Crash Modification Factor for Corner Radius, Right-Turn Speed, and Prediction of Pedestrian Crashes at Signalized Intersections

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FOREWORD

In the last decade, the number of pedestrian fatalities has increased even as overall traffic fatalities have increased. The objective of this project was to determine the safety effectiveness of low- to medium-cost pedestrian engineering countermeasures in reducing nonmotorist fatalities and injuries at controlled and uncontrolled intersections. Expanding the availability of robust crash modification factors (CMFs) can aid in the implementation of valuable countermeasures for addressing pedestrian crashes. The findings from the study supported the development of a CMF for corner radius, as well as the establishment of a predictive model for vehicle right-turn speed based on corner geometry. This report details the method and results of this study.

This report may be of interest to transportation practitioners, those conducting transportation safety research, industry, and those working to improve transportation safety.

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16. Abstract This project investigated the influence of intersection corner radius on pedestrian crashes and right-turn vehicle speed. The corner radius can be unique to each corner at an intersection; therefore, this study assigned crashes to an intersection corner rather than to the entire intersection. For corner-level pedestrian crashes, the following variables were found to be positively related: pedestrian volume on the approach leg, pedestrian volume on the receiving leg, vehicle volume on the approach leg, vehicle volume on the receiving leg, corner radius, and shoulder width. The number of pedestrian crashes was higher when both legs at a corner were one-way streets with traffic moving away from the corner or when there was a mix of two-way and one-way operations present at the intersection. Fewer pedestrian crashes occurred when on-street parking existed on the approach leg. The findings from the study support the development of a crash modification factor (CMF) for corner radius. Assuming a baseline condition of 10 ft, the pedestrian CMFs for corner radius for the range of corner radii included in the evaluation went from 1.00 for a 10-ft radius to 1.59 for a 70-ft radius. In the operational analysis, right-turn speeds were found to be a function of corner radius. Other variables that influenced right-turn speed included headway to the preceding vehicle, traffic signal indication (yellow versus green), turning vehicle type (car or truck), and preceding vehicle movement (straight or right). The final selected model from this study can be used to predict turning speeds at different percentile levels. For example, the model can predict 50th or 85th percentile speeds. The findings from this study can also be used to update the discussion contained in design manuals, especially with respect to designing intersections.		
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AADP	annual average daily pedestrians
AADT	annual average daily traffic
AIC	Akaike information criterion
BIC	Bayes information criterion
CMF	crash modification factor
FHWA	Federal Highway Administration
GLM	generalized linear model
GLMM	generalized linear mixed model
GPS	global positioning system
KABC	fatal or injury crashes (part of the KABCO scale)
KABCO	fatal, injury, or no injury crashes
LEDs	light-emitting diodes
LTLwoR	left-turn lane without pedestrian refuge island
ML	maximum likelihood
MUTCD	Manual on Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
NB	negative binomial
NCHRP	National Cooperative Highway Research Program
OR	odds ratio
RRFB	rectangular rapid-flashing beacon
SPF	safety performance function
TAC	Technical Advisory Committee
TxDOT	Texas Department of Transportation

EXECUTIVE SUMMARY

The initial efforts for this project identified candidate pedestrian treatments of interest that did not have a high-quality crash modification factor (CMF). Discussions with the Federal Highway Administration (FHWA) and Technical Advisory Committee (TAC) resulted in intersection corner radius being selected for study, focusing on both a crash and an operational analysis.

CRASH ANALYSIS

Corner-Level Analysis

In the crash analysis study, the objective was to determine the safety effectiveness of intersection corner radii in reducing nonmotorist crashes at signalized intersections. The research team selected intersections with the following characteristics:

- At least a 2-h turning movement count of vehicles and pedestrians, which was expanded to represent a daily count and then an annual value.
- Traffic control signal presence.
- Typical intersection geometric configurations (including three-leg and four-leg intersections), removing intersections with five legs or a large skew.
- No road or sidewalk construction visible during the years matching the crash data.

The corner radius can be unique to each corner at an intersection; therefore, this study attempted to assign crashes to an intersection corner rather than to the entire intersection using the latitude and longitude of the crash, along with information on the directions the vehicles were moving prior to the crash and the crash type. Because the assignment to a corner did not always agree between those methods, the research team created a weighting scheme to consider the level of certainty of the corner crash assignment. Crashes with higher certainly level would influence the result to a larger degree than crashes with a low level of certainty.

For corner-level pedestrian crashes, the following variables were found to be positively related: pedestrian volume on the approach leg, pedestrian volume on the receiving leg, vehicle volume on the approach leg, vehicle volume on the receiving leg, corner radius, and shoulder width. The number of pedestrian crashes was higher when both legs at a corner were one-way streets with traffic moving away from the corner, or when there was a mix of two-way and one-way operations present at the intersection. Fewer pedestrian crashes occurred when on-street parking existed on the approach leg. The pedestrian crashes represented all crashes that were coded as involving a pedestrian and included crashes with a motor vehicle making any movement, including making a right turn, moving through an intersection, or making a left turn.

For corner-level right-turn crashes, pedestrian and vehicle volumes on the approach and receiving legs were found to be positively related. The number of vehicles making a right turn at the corner was also positively related. Other variables positively related to corner-level right-turn crashes included the presence of a median or the shoulder width on the receiving leg. Variables associated with fewer right-turn crashes included when one of the legs had only one lane on the approach or when the intersection had four legs rather than three legs. Right-turn crashes represented all crashes involving a right-turn vehicle and included crashes between motor vehicles, crashes involving a single vehicle, or crashes between a pedestrian or bicyclist and a vehicle where at least one vehicle was coded with a right-turn maneuver.

The focus of this study was to investigate the relationship of the intersection corner radius with pedestrian or right-turn crashes. The evaluation using right-turn crashes did not find a statistically significant relationship for the corner radius variable. This finding does not necessarily imply that there is no relationship between corner radius and right-turn crashes, only that this analysis does not provide evidence favoring such a relationship. For pedestrian crashes, the evaluation found a statistical relationship with corner radius. Assuming a baseline condition of 10 ft, the pedestrian CMFs for corner radius for the range of corner radii included in the evaluation went from 1.00 for a 10-ft radius to 1.59 for a 70-ft radius.

