.42 (0.03)	0.0001 (0.0000)	0.38	0.32
(13)	-	<i>-0.02 (0.01)</i>	0.51 (0.03)	0.0001 (0.0000)	0.43	0.27
(14)	<i>-8.82 (0.60)</i>	0.48 (0.05)	0.26 (0.03)	0.4768 (0.0230)	0.22	0.48
(15)	-	<i>-0.28 (0.02)</i>	0.43 (0.03)	0.3937 (0.0238)	0.32	0.38

NOTE: Coefficients shown in italics are not statistically significant at the 90% confidence level.

^a Based on data for 366 intersections.

^b Based on data for 1,166 intersections.

TABLE 16. Models for Vehicle-Pedestrian Collisions at Toronto Intersections.

Intersection type	No. of sites	Regression coefficient (standard error)				Over-dispersion parameter (k)	R_{LR}^2
		Intercept (a)	ADT _{tot} (b)	ADT _{min} /ADT _{maj} (c)	PedVol (d)		
3SG	366	-3.84 (1.78)	-0.04 (0.16) ^a	0.25 (0.07)	0.52 (0.06)	0.48	0.26
4SG	1,166	-8.82 (0.60)	0.48 (0.05)	0.26 (0.03)	0.48 (0.02)	0.22	0.48

NOTE: All models are in the form shown in Equation (14).

^a Coefficient is not statistically significant at the 90% confidence level.

TABLE 17. Models for Vehicle-Pedestrian Collisions at Toronto Intersections Including Term for Number of Lanes Crossed by Pedestrians.

Intersection type	No. of sites	Regression coefficient (standard error)					Over-dispersion parameter (k)	R^2_{LR}
		Intercept (a)	ADT _{tot} (b)	ADT _{min} /ADT _{maj} (c)	PedVol (d)	n_{lanesx} (e)		
3SG	366	-2.06 (1.82)	-0.32 (0.18)	0.30 (0.07)	0.54 (0.06)	0.20 (0.06)	0.44	0.28
4SG	1,166	-8.10 (0.67)	0.38 (0.07)	0.27 (0.03)	0.48 (0.02)	0.05 (0.02)	0.21	0.49

NOTE: All models are in the form shown in Equation (16).

The Toronto model for 4SG intersections shown in Table 17 could potentially be used in the HSM. The models for 3SG intersections in Table 17 would require further investigation because of the negative coefficient for total traffic volume.

The model forms discussed above were applied to predict vehicle-pedestrian collisions for each intersection as a whole. Consideration was given to predicting vehicle-pedestrian collisions for individual intersection legs using traffic volumes, pedestrian volumes, and other characteristics of those intersection legs, but preliminary investigation found that the vehicle-pedestrian collision data by leg were too sparse to provide useful models.

MODELS FOR CHARLOTTE INTERSECTIONS

Tables 18 through 20 present modeling results for Charlotte intersections that are analogous to the results for Toronto intersections shown in Tables 15 through 17, respectively. The models in Table 18 show predictive relationships for Charlotte intersections for the functional forms in Equations (8) through (15). As in Toronto, the models with the best fit appear to be those for the functional form shown in Equation (14). Table 19 shows the Charlotte models in this functional form. With the exception of the pedestrian volume coefficient for 4SG intersections, neither the 3SG- or 4SG-intersection models shown in Table 19 have coefficients that are statistically significant at the 90 percent confidence level. Similarly, the Charlotte models shown in Table 20 for the functional form in Equation (16) consist primarily of coefficients that are not statistically significant at the 90 percent confidence level. This result is not unexpected because both the pedestrian volumes and the vehicle-pedestrian collision frequencies are substantially lower for Charlotte than for Toronto. Also, given the smaller sample sizes for the Charlotte intersections, it is much more difficult to find statistically significant effects for vehicle and pedestrian volumes.

COMBINED MODELS FOR TORONTO AND CHARLOTTE INTERSECTIONS

The Toronto and Charlotte databases were further combined to obtain a more widely applicable pedestrian accident model at intersections (in other words, a model not specific to just the Toronto and Charlotte areas). A random city factor was added to the model to account for potential differences between the two cities. This random effect was found not to be significant and the random city effect was then removed from the model estimation. The final models selected for the two intersection types are presented in Table 21.

The model for 4SG intersections developed with the combined Toronto and Charlotte data and presented in Table 21 appears appropriate for use in the HSM. All of the coefficients are statistically significant at the 90 percent confidence level and the goodness-of-fit measure, R_{LR}^2 , equal to 0.52 is the highest of any of the models developed.

Models for 3SG intersections developed with the combined Toronto and Charlotte data suffered from the same problem of a negative coefficient for total traffic volume as the model for 3SG intersections shown in Table 17. Further investigation found that the negative coefficient

may result from multi-colinearity or correlation between the total traffic volume term (ADT_{tot}) and the maximum number of lanes crossed term (n_{lanesx}). Two alternative approaches to resolving this issue were considered, resulting in the two alternative models shown for 3SG intersections in Table 21. The Alternative 1 model for 3SG intersections omits the total traffic volume term. All of the remaining coefficients for this model are statistically significant. The drawback to the Alternative 1 model is that a model lacking the total traffic volume term does not show any change in vehicle-pedestrian collisions as traffic volumes increase or decrease, as would be expected.