Intersection-Level Analysis

The development of the corner-based database provided the opportunity to also create an intersection-level database. The analysis of the pedestrian crashes at signalized intersections considered data for 299 intersections located in Oregon, Virginia, and Washington. The database included both three-leg and four-leg signalized intersections composed of streets with two-way traffic operations. The best model found very convincing evidence of an increase in pedestrian crashes with increases in pedestrian and bicycle volume (when available), major street vehicle volume, or minor street vehicle volume for Oregon and Virginia. Overall, and using a general rule-of-thumb summary, a 10 percent increase in any of these volumes corresponded to about a 5 percent increase in pedestrian crashes. This result is not surprising because it is reasonable to assume that pedestrian crash risk will rise with increasing exposure of pedestrians and vehicles at the intersection. While several median types were represented in the dataset, only left-turn lane without pedestrian refuge island (LTLwoR) remained in the statistical model, while the other groups—none, raised, and mixed median types—did not remain in the model. Assuming everything else being equal, this safety association was estimated as an increase in pedestrian crash frequency by a factor of 1.5636 when the LTLwoR was present on the major street compared to all other median types (none, raised, or a mix of median types for the major street approaches).

OPERATIONAL ANALYSIS USING RIGHT-TURN SPEED

The operational analysis explored the relationship between in-field right-turn vehicle speeds and roadway geometrics, especially corner radius, at signalized intersections. Other geometric variables considered included: type of right-turn lane, number of right-turn lanes, length of right-turn lane, distance to nearest upstream and downstream driveways, number of lanes on the receiving leg, and the speed limit. No bicycle or parking lanes were present on the approach or the receiving leg for any of the sites.

Speed data were obtained from video of signalized intersection approaches. In addition to the right-turn speed, the research team collected conditions present when the subject vehicle was turning right, including the signal indication (green or yellow), type of turning vehicle (car or truck), and characteristics of the vehicle immediately preceding the turning vehicle (going straight or turning right). The evaluation revealed that conditions during the specific right turn are more influential than the site characteristics except for corner radius. The analysis found convincing evidence that right-turn speeds are a function of corner radius, with the range of increases in turning speed for corner radii between 15 and 70 ft being about 4 mph. Other variables that influence right-turn speed include headway to the preceding vehicle, traffic signal indication (yellow versus green), turning vehicle type (car or truck), and preceding vehicle movement (straight or right). The final selected model from this study can be used to predict turning speeds at different percentile levels. For example, the model can predict 50th or 85th percentile speeds. The findings from this study can be used to update the discussion in design manuals, especially on designing intersections.

CHAPTER 1. INTRODUCTION

INTRODUCTION

Many transportation agencies are placing more emphasis on improving pedestrian safety and reducing the risk of a fatality or serious injury to pedestrians. Practitioners need and have been asking for a methodical approach to assess pedestrian safety benefits for different countermeasure options. The Crash Modification Factors Clearinghouse provides several crash modification factors (CMFs); however, most factors related to pedestrian crashes do not have a respectable star rating.(1) Expanding the availability of robust CMFs can aid in the implementation of valuable countermeasures for addressing pedestrian crashes.

PROJECT OBJECTIVE

The objective of this Federal Highway Administration (FHWA) project was to determine the safety effectiveness of low- to medium-cost pedestrian engineering countermeasures in reducing nonmotorist fatalities and injuries at controlled and uncontrolled intersections. The project started with a survey that set the research direction of investigating the relationship of intersection corner radius design with crashes and turning speed.

STUDY APPROACH

The project began by identifying candidate pedestrian treatments of interest to the profession and determining the quality of CMFs that exist for the treatment. If no CMFs exist, the researchers wanted to determine if a CMF could be successfully developed for the treatment of interest in terms of presence of sufficient number of candidate sites, the length of time after the treatment was installed, and the availability of exposure data (both vehicle and pedestrian). Corner radius was selected for study from the identified treatments, with the focus on an operational analysis approach and a crash analysis approach.

The safety study gathered crash data along with traffic volume, especially available pedestrian and turning movement counts, and roadway geometric characteristics. Because the corner radius can be unique to each corner at an intersection, this study explored methods that could be used to assign crashes to an intersection corner rather than to the entire intersection.

The conducted field study obtained actual right-turn speeds, which were used to develop an equation to predict average and 85th percentile right-turn speeds for a range of corner radii.

CHAPTER 2. IDENTIFY CANDIDATE COUNTERMEASURES THAT LACK SAFETY RESEARCH

The initial effort in the project was to identify candidate countermeasures. The candidate countermeasures or treatments were selected because of their lack of an available CMF or the desire to have a better understanding of their potential safety performance. A survey discussed in the following sections was used to gather the transportation safety profession's thoughts, which were then presented to FHWA and the Technical Advisory Committee (TAC). Discussions were then held with those groups to select the final countermeasures to be studied in this project.

REVIEW OF AVAILABLE CMFs

The research team developed the initial list of potential pedestrian treatments for consideration in this project. The CMF Clearinghouse was reviewed to identify whether a CMF currently exists for these treatments.[(1)]

SURVEY DEVELOPMENT

The research team, working with FHWA, developed a survey to identify the transportation safety profession's use of pedestrian treatments and preference for which treatments need a CMF. The list of treatments began with review of available CMFs and then was refined to better fit the format of the survey. A total of 52 pedestrian treatments were included in the survey, along with the opportunity for the participants to add treatments within each of the 4 groups used to bundle the treatments. The 52 pedestrian treatments were grouped into:

- Signing and marking treatments.
- Signal treatments.
- Geometric treatments.
- Program treatments.

The following are the treatments included in the survey, along with the available responses for the demographic questions. For each treatment, the participants were asked whether they had installed the treatment (yes or no) and then their priority for having detailed safety effectiveness data/CMF. The available responses for the priority questions were "already have it," "really need it," "not as important," or "not a priority." At the end of the survey, participants could provide a general comment.

- Signing and marking treatments.
    - Advance yield or stop markings and signs (*Manual on Uniform Traffic Control Devices* (MUTCD) section 3B.16, paragraph 12).[(2)]
    - Speed feedback sign.
    - High-visibility crosswalk markings.
    - In-street pedestrian crossing sign (R1-6). The R1-6 label reflects the sign number used in the MUTCD.[(2)]
    - Parking restriction on crosswalk approach.

    - Pedestrian crossing warning sign (W11-2) with imbedded light-emitting diodes (LEDs) in borders.
    - Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed overhead.
    - Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed roadside.
    - Rectangular rapid-flashing beacon (RRFB) (Interim Approval 21).
    - RRFB (Interim Approval 21), installed overhead.
    - Right-turn-on-red prohibition, with NO TURN ON RED sign (R10-11a or R10-11b).
    - Turning vehicles yield to pedestrians sign (R10-15).
    - Other: [provide description of other signings and markings].
- Signal treatments.
    - Automated pedestrian detection.
    - Barnes Dance (i.e., exclusive pedestrian phase, also known as pedestrian scramble).
    - Combined bus stops with traffic signal locations.
    - Confirmation light for pedestrian call button.
    - Conversion from permissive to protected turn phasing.
    - Decreased cycle length for more frequent pedestrian crossings.
    - Flashing yellow arrow.
    - Increase of cycle length for pedestrian crossing at a signal.
    - In-roadway lights at pedestrian crossing.
    - Leading pedestrian interval.
    - Pedestrian countdown indications.
    - Pedestrian hybrid beacon, also known as a HAWK.
    - Pedestrian signal.
    - Signal timing for pedestrian progression.
    - Split phases.
    - Traffic signal.
    - Other: [provide description of other signal treatments].
- Geometric treatments.
    - Crosswalk lighting, constant.
    - Crosswalk lighting, dynamic.
    - Crosswalk lighting.
    - Curb extension/bulb out.
    - Driveway modifications (avoiding road-like characteristics of a driveway).
    - Installation of new sidewalk to fill in gaps within a sidewalk network.
    - Landscape strip buffer to separate curb-tight sidewalk from roadway.
    - Median treatment for pedestrian/bicycle safety or pedestrian refuge island.
    - Offset crossing (e.g., Z-crossing or Danish offset, which are staggered crosswalks).
    - Pedestrian fencing, channelization, or barriers.
    - Pedestrian grade separation.
    - Raised crosswalk.
    - Raised intersections.

    - Relocation of transit stop.
    - Road diet (reallocate roadway cross section).
    - Roundabouts (modern).
    - Roundabouts (neighborhood).
    - Smaller curb return radius.
    - Traffic calming (e.g., speed hump, chicane [artificial narrowing or turn on a road], circles, narrowed street, or woonerf [a living street as used in the Netherlands and Belgium]).
    - Transverse rumble strips at pedestrian crosswalks.
    - Upgrade or installation of curb ramps.
    - Widening of sidewalks.
    - Other: [provide description of other geometric treatments].
- Program treatments.
    - Enforcement and adjudication changes.
    - Safe Routes to School program.
    - Other: [provide description of other program treatments].
- Employer type.
    - Academic.
    - City agency—large (≥300,000 population).
    - City agency—small/midsize (between 100,000 and 300,000 population).
    - City agency—small (≤100,000 population).
    - Consultant.
    - County/regional agency.
    - Federal agency.
    - State agency/department of transportation (DOT).
    - Other: [provide description of other employer type].
- Years of professional experience.
    - <6 yr.
    - 6–10 yr.
    - 11–20 yr.
    - 21–30 yr.
    - >30 yr.
- Please provide your comments or observations regarding this topic: [space for comments].

SURVEY DISTRIBUTION

The survey was distributed on September 12, 2018, and ended on October 4, 2018. The survey was distributed to:

- Institute of Transportation Engineers.
- Transportation Research Board Pedestrian and Highway Safety Performance Committees.
- National Committee on Uniform Traffic Control Devices Pedestrian Task Force.

- American Association of State Highway and Transportation Officials traffic engineers and safety management.
- National Association of City Transportation Officials (NACTO).

At the close of the survey, 66 responses had been received.

FINDINGS FROM SURVEY

Table 1 provides the survey results regarding the question on whether the participants had installed the given pedestrian treatment within the past 10 yr. Table 2 and table 3 provide the survey results regarding the priority for a CMF. These tables are provided in the order that the treatments were presented to the participants.

Table 1. Survey results for installation of pedestrian treatment.

Pedestrian Treatment	Freq-Yes (No.)	Freq-Not (No.)	Freq-No R (No.)	Yes (Percent)	No (Percent)
S&M: Advance yield or stop markings and signs (MUTCD section 3B.16, paragraph 12).(2)	55	10	1	85	15
S&M: Speed feedback sign.	53	13	0	80	20
S&M: High-visibility crosswalk markings.	54	12	0	82	18
S&M: In-street pedestrian crossing sign (R1-6).	48	18	0	73	27
S&M: Parking restriction on crosswalk approach.	49	16	1	75	25
S&M: Pedestrian crossing warning sign (W11-2) with imbedded LEDs in borders.	18	47	1	28	72
S&M: Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed overhead.	23	42	1	35	65
S&M: Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed roadside.	32	33	1	49	51
S&M: RRFB (Interim Approval 21).	46	19	1	71	29
S&M: RRFB (Interim Approval 21), installed overhead.	13	50	3	21	79
S&M: Right-turn-on-red prohibition, with NO TURN ON RED sign (R10-11a or R10-1b).	46	19	1	71	29
S&M: Turning vehicles yield to pedestrians sign (R10-15).	46	19	1	71	29
S&M: Other: [provide description].	14	9	43	61	39
Sig: Automated pedestrian detection.	8	57	1	12	88

Pedestrian Treatment	Freq-Yes (No.)	Freq-Not (No.)	Freq-No R (No.)	Yes (Percent)	No (Percent)
Sig: Barnes Dance (i.e., exclusive pedestrian phase, also known as pedestrian scramble).	18	48	0	27	73
Sig: Combine bus stops with traffic signal locations.	30	35	1	46	54
Sig: Confirmation light for pedestrian call button.	36	30	0	55	45
Sig: Convert from permissive to protected turn phasing.	50	16	0	76	24
Sig: Decreased cycle length for more frequent pedestrian crossings.	17	48	1	26	74
Sig: Flashing yellow arrow.	45	20	1	69	31
Sig: Increase cycle length for pedestrian crossing at a signal.	44	21	1	68	32
Sig: In-roadway lights at pedestrian crossing.	14	51	1	22	78
Sig: Leading pedestrian interval.	42	24	0	64	36
Sig: Pedestrian countdown indications.	61	5	0	92	8
Sig: Pedestrian hybrid beacon, also known as a HAWK.	39	27	0	59	41
Sig: Pedestrian signal.	45	20	1	69	31
Sig: Signal timing for pedestrian progression.	10	55	1	15	85
Sig: Split phases.	47	18	1	72	28
Sig: Traffic signal.	60	6	0	91	9
Sig: Other: [provide description].	7	11	48	39	61
Geo: Crosswalk lighting, constant.	40	25	1	62	38
Geo: Crosswalk lighting, dynamic.	4	61	1	6	94
Geo: Crosswalk lighting.	45	19	2	70	30
Geo: Curb extension/bulb out.	57	8	1	88	12
Geo: Driveway modifications (avoiding road-like characteristics of a driveway).	30	35	1	46	54
Geo: Install new sidewalk to fill in gaps within a sidewalk network.	53	12	1	82	18
Geo: Landscape strip buffer to separate curb-tight sidewalk from roadway.	44	21	1	68	32
Geo: Median treatment for pedestrian/bicycle safety or pedestrian refuge island.	56	8	2	87	13
Geo: Offset crossing (e.g., Z-crossing/Danish offset).	24	41	1	37	63