A further investigation was performed to determine how large the coefficient of total traffic volume could be made while maintaining the statistical significance of the other model terms, and especially the term for maximum lanes crossed at the 90 percent confidence level. The largest such coefficient for the total traffic volume term was found to be 0.05. A model for 3SG intersections fitted to the combined Toronto and Charlotte data, but including this 0.05 coefficient value, is shown as Alternative 2 in Table 21. It can be seen that the Alternative 2 model has a different intercept, but virtually the same coefficient values for other variables, as the Alternative 1 model. All of the coefficients in the Alternative 2 model are statistically significant at the 90% confidence level and the goodness-of-fit measure, R_{LR}^2 , equal to 0.27 indicates that the model explains substantially more of the variance in vehicle-pedestrian collision frequency than an intercept-only model. This Alternative 2 model appears to be the best choice for application to 3SG intersections in the HSM.

BASE MODELS FOR SIGNALIZED INTERSECTIONS

The base models for signalized intersections for use in the HSM are the model for 4SG intersections and the Alternative 2 model for 3SG intersections presented in Table 21, which use the functional form shown in Equation (16). Specifically, the recommended model for 3SG intersections is:

$$N_{ped} = \exp \left(-5.02 + 0.05 \ln ADT_{tot} + 0.24 \ln \left(\frac{ADT_{min}}{ADT_{maj}} \right) + 0.41 \ln PedVol + 0.09 n_{lanesx} \right) \quad (17)$$

The recommended model for 4SG intersections is:

$$N_{ped} = \exp \left(-7.95 + 0.40 \ln ADT_{tot} + 0.26 \ln \left(\frac{ADT_{min}}{ADT_{maj}} \right) + 0.45 \ln PedVol + 0.04 n_{lanesx} \right) \quad (18)$$

TABLE 18. Models in Various Functional Forms for Vehicle-Pedestrian Collisions at Charlotte Intersections.

Functional form in Equation	Regression coefficient (standard error)				Over-dispersion parameter (k)	R ² _{LR}
	a	b	c	d		
THREE-LEG SIGNALIZED INTERSECTIONS (3SG)^a						
(8)	-10.53 (6.51)	<i>0.87 (0.64)</i>	<i>-0.14 (0.25)</i>	<i>0.1053 (0.0951)</i>	1.69	0.04
(9)	-	-	<i>-0.09 (0.22)</i>	<i>-0.23 (0.25)</i>	1.85	0.01
(10)	-11.34 (6.38)	<i>0.88 (0.62)</i>	<i>-0.05 (0.24)</i>	0.0064 (0.0035)	1.49	0.07
(11)	-	-	<i>-0.15 (0.21)</i>	<i>-0.16 (0.24)</i>	1.68	0.03
(12)	-10.73 (6.77)	<i>0.72 (0.65)</i>	<i>-0.16 (0.24)</i>	0.0064 (0.0036)	1.52	0.07
(13)	-	-	<i>-0.30 (0.04)</i>	<i>-0.11 (0.24)</i>	1.66	0.04
(14)	-9.69 (6.91)	<i>0.62 (0.67)</i>	<i>-0.24 (0.25)</i>	<i>0.1045 (0.0952)</i>	1.72	0.04
(15)	-	-	<i>-0.31 (0.04)</i>	<i>0.1066 (0.0960)</i>	1.83	0.02
FOUR-LEG SIGNALIZED INTERSECTIONS (4SG)^b						
(8)	-5.16 (1.98)	<i>0.04 (0.20)</i>	<i>0.15 (0.11)</i>	0.3359 (0.0530)	0.96	0.16
(9)	-	-	<i>-0.41 (0.10)</i>	0.3097 (0.0517)	1.06	0.14
(10)	-4.73 (2.11)	<i>0.09 (0.21)</i>	<i>0.19 (0.12)</i>	0.0006 (0.0002)	1.36	0.05
(11)	-	-	<i>-0.33 (0.10)</i>	0.0005 (0.0002)	1.43	0.03
(12)	-4.84 (2.23)	<i>0.27 (0.21)</i>	<i>0.14 (0.11)</i>	0.0006 (0.0002)	1.36	0.05
(13)	-	-	<i>-0.19 (0.02)</i>	<i>0.0005 (0.0002)</i>	1.43	0.04
(14)	-5.16 (2.09)	<i>0.18 (0.20)</i>	<i>0.11 (0.11)</i>	0.3354 (0.0503)	0.96	0.16
(15)	-	-	<i>-0.30 (0.03)</i>	0.3115 (0.0517)	1.05	0.14

NOTE: Coefficients shown in italics are not statistically significant at the 90% confidence level.