Pedestrian Treatment	Freq-Yes (No.)	Freq-Not (No.)	Freq-No R (No.)	Yes (Percent)	No (Percent)
Geo: Pedestrian fencing, channelization, or barriers.	29	36	1	45	55
Geo: Pedestrian grade separation.	23	41	2	36	64
Geo: Raised crosswalk.	28	38	0	42	58
Geo: Raised intersections.	12	54	0	18	82
Geo: Relocate transit stop.	37	29	0	56	44
Geo: Road diet (reallocate roadway cross section).	44	22	0	67	33
Geo: Roundabouts (modern).	55	11	0	83	17
Geo: Roundabouts (neighborhood).	29	37	0	44	56
Geo: Smaller curb return radius.	30	36	0	45	55
Geo: Traffic calming (e.g., speed hump, chicane, circles, narrowed street, or woonerf).	43	23	0	65	35
Geo: Transverse rumble strips at pedestrian crosswalks.	10	56	0	15	85
Geo: Upgrade or install curb ramps.	57	9	0	86	14
Geo: Widen sidewalks.	41	24	1	63	37
Geo: Other: [provide description].	6	7	53	46	54
Pro: Enforcement and adjudication changes.	31	35	0	47	53
Pro: Safe Routes to School program.	52	14	0	79	21
Pro: Other: [provide description].	2	7	57	22	78

S&M = signing and marking; Sig = signal; Geo = geometry; Pro = program; No. = number; Freq-Yes = agencies indicating they had installed the treatment; Freq-Not = agencies indicating they had not installed the treatment; Freq-No R = agencies who did not provide a response for the treatment; Yes = agencies who responded to the question indicating they had installed the treatment; No = agencies who responded to the question indicating they had not installed the treatment.

Table 2. Survey results (frequency) for pedestrian treatment CMF.

Pedestrian Treatment	Really Need It	Not as Important	Not a Priority	Already Have It	No Response
S&M: Advance yield or stop markings and signs (MUTCD section 3B.16, paragraph 12).(2)	9	25	23	8	1
S&M: Speed feedback sign.	9	43	8	4	2
S&M: High-visibility crosswalk markings.	14	32	16	3	1
S&M: In-street pedestrian crossing (R1-6) sign.	7	34	14	11	0
S&M: Parking restriction on crosswalk approach.	7	20	19	17	3

Pedestrian Treatment	Really Need It	Not as Important	Not a Priority	Already Have It	No Response
S&M: Pedestrian crossing warning sign (W11-2) with imbedded LEDs in borders.	2	32	24	7	1
S&M: Pedestrian crossing warning sign with supplemental beacon, installed overhead.	4	29	23	9	1
S&M: Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed roadside.	7	30	18	10	1
S&M: RRFB (Interim Approval 21).	20	39	5	2	0
S&M: RRFB (Interim Approval 21), installed overhead.	2	38	18	3	5
S&M: Right-turn-on-red prohibition, with NO TURN ON RED sign (R10-11a or R10-11b).	8	29	19	8	2
S&M: Turning vehicles yield to pedestrians sign (R10-15).	7	30	19	9	1
S&M: Other: [provide description].	2	16	1	6	41
Sig: Automated pedestrian detection.	1	26	27	7	5
Sig: Barnes Dance (i.e., exclusive pedestrian phase, also known as pedestrian scramble).	6	23	23	12	2
Sig: Combine bus stops with traffic signal locations.	4	22	22	13	5
Sig: Confirmation light for pedestrian call button.	4	19	27	14	2
Sig: Convert from permissive to protected turn phasing.	18	33	10	3	2
Sig: Decreased cycle length for more frequent pedestrian crossings.	3	30	22	8	3
Sig: Flashing yellow arrow.	21	27	13	3	2
Sig: Increase cycle length for pedestrian crossing at a signal.	10	26	19	9	2
Sig: In-roadway lights at pedestrian crossing.	1	19	25	18	3
Sig: Leading pedestrian interval.	13	41	8	3	1
Sig: Pedestrian countdown indications.	21	24	16	5	0
Sig: Pedestrian hybrid beacon, also known as a HAWK.	22	32	6	4	2
Sig: Pedestrian signal.	11	31	16	6	2

Pedestrian Treatment	Really Need It	Not as Important	Not a Priority	Already Have It	No Response
Sig: Signal timing for pedestrian progression.	5	15	25	20	1
Sig: Split phases.	4	21	28	11	2
Sig: Traffic signal.	23	23	10	8	2
Sig: Other: [provide description].	0	8	2	7	49
Geo: Crosswalk lighting, constant.	7	31	19	6	3
Geo: Crosswalk lighting, dynamic.	1	28	24	8	5
Geo: Crosswalk lighting.	10	36	12	5	3
Geo: Curb extension/bulb out.	12	37	10	5	2
Geo: Driveway modifications (avoiding road-like characteristics of a driveway).	5	23	24	9	5
Geo: Install new sidewalk to fill in gaps within a sidewalk network.	8	27	20	9	2
Geo: Landscape strip buffer to separate curb-tight sidewalk from roadway.	5	26	25	7	3
Geo: Median treatment for pedestrian/bicycle safety or pedestrian refuge island.	16	37	9	1	3
Geo: Offset crossing (e.g., Z-crossing/Danish offset).	3	30	22	7	4
Geo: Pedestrian fencing, channelization, or barriers.	5	27	21	8	5
Geo: Pedestrian grade separation.	7	18	20	15	6
Geo: Raised crosswalk.	5	31	19	7	4
Geo: Raised intersections.	2	26	19	14	5
Geo: Relocate transit stop.	5	31	17	10	3
Geo: Road diet (reallocate roadway cross section).	15	38	7	3	3
Geo: Roundabouts (modern).	24	35	6	1	0
Geo: Roundabouts (neighborhood).	10	31	14	7	4
Geo: Smaller curb return radius.	3	37	14	8	4
Geo: Traffic calming (e.g., speed hump, chicane, circles, narrowed street, or woonerf).	8	36	11	8	3
Geo: Transverse rumble strips at pedestrian crosswalks.	2	26	18	17	3
Geo: Upgrade or install curb ramps.	7	25	23	10	1
Geo: Widen sidewalks.	7	19	25	14	1
Geo: Other: [provide description].	1	6	0	2	57

Pedestrian Treatment	Really Need It	Not as Important	Not a Priority	Already Have It	No Response
Pro: Enforcement and adjudication changes.	4	37	19	5	1
Pro: Safe Routes to School program.	11	33	20	2	0
Pro: Other: [provide description].	1	3	1	1	60

Table 3. Survey results (percent) for pedestrian treatment CMF.

Pedestrian Treatment	Really Need It (Percent)	Not as Important (Percent)	Not a Priority (Percent)
S&M: Advance yield or stop markings and signs (MUTCD section 3B16, paragraph 12).(2)	45	41	14
S&M: Speed feedback sign.	78	15	7
S&M: High-visibility crosswalk markings.	63	31	6
S&M: In-street pedestrian crossing sign (R1-6).	58	24	18
S&M: Parking restriction on crosswalk approach.	36	34	30
S&M: Pedestrian crossing warning sign (W11-2) with imbedded LEDs in borders.	51	38	11
S&M: Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed overhead.	47	38	15
S&M: Pedestrian crossing warning sign (W11-2) with supplemental beacon, installed roadside.	52	31	17
S&M: RRFB (Interim Approval 21).	85	11	4
S&M: RRFB (Interim Approval 21), installed overhead.	64	31	5
S&M: Right-turn-on-red prohibition, with NO TURN ON RED sign (R10-11a or R10-11b).	52	34	14
S&M: Turning vehicles yield to pedestrians sign (R10-15).	52	32	16
S&M: Other: [provide description].	70	4	26
Sig: Automated pedestrian detection.	43	45	12
Sig: Barnes Dance (i.e., exclusive pedestrian phase, also known as pedestrian scramble).	40	40	20
Sig: Combine bus stops with traffic signal locations.	39	39	22
Sig: Confirmation light for pedestrian call button.	32	45	23
Sig: Convert from permissive to protected turn phasing.	71	22	7
Sig: Decreased cycle length for more frequent pedestrian crossings.	50	37	13
Sig: Flashing yellow arrow.	63	30	7
Sig: Increase cycle length for pedestrian crossing at a signal.	48	35	17
Sig: In-roadway lights at pedestrian crossing.	31	40	29
Sig: Leading pedestrian interval.	79	15	6
Sig: Pedestrian countdown indications.	53	36	11

Pedestrian Treatment	Really Need It (Percent)	Not as Important (Percent)	Not a Priority (Percent)
Sig: Pedestrian hybrid beacon, also known as a HAWK.	76	14	10
Sig: Pedestrian signal.	59	30	11
Sig: Signal timing for pedestrian progression.	25	42	33
Sig: Split phases.	35	47	18
Sig: Traffic signal.	56	24	20
Sig: Other: [provide description].	47	12	41
Geo: Crosswalk lighting, constant.	55	34	11
Geo: Crosswalk lighting, dynamic.	47	40	13
Geo: Crosswalk lighting.	68	23	9
Geo: Curb extension/bulb out.	71	19	10
Geo: Driveway modifications (avoiding road-like characteristics of a driveway).	41	43	16
Geo: Install new sidewalk to fill in gaps within a sidewalk network.	48	36	16
Geo: Landscape strip buffer to separate curb-tight sidewalk from roadway.	45	43	12
Geo: Median treatment for pedestrian/bicycle safety or pedestrian refuge island.	79	19	2
Geo: Offset crossing (e.g., Z-crossing/Danish offset).	51	37	12
Geo: Pedestrian fencing, channelization, or barriers.	48	38	14
Geo: Pedestrian grade separation.	34	38	28
Geo: Raised crosswalk.	55	33	12
Geo: Raised intersections.	44	32	24
Geo: Relocate transit stop.	54	29	17
Geo: Road diet (reallocate roadway cross section).	79	15	6
Geo: Roundabouts (modern).	84	14	2
Geo: Roundabouts (neighborhood).	60	27	13
Geo: Smaller curb return radius.	62	24	14
Geo: Traffic calming (e.g., speed hump, chicane, circles, narrowed street, or woonerf).	65	20	15
Geo: Transverse rumble strips at pedestrian crosswalks.	42	30	28
Geo: Upgrade or install curb ramps.	43	40	17
Geo: Widen sidewalks.	33	43	24
Geo: Other: [provide description].	75	0	25
Pro: Enforcement and adjudication changes.	61	31	8
Pro: Safe Routes to School program.	60	36	4
Pro: Other: [provide description].	60	20	20

Treatments Installed

Figure 1 shows the treatments installed by more than 75 percent of the respondents. The most common pedestrian treatments installed by more than 90 percent of the respondents were pedestrian countdown indications and traffic signals. Curb extensions and pedestrian refuge islands were installed by 88 percent of the respondents. Of the treatments included on the survey, the ones that were rarely installed included dynamic crosswalk lighting (6 percent) and automated pedestrian detection (12 percent).