^a Based on data for 84 intersections.

^b Based on data for 267 intersections.

TABLE 19. Models for Vehicle-Pedestrian Collisions at Charlotte Intersections.

Intersection type	No. of sites	Regression coefficient (standard error)				Over-dispersion parameter (k)	R ² _{LR}
		Intercept (a)	ADT _{tot} (b)	ADT _{min} /ADT _{maj} (c)	Ped Vol (d)		
3SG	84	-9.69 (6.91) ^a	0.62 (0.67) ^a	-0.24 (0.25) ^a	0.10 (0.10) ^a	1.72	0.04
4SG	267	-5.16 (2.09)	0.18 (0.20) ^a	0.11 (0.11) ^a	0.34 (0.05)	0.96	0.16

NOTE: All models are in the form shown in Equation (14).

^a Coefficient is not statistically significant at the 90% confidence level.

TABLE 20. Models for Vehicle-Pedestrian Collisions at Charlotte Intersections Including Term for Number of Lanes Crossed by Pedestrians.

Intersection type	No. of sites	Regression coefficient (standard error)					Over-dispersion parameter (k)	R^2_{LR}
		Intercept (a)	ADT _{tot} (b)	ADT _{min} /ADT _{maj} (c)	PedVol (d)	n _{lanesx} (e)		
3SG	84	-10.58 (6.98) ^a	0.78 (0.70) ^a	-0.20 (0.25) ^a	0.11 (0.10) ^a	-0.18 (0.27) ^a	1.66	0.04
4SG	267	-5.43 (2.10)	0.26 (0.21) ^a	0.14 (0.11) ^a	0.33 (0.05)	-0.11 (0.11) ^a	0.95	0.16

NOTE: All models are in the form shown in Equation (16).

^a Coefficient is not statistically significant at the 90% confidence level.

TABLE 21. Models for Vehicle-Pedestrian Collisions From Combined Data for Toronto and Charlotte Intersections.

Intersection type	No. of sites	Regression coefficient (standard error)					Over-dispersion parameter (k)	R^2_{LR}
		Intercept (a)	ADT _{tot} (b)	ADT _{min} /ADT _{maj} (c)	Ped Vol (d)	n_{lanesx} (e)		
3SG (Alt 1)	450	-4.04 (0.36)	–	0.25 (0.06)	0.41 (0.04)	0.10 (0.05)	0.52	0.28
3SG (Alt 2)	450	-5.02 (0.36)	0.05	0.24 (0.06)	0.41 (0.04)	0.09 (0.05)	0.52	0.27
4SG	1,433	-7.95 (0.61)	0.40 (0.06)	0.26 (0.03)	0.45 (0.02)	0.04 (0.02)	0.24	0.52

NOTE: All models are in the form shown in Equation (16).

EFFECTS OF LAND USE AND DEMOGRAPHIC VARIABLES FOR SIGNALIZED INTERSECTIONS

Basic Modeling With Data for Charlotte Intersections

Data were available in Charlotte, but not in Toronto, for a range of land use and demographic variables including:

- presence of bus stops within 300 m (1,000 ft) of the intersection
- presence of schools (either public or private) with 300 m (1,000 ft) of the intersection
- presence of parks within 300 m (1,000 ft) of the intersection
- number of alcohol sales establishments within 300 m (1,000 ft) of the intersection
- average per capita income of all census block groups within 300 m (1,000 ft) of the intersection
- number of square feet of buildings on commercial land parcels partially or entirely within 0.8 km (0.5 mi) of the intersection
- number of commercial structures on commercial land parcels within 0.8 km (0.5 mi) of the intersection
- number of commercial land parcels within 300 m (1,000 ft) of the intersection

A preliminary investigation of these data was conducted with the Charlotte data for 3SG and 4SG intersections. Of the land use and demographic variables considered, the ones that were found to have a statistically significant relationship to vehicle-pedestrian collisions are:

- presence of bus stops within 300 m (1,000 ft) of the intersection (for 4SG intersections only)
- presence of schools (either public or private) within 300 m (1,000 ft) of the intersection (at 80 percent confidence level for 4SG intersections only)
- number of alcohol sales establishments within 300 m (1,000 ft) of the intersection (for 4SG intersections only)
- average per capita income of all census block groups within 300 m (1,000 ft) of the intersection (higher income levels are associated with fewer crashes) (for both 3SG and 4SG intersections)
- number of commercial structures on commercial land parcels within 0.8 km (0.5 mi) of the intersection (for 4SG intersections only)

To further explore the effects of these land use and demographic variables on pedestrian safety, the model for 4SG intersections presented in Table 21 was expanded to include the variables listed above one at a time. The coefficients in the combined base model were fixed and the coefficients of each of the additional land use and demographic variables was estimated. This analysis was limited to 4SG intersections because the preliminary analysis results found few statistically significant effects for land use and demographic variables at 3SG intersections,

probably due to limited sample sizes and low accident counts. The results of the analysis for 4SG intersections in Charlotte are presented in Table 22. Accident modification factors (AMFs) were developed based on the results shown in Table 22 for number of bus stops, presence of schools, number of alcohol sales establishments, and neighborhood income level. No AMF was developed for presence of parks within 300 m (1,000 ft) of the intersection because the effect found was in a counterintuitive direction with fewer vehicle-pedestrian collisions at intersections near parks. No AMF was developed for commercial structures because the wide radius considered around the intersection, 0.8 km (0.5 mi), would make the AMF impractical to apply.