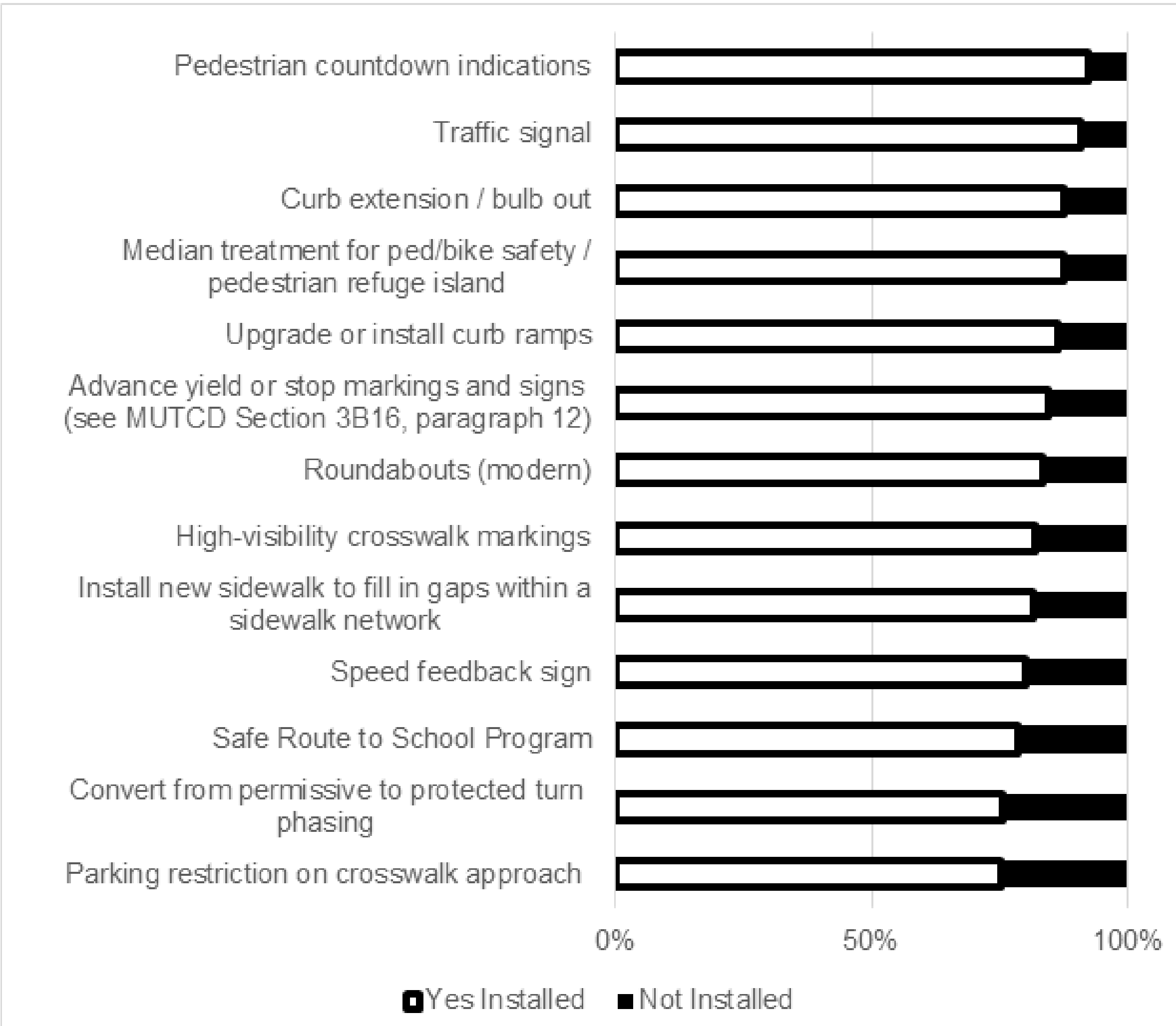


Figure 1. Graph. Treatments installed by more than 75 percent of the respondents.

Treatments added by the participants are listed below. In some cases, they repeat treatments provided in other sections, such as RRFB or road diets.

- Signing and marking treatments added by participants.
  - Painted median pedestrian refuge island on two-way, two-lane street.
  - Double-sided flanking pedestrian signs (W11-2), like an RRFB without the beacons.
  - In-pavement lighting.
  - Raised crosswalk.

    - Bicycle lane striping.
    - RRFB.
    - Overhead targeted illumination of crosswalks activated by pedestrian.
    - Restriction of right-turn-on-red with blank-out sign.
    - Double solid white-lane lines approaching marked crosswalk.
    - State law—yield to pedestrians sign instead of W11-2.
    - Road diets.
    - Bushes/fences to control pedestrians.
    - Shared-use bicycle/pedestrian crosswalks.
    - Rectangular sign identifying crossing in lieu of warning sign and arrow plaque.
    - Curbside R1-6.
    - "LOOK" pavement symbols.
    - Animated eye symbols in pedestrian signal face.
- Signal treatments added by participants.
    - Installation of protected/permissive phasing with flashing yellow arrow.
    - Leading pedestrian phase (jump 2 to 4 s).
    - RRFB at roundabout approach.
    - Over- and underpasses.
    - Lagging pedestrian phase.
    - No installation of split phases.
    - Installation of lagging left-turn phase with pedestrian lead.
    - Median pedestrian signalization.
    - Red interval at right/left turns only when conflicting pedestrian phase is activated.
- Geometry treatments added by participants.
    - Corner apron/mountable truck island.
    - Raised crossing on right-turn bypass islands.
    - Using common sense; no CMFs required to save lives.
    - Transit stop moved to departure side of intersection.
    - CMF for school speed zone flashers, urban and rural area.
    - Bullnose on median.
    - Median refuge and channelizing islands.
    - Raised crosswalks at roundabouts.
- Program treatments added by participants.
- Bike-to-work programs.
- 20-mph bicycle way and residential legislative change.
- Minimum pedestrian crossing length.
- Use of systematic crash analysis.

Priority of CMFs for a Treatment

The data for priority of CMFs were examined in two groups. The first group focused on whether the participants felt they already had detailed safety effectiveness data/CMFs available. The second group examined the responses when the participant indicated there was a need to develop a CMF by indicating a priority of either "Really Need It," "Not as Important," or "Not a Priority."

CMFs Already Available per Survey Participants

Table 4 lists the pedestrian treatments when 15 or more participants indicated detailed safety effectiveness data/CMFs were already available.

Table 4. Pedestrian treatments with 15 or more participants indicating detailed safety effectiveness data/CMFs already available.

Pedestrian Treatment	Frequency
Geo: Roundabouts (modern)	24
Sig: Traffic signal	23
Sig: Pedestrian hybrid beacon, also known as a HAWK	22
Sig: Flashing yellow arrow	21
Sig: Pedestrian countdown indications	21
S&M: RRFB (Interim Approval 21)	20
Sig: Convert from permissive to protected turn phasing	18
Geo: Median treatment for pedestrian/bicycle safety or pedestrian refuge island	16
Geo: Road diet (reallocate roadway cross section)	15

CMFs Needed

Those participants who did not already have a CMF or detailed safety data for a treatment could indicate their priority for the development of a CMF with "Really Need It," "Not as Important," or "Not a Priority." Table 2 provides the frequency data for all the treatments. Table 3 shows the results by percentage for those who indicated that a CMF was not already available.

Figure 2 shows the top 18 of the available 52 treatments, with the highest number of responses for "Really Need It." Interestingly, some of the treatments where more than 15 participants believed CMFs were already available also had a large number of other participants who believed a CMF was really needed.

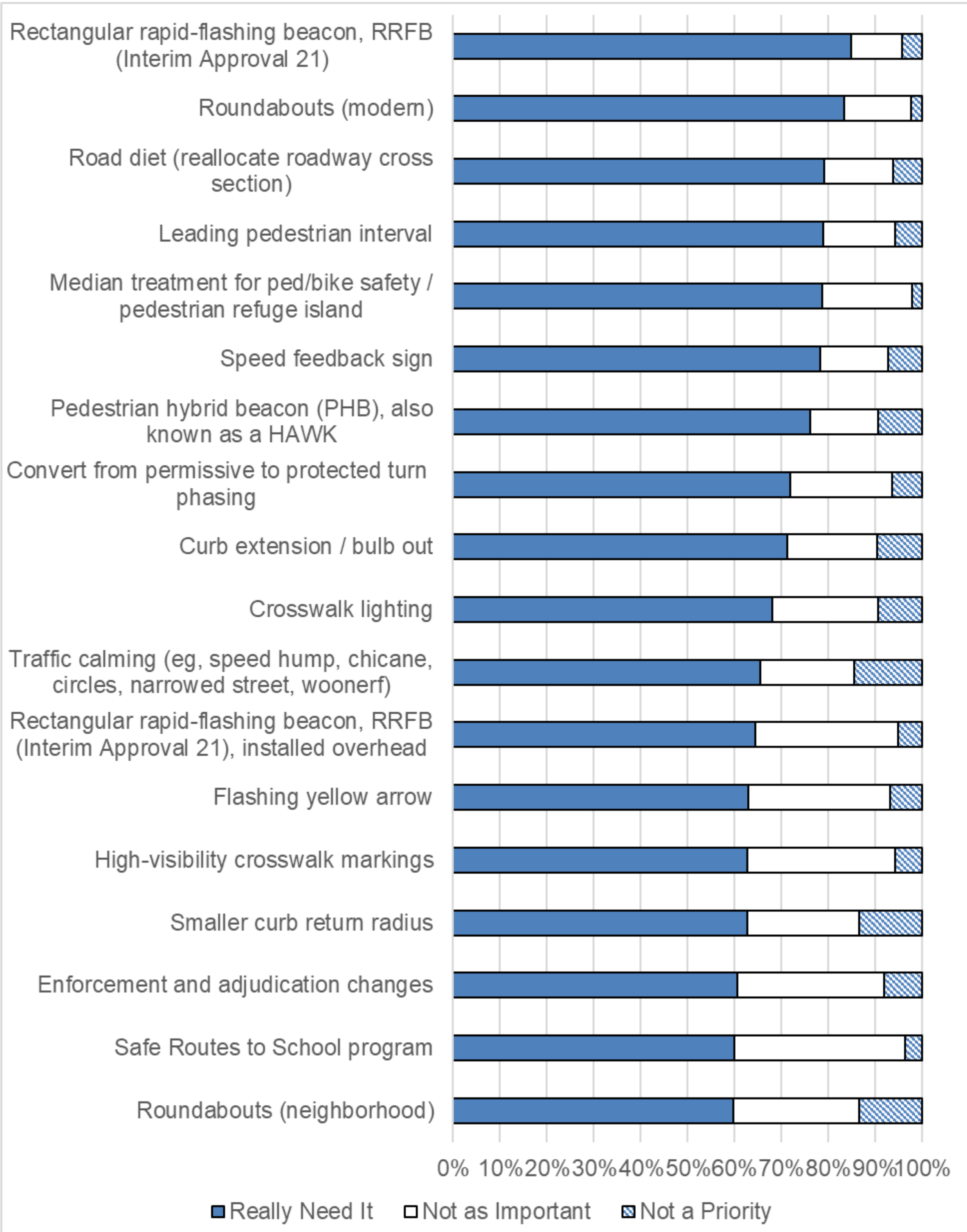


Figure 2. Graph. Top 18 CMFs needed per survey participants.

CMFs That Are Not a Priority

The treatments that 15 or more participants felt were not a priority included the following:

- Signal timing for pedestrian progression.
- In-roadway lights at pedestrian crossing.
- Pedestrian grade separation.
- Parking restriction on crosswalk approach.
- Transverse rumble strips at pedestrian crosswalks.

Demographic Questions

The survey included two questions to obtain an appreciation of each participant's employer and number of years of experience. Most of the participants had several years of experience, with only 6 of the 65 participants (<10 percent) having 10 yr of experience or less. The participants were generally split between cities, States, and consultants, with most being from State agencies. The following is a breakdown of the demographics:

- Number of participants by employer type:
    - Academic = 0 participants.
    - City agency—large = 7 participants.
    - City agency—small/midsize = 6 participants.
    - City agency—small = 6 participants.
    - Consultant = 12 participants.
    - County/regional agency = 7 participants.
    - Federal agency = 0 participants.
    - State agency/DOT = 26 participants.
    - Other = 1 participant.
    - No response = 1 participant.
- Years of professional experience:
    - <6 yr = 3 participants.
    - 6–10 yr = 4 participants.
    - 11–20 yr = 19 participants.
    - 21–30 yr = 22 participants.
    - 30 yr = 17 participants.
    - No response = 1 participant.

Participants' Comments

The final section of the survey gave participants the opportunity to provide comments, which are included and numbered here for ease of discussion. Entire comments are provided except in cases where a name was given by the participant. In those cases, the identifying information has been removed.

1. "Pedestrian nonmotorist involved crashes are currently our third most prevalent crash category, but the random nature of the events makes prioritization of needed systemic improvement sites difficult. We currently assess needs based on evidence of pedestrian

use and obvious travel routes between known pedestrian generators. Any guidance on assessing priority site priority would be helpful along with a full set of CMFs for all or most of the above treatments."

2. "Some of your topics already have analysis and CMFs conducted, but for many of these same topics the data sets are quite old. It would be nice to see some comprehensive work done on traffic calming applications to help practitioners choose and explain best design solutions. Additionally, I really look forward to having a CMF for bump-outs at crosswalks."

3. "This a very well-designed survey. I look forward to having more backup and being able to calculate corresponding B/C for recommending and installing these safety improvements on projects. Thank you."

4. "Regarding CMFs, the challenge very often (roundabouts are a good example) is to choose among the many studies which CMF is the most relevant. The range among CMFs can be substantial despite the details of their applicability being very similar."

5. "Thanks."

6. "So many pedestrians and drivers are plugged in to their electronic devices and are oblivious to the world around them. They are walking distracted and driving distracted. I believe it will get worse before it gets better. . . . I hope I am wrong."

7. "Traffic calming is a major concern for our jurisdiction as speeding has become prevalent. Resources for enforcement are limited. Need alternatives to high-cost countermeasures."

8. "This effort should be coordinated with FHWA's low-cost safety improvement pooled fund study."

9. "We have been installing many of the treatments with little or no data to support effectiveness. Most before/after data was inconclusive. It will take some very good work to define CMF for most of these safety treatments."

10. "Not exactly sure the difference between 'Not As Important' vs. 'Not A Priority.' I assume 'Not A Priority' is the least significant of these two options."