The effect of alcohol sales establishments was determined in categories of zero, one to eight, and nine or more establishments within 300 m (1,000 ft) of an intersection. Table 22 indicates that the effect of this variable for one to eight establishments was not statistically significant, while the effect for nine or more establishments was statistically significant at the 80% confidence level. An AMF is provided for this effect because, overall, the alcohol sales establishment effect is statistically significant at the 84% confidence level. An AMF based on a continuous linear relationship between vehicle-pedestrian collisions and the number of alcohol sales establishments was considered, but was not used because this effect was not statistically significant as a continuous function.

Accident Modification Factors

The results shown in Table 22 have been expressed as accident modification factors (AMFs) for use in the HSM safety prediction methodology. Four AMFs are presented below; three of these AMFs are recommended for use in the HSM methodology.

Number of Bus Stops Near an Intersection

An AMF for bus stops, based on the regression coefficients in Table 22, can be presented as follows:

Number of bus stops within 300 m (1,000 ft) of the intersection	AMF
0	1.00
1 or 2	2.78
3 or more	4.15

To use this AMF, the base models shown in Equations (17) and (18) must be multiplied by 0.289. This multiplier translates the base model so that it corresponds to the base condition without bus stops.

While no explicit effect of bus stops on pedestrian safety has been reported previously, Burner and Clifton (34) reported that pedestrian crash risk increases with transit accessibility and Hess (41) and Vernez-Moudon (42) reported that pedestrian crash risk increases with the number of transit uses within an area.

TABLE 22. Effects of Land Use and Demographic Variables for Charlotte Intersections Added to the 4SG Model Shown in Table 21.

Land use or demographic variable	Level	Regression coefficient (standard error)	Chi Sq	P _r > Chi Sq	Significant at 90% level?
Number of bus stops	0	– –	–	–	–
	1-2	1.0222 (0.57)	3.27	0.0707	Yes
	3 or more	1.4242 (0.50)	8.20	0.0042	Yes
Presence of schools	–	0.2963 (0.23)	1.64	0.1998	No ^a
Presence of parks	–	–0.3324 (0.24)	1.78	0.1822	No ^a
Number of alcohol sales establishments	0	– –	–	–	–
	1-8	0.1151 (0.23)	0.26	0.6122	No
	9 or more	0.4413 (0.31)	1.97	0.1601	No ^a
Neighborhood average per capita income	–	–0.0301 (0.008)	15.25	0.0001	Yes
Number of commercial structures	–	0.0280 (0.009)	10.38	0.0013	Yes

^a Statistically significant at 80% level.

Schools Near an Intersection

An AMF for intersections near schools, based on the regression coefficients in Table 22, can be presented as follows:

Presence of school within 300 m (1,000 ft) of the intersection	AMF
No school present	1.00
School present	1.35

To use this AMF, the base models shown in Equations (17) and (18) should be multiplied by 1.005. This multiplier translates the base model so that it corresponds to the base condition with no nearby school.

Alcohol Sales Establishments Near an Intersection

An AMF for intersections near alcohol sales establishments based on the regression coefficients in Table 22 can be presented as follows:

Number of alcohol sales establishments within 300 m (1,000 ft) of the intersection	AMF
0	1.00
1-8	1.12
9 or more	1.56

To use this AMF, the base models shown in Equations (17) and (18) should be multiplied by 0.931. This multiplier translates the base model so that it corresponds to the base condition with no nearby alcohol sales establishments.

This AMF confirms a relationship observed by LaScala (36, 38) (see Table 9).

Neighborhood Income Level

An AMF for intersections based on the per capita income for all census block groups within 300 m (1,000 ft) of the intersection was considered for inclusion in the HSM methodology. This AMF would have taken the following form based on Table 22:

$$AMF_{inc} = \exp(-0.000030 (pci-25000)) \quad (19)$$

where:

- AMF_{inc} = accident modification factor for pedestrian safety at intersections based on per capita income for the neighborhood
- pci = average per capita income for all census block groups within 300 m (1,000 ft) of the intersection

In applying this AMF, pci should be limited to the range from \$9,000 to \$85,000, which is the range of average per capita income in the data used to develop this relationship. This will result in a maximum range of AMFs from 0.17 to 1.62.

The direction of the effect for this AMF confirms a relationship observed by Burnier and Clifton (34) (see Table 9). However, the magnitude of the effect is larger than would be expected if this truly represented an effect of pedestrian behavior alone. It is likely that this effect reflects, in part, an influence of neighborhood income level on pedestrian volume. Therefore, a decision was made not to include the neighborhood income level AMF in the HSM methodology.

Other AMFs

Consideration was given to adapting some of the findings reported in the literature (see Chapter 2 of this report) for use as AMFs. However, no satisfactory AMFs were found. In summary, while the direction of the effect of many factors on pedestrian safety is known from the literature, their effects have not been sufficiently quantified for incorporation in a predictive methodology.

Adjustment of Base Model

The base model adjustments shown above for each AMF should be combined as follows:

$$(0.289) (1.005) (0.931) = 0.270$$

Combining the base model adjustments in this way involves the assumption that the effects of the AMFs are independent. This assumption has been made for all AMFs used in the HSM.

FINAL BASE MODELS ADJUSTED FOR AMFS

With the adjustments for the AMFs presented above, the base model for 3SG intersections should be modified as follows:

$$N_{ped} = 0.270 \exp \left(-5.02 + 0.05 \ln ADT_{tot} + 0.24 \ln \left(\frac{ADT_{min}}{ADT_{maj}} \right) + 0.41 \ln PedVol + 0.09 n_{lanes} \right) \quad (20)$$

The base model for 4SG intersections should be similarly modified as:

$$N_{ped} = 0.270 \exp \left(-7.95 + 0.40 \ln ADT_{tot} + 0.26 \ln \left(\frac{ADT_{min}}{ADT_{maj}} \right) + 0.45 \ln PedVol + 0.04 n_{lanes} \right) \quad (21)$$

These base models can be simplified by moving the 0.270 adjustment inside the exponential function and combining it with the intercept term. In this final form, the base model for 3SG intersections is:

$$N_{\text{ped}} = \exp \left(-6.60 + 0.05 \ln \text{ADT}_{\text{tot}} + 0.24 \ln \left(\frac{\text{ADT}_{\text{min}}}{\text{ADT}_{\text{maj}}} \right) + 0.41 \ln \text{PedVol} + 0.09 n_{\text{lanesx}} \right) \quad (22)$$

Similarly, the base model for 4SG intersections in final form is:

$$N_{\text{ped}} = \exp \left(-9.53 + 0.40 \ln \text{ADT}_{\text{tot}} + 0.26 \ln \left(\frac{\text{ADT}_{\text{min}}}{\text{ADT}_{\text{maj}}} \right) + 0.45 \ln \text{PedVol} + 0.04 n_{\text{lanesx}} \right) \quad (23)$$

These base models apply to signalized intersections with the following base conditions:

- no bus stops within 300 m (1,000 ft) of the intersection
- no schools within 300 m (1,000 ft) of the intersection
- no alcohol sales establishments within 300 m (1,000 ft) of the intersection
- average per capita income of \$25,000 for the surrounding neighborhood

Figure 1 illustrates the sensitivity of vehicle-pedestrian collision frequency to each parameter in the model for 3SG intersections shown in Equation (22). The vertical axis in each sensitivity plot is the expected annual vehicle-pedestrian collision frequency, N_{ped} (collisions/intersection/year). The first plot in the figure shows the sensitivity of collision frequency to pedestrian crossing volume, PedVol (pedestrians/day), for specific values of the maximum number of lanes crossed at an intersection. The middle row of plots show the sensitivity of vehicle-pedestrian collision frequency to traffic volume ratio, $\text{ADT}_{\text{min}}/\text{ADT}_{\text{maj}}$ for two representative values of PedVol, a low activity level (20 pedestrians/day) and a medium-high activity level (750 pedestrians/day). The bottom row of plots shows that for the same two values of PedVol, there is very little sensitivity of vehicle-pedestrian collision frequency to total traffic volume, ADT_{tot} . This low sensitivity results from the small coefficient value (0.05) for the ADT_{tot} term.

Figure 2 illustrates a sensitivity analysis analogous to Figure 1 for the model for 4SG intersections shown in Equation (23). The sensitivity plots were prepared for representative values for PedVol for 4SG intersections, including a low activity level (50 pedestrians/day) and a medium-high activity level (1,500 pedestrians/day). These pedestrian activity levels for 4SG intersections are higher than those observed for 3SG intersections. The coefficient of the ADT_{tot} term (0.40) in the base model for 4SG intersections is substantially higher than the coefficient for 3SG intersections, as illustrated by the greater sensitivity shown in the plots in the bottom row of Figure 2.

MODELS FOR ROADWAY SEGMENTS

The use of the Minnesota roadway segment database to develop a replacement for pedestrian safety adjustment factor [see Equation (6) and Table 8] used in the current draft of HSM Chapter 12 was explored. This was recognized as a substantial challenge because of the lack of pedestrian volume data. Further analyses confirmed that divided roadways have lower vehicle-pedestrian collision frequencies than undivided roadways, presumably because of the presence of a median that can serve as a refuge for pedestrians crossing the arterial. However, as expected, given the lack of pedestrian volume data, no alternative methodology could be developed.

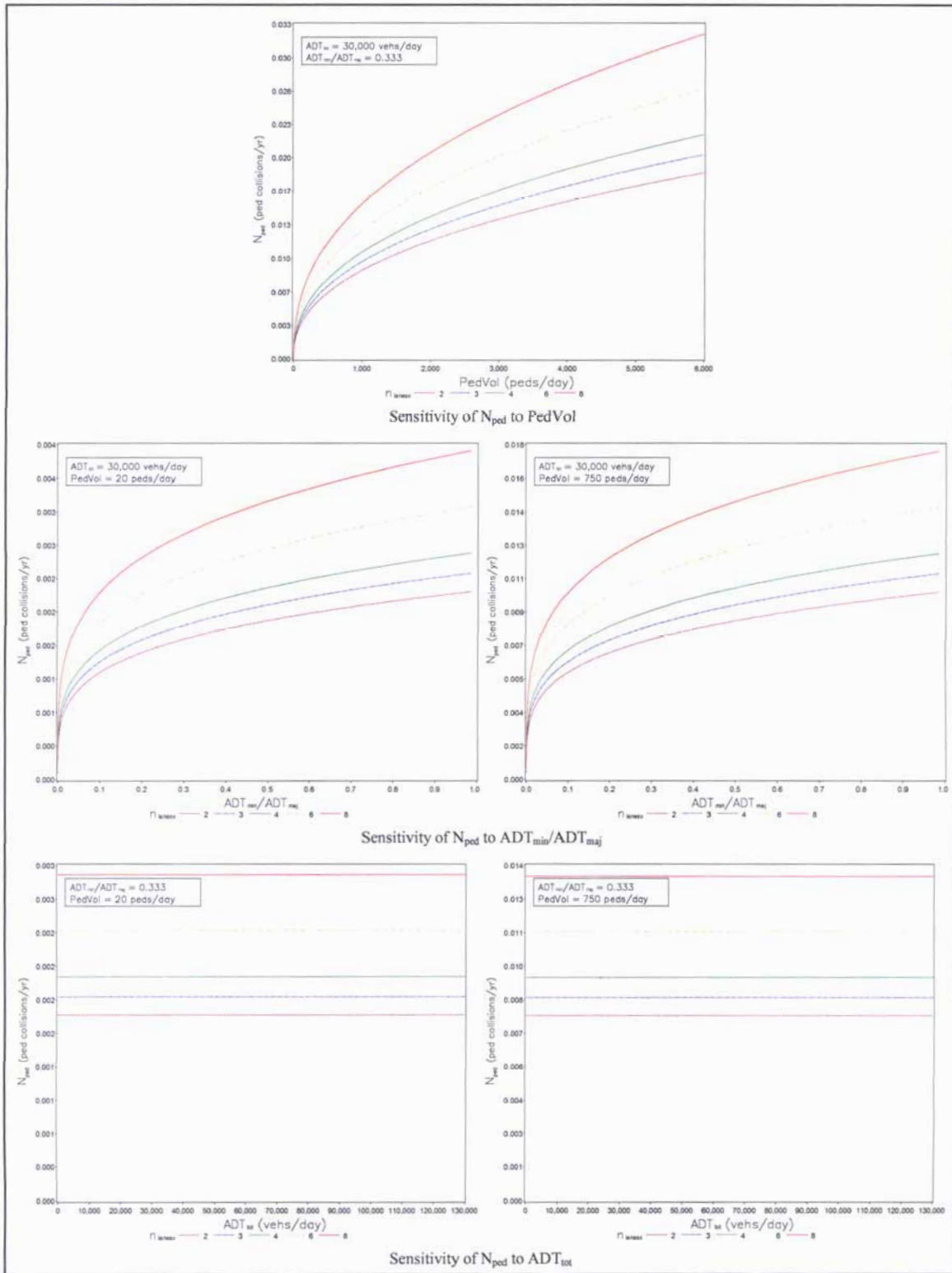


Figure 1. Sensitivity analysis of pedestrian safety base models for 3SG intersections.

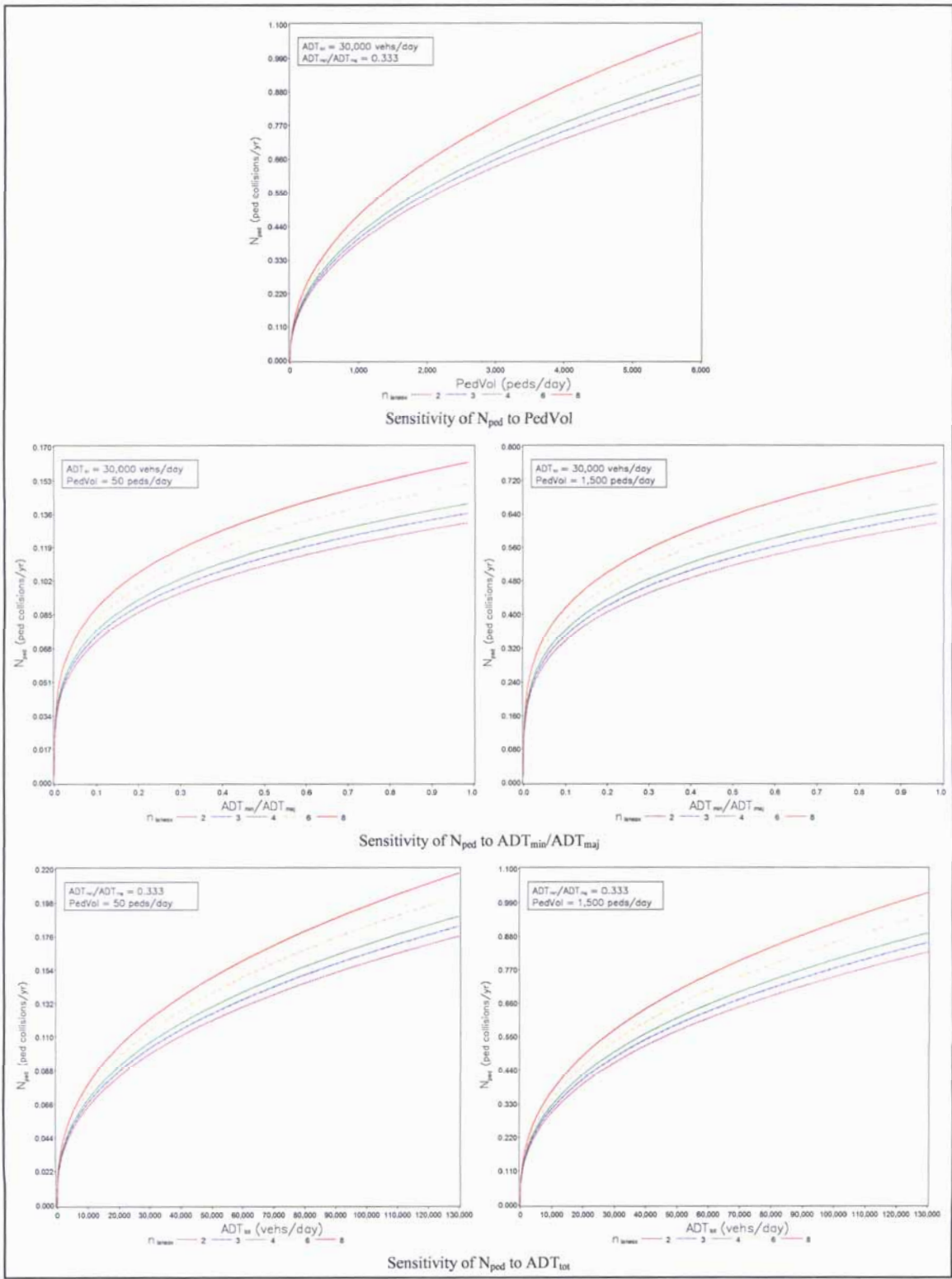


Figure 2. Sensitivity analysis of pedestrian safety base models for 4SG intersections.

CHAPTER 5.

RECOMMENDED HSM METHODOLOGY

This chapter summarizes the recommended pedestrian safety prediction methodology for application in HSM Chapter 12 (formerly designated as HSM Chapter 10).

SIGNALIZED INTERSECTIONS

A revised methodology for predicting pedestrian safety at signalized intersections has been developed to replace the current methodology (25) that is based on Equation (3) and Table 7. The recommended methodology includes base models for 3SG and 4SG intersections shown in Equations (20) and (21), respectively. The recommended methodology also includes AMFs for bus stops, schools, and alcohol sales establishments presented in Chapter 4 of this report. While these AMFs were developed for 4SG intersections, it appears reasonable to assume that these same AMFs can be applied to 3SG intersections, as well. In other words, it is presumed that similar pedestrian behavior would be observed at both 3SG and 4SG intersections, but that statistically significant relationships for 3SG intersections were not found because of the low vehicle-pedestrian frequencies at 3SG intersections.

It is anticipated that not all HSM users will have pedestrian volume counts available for signalized intersection to which the HSM methodology will be applied. Table 23 provides guidance on the estimation of specific pedestrian volumes for signalized intersections with general pedestrian activity levels. The pedestrian volumes estimates in the table represent the sum of all daily pedestrian crossing volumes at an intersection and are based on percentiles of the combined pedestrian crossing volume data for the Toronto and Charlotte intersections, as follows:

General pedestrian activity level	Pedestrian volume percentile in combined Toronto and Charlotte data
High	90 th percentile
Medium-high	75 th percentile
Medium	50 th percentile
Low-medium	25 th percentile
Low	10 th percentile

The pedestrian volume estimates in Table 23 may be calibrated by individual highway agencies to match their local conditions.

Table 23. Guidelines for Estimating Pedestrian Crossing Volumes Based on General Pedestrian Activity Levels

General pedestrian activity level	Estimated pedestrian crossing volume (pedestrians/day)	
	3SG intersections	4SG intersections
High	1,700	3,200
Medium-high	750	1,500
Medium	400	700
Low-medium	120	240
Low	20	50

NOTE: Estimated pedestrian crossing volumes are based on the distribution of intersections in the combined data sets for Toronto and Charlotte. The estimated pedestrian crossing volume represents the sum of the pedestrian crossing volumes for all intersection legs.

UNSIGNALIZED INTERSECTIONS

The unsignalized intersection methodology in the second draft of HSM Chapter 12 (25), based on Equation (3) in this report, and the factors for three-leg STOP-controlled (3ST) and four-leg STOP-controlled (4ST) intersections presented in Table 7 of this report, should remain unchanged.

ROADWAY SEGMENTS

The roadway segment methodology in the second draft of HSM Chapter 12 (25), based on Equation (6) in this report and the factors for roadway segments presented in Table 8 in this report, should remain unchanged.

CALIBRATION

Calibration issues for the HSM methodologies are being addressed as part of the HSM production work in NCHRP Project 17-36. Therefore, no specific calibration methodology has been included in the draft HSM chapter. A decision will need to be reached in Project 17-36 as to whether the pedestrian safety methodology for signalized intersections developed as part of this research will be calibrated separately or will be calibrated as shown in Equation (1) as part of the overall predictive methodology.

REVISED HSM DRAFT

The second draft of HSM Chapter 12, presented in the Phase I and II report for this research (25), has been revised to incorporate the changes to pedestrian safety prediction methodology for signalized intersections presented above. A third draft of HSM Chapter 12 incorporating the pedestrian safety prediction methodology was presented in the draft version of this report. This third draft has been further revised in response to review comments and a fourth draft of HSM Chapter 12 is presented in Appendix A of this report.

In addition to incorporating the revised pedestrian safety methodology, the fourth draft of HSM Chapter 12 has been updated in response to review comments on the earlier drafts. All comments from the NCHRP project panel and many comments from other reviewers have been considered. Some comments raise issues beyond the scope of this research or that need to be handled in coordination with other HSM chapters. In particular, there are several issues that need to be addressed consistently across the three predictive methodologies in HSM Chapters 10, 11, and 12. These issues will need to be addressed in the HSM production work in NCHRP Project 17-36.

CHAPTER 6.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of the research are as follows:

1. A prediction methodology for vehicle-pedestrian collisions at signalized intersections has been developed. This methodology includes base models for three- and four-leg signalized intersections, presented in Equations (22) and (23), respectively, and AMFs presented in Chapter 4 of this report.
2. The variables whose effects on vehicle-pedestrian collisions are incorporated in the base models include:
 - total traffic volume expressed as vehicles/day (sum of major- and minor-road ADTs)
 - ratio of minor-road ADT to major-road ADT
 - pedestrian volume expressed as pedestrians/day
 - maximum number of traffic lanes crossed by a pedestrian in any crossing maneuver at the intersection (considering presence of refuge islands)
3. AMFs for vehicle-pedestrian collisions have been developed for the following variables:
 - presence of bus stops within 300 m (1,000 ft) of the intersection
 - presence of schools (either public or private) within 300 m (1,000 ft) of the intersection
 - number of alcohol sales establishments within 300 m (1,000 ft) of the intersection
4. Daily pedestrian crossing volume has a statistically significant relationship to vehicle-pedestrian collisions at signalized intersections.
5. Vehicle volumes are also statistically significant predictors of vehicle-pedestrian collisions at signalized intersections. In particular, vehicle-pedestrian collision frequency is highest when the ratio of minor-road traffic volume to major-road traffic volume is highest.
6. The maximum number of lanes crossed by a pedestrian in any crossing maneuver at a signalized intersection (considering the presence of refuge islands) is a statistically significant predictor of the frequency of vehicle-pedestrian collisions, with higher collision frequencies at intersections where more lanes must be crossed.
7. The prediction methodology for vehicle-pedestrian collisions at signalized intersections has been incorporated in a fourth draft of the HSM Chapter 12 (urban and suburban arterials) presented in Appendix A of this report. This draft should be considered in NCHRP Project 17-36 for inclusion in the HSM.

8. Further research to extend and improve the pedestrian safety prediction methodology for signalized intersections presented in this report is recommended. In particular, it would be desirable to quantify the effect on safety of providing pedestrian signals. The effects on pedestrian safety of signal timing and right-turn-on-red operation which appear in the literature to be small or inconclusive should be clarified.
9. The pedestrian safety prediction methodology should be extended to address unsignalized intersections and roadway segments. Such research will require either extensive databases that contain pedestrian volume data or the development of models to estimate pedestrian volumes from land-use and demographic data.

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Appendix A—Draft Version of HSM Chapter 10 can be provided upon request to NCHRP.