11. "Retired from county and responses reflect that time period. Now a consultant."

12. "Arizona Department of Transportation (ADOT) would be very interested in expanding the available CMFs for pedestrian safety projects."

13. "Currently, most of the pedestrian-related CMFs can only be applied to vehicle-pedestrian crashes. This causes very low benefit/cost ratio such that pedestrian facility projects are usually turned down from funding. More pedestrian-related CMFs that apply to all crashes and all severities should be developed."

14. “Thank you!”

15. “Much of what I reported as ‘installed in the last 10 years’ was when I was working for a city.”

16. “There seem to be no studies that help implement projects. For example, the crosswalk study combines both signalized and signalized locations. Also, we need better categories for implementations such as a difference between urban core, urban low speed and high-speed roadways. There are also not enough studies on traffic calming a road with speeds greater than 35 mph.”

17. “This is silly. These treatments shouldn’t require justification for use. They should be mostly inherent in everyday design. Why is it that saving lives needs justification?!”

18. “My answers reflect a State DOT that has less interaction with low-volume urban roads (we have a lot of high-volume urban roads and low-volume rural roads). Also, we tend to avoid pavement marking treatments due to the problems associated with maintaining markings in a snow-plow rich environment.”

19. “I’m particularly interested in lighting effectiveness because our State requires local jurisdictions to maintain lighting and the results are inconsistent (i.e., we have a lot of nonfunctioning lighting).”

20. “I noticed that this survey did not directly mention the topic of marked crosswalks at uncontrolled multi-lane locations (as per Zeeger, et al. 2005 study). Hopefully CMFs will, or perhaps already do, note the hazard of such locations in the absence of these other enhancements. However, there is much that is still unknown about the effectiveness of these other enhancements, so I am glad to see that this study seeks to shed some light on that.”

21. “Other CMFs of interest include those regarding the application of truck aprons on right turns and for pedestrian crashes with respect to the installation of a full traffic signal.”

22. “The MUTCD needs to provide a table that shows progressive treatment implementation plans that start with no markings or signing and move toward warning signs, crosswalk identification signs (rectangular, the Canadian application), and other devices so that devices are implemented in an orderly way that clearly demonstrate the likely hazard.”

23. “Having more CMFs we have for pedestrian and bicycle safety treatments will further help to justify funding requests for these treatments.”

24. “I took ‘installed’ to mean designed, litigated, or recommended for design as part of a planning process. Mostly the improvements listed were physically installed by others, namely the respective agency having jurisdiction over the roadway.”

25. “You need a category between ‘Need it’ and ‘Not Important.’”

26. “Would appreciate the results of this survey. Thank you.”

27. "Treatment priority of 'Already Have It,' 'Really Need It,' 'Not as Important,' and 'Not a Priority' were a bit confusing mostly due to their order."

28. "I have struggled with the changing behavior of the pedestrian. The more treatments I add, the less safe is the pedestrian's behavior. When is enough, enough?"

29. "I was with a municipality for 37 years, retired late 2018 and joined a professional consulting engineering firm. My responses are my experience as a municipal engineer."

30. "There are some CMFs available for treatments, such as roundabouts, but they are not pedestrian specific. Therefore, the answer has been marked as 'Already Have It,' but it may not be for the intended focus of this survey. It is always preferable to have the general CMFs as well as specific CMFs for each treatment."

DIRECTION FOR RESEARCH

The research team presented the survey findings to the project TAC and FHWA in December 2018. The discussions from that meeting identified three treatments with the highest priorities (table 5). Additional discussions with FHWA and the TAC resulted in those groups setting the following direction for this FHWA project:

- Develop a CMF for intersection corner radius.
- Investigate the relationship between turning speeds for right-turn vehicles and intersection corner radius.

The research team set a goal to conduct both a crash-based study and a surrogate safety study (turning speed) for intersection corner radius.

Table 5. Potential short list of treatments.

Treatment	Availability of Crash Data	Potential for Surrogate Measures
Tighter intersection corner radius	Yes, but the preference would be to assign crashes to unique corners rather than just to the intersection to better identify the relationship between crashes and intersection corner radius.	Yes, for example, vehicle turning speed.
Signal treatments (e.g., convert to protected left-turn phase, install a flashing yellow arrow, install traffic signal where one has not been previously)	Yes, but previous studies have had difficulties with isolating how pedestrian crashes vary with respect to the signal timing change. (Using surrogate measures may provide more insights.)	Yes, including: • Driver yielding behavior. • Vehicle approach speed. • Vehicle turning speed. • Pedestrian behavior, especially the decision on whether to go/not to go based on the site and temporal conditions (pedestrian head indication, whether vehicle has protected or permission indication, whether the pedestrian pushed the button, number of vehicles wanting to turn left, whether the turning vehicle is in the pedestrian line of sight). • Driver behavior, such as how far into the intersection the driver was when the driver yielded. • Distance between vehicle and pedestrian during the interaction. • Evasive maneuvers. • Traffic conflicts.
RRFB	Yes. Note: NCHRP report no. 841 attempted to develop a CMF for RRFB and concluded that "the CMF for the RRFB was based on a very limited sample (i.e., 50 treatment sites) and hence should be used with caution."(3) Although there is high interest in developing a more robust RRFB CMF, sufficient time has not yet passed to resolve the sample size challenge.	Yes, the surrogate measure would need to be developed based on refinement to the question(s) that the study would investigate.
Any	Having pedestrian counts is important in the development of CMF for a pedestrian treatment.	Several techniques are available.

NCHRP = National Cooperative Highway Research Program.

CHAPTER 3. LITERATURE

LITERATURE REVIEW OVERVIEW

Few safety studies focusing on pedestrian crashes at signalized intersections exist, perhaps due to the relatively rare occurrence of such crashes. On a national basis, approximately 25 percent of pedestrian fatalities in 2018 occurred at intersections or were intersection-related; however, the split between signalized and unsignalized intersections was not available.(4) Crash underreporting and the need for long observational periods, along with the difficulties in obtaining exposure data, contribute to the difficulties in evaluating safety for pedestrians at signalized intersections.

This chapter presents a summary of the identified literature on pedestrian crashes at signalized intersections—both crash frequency and CMFs. It also summarizes CMFs for right-turn crashes at signalized intersections and current knowledge regarding turning speed for right-turn vehicles. The chapter begins with an overview of intersection corner radius design.

OVERVIEW ON INTERSECTION CORNER RADIUS DESIGN

The intersection of two streets creates multiple corners. These corners are typically rounded using a turning radius, also called a corner radius or the radius of turning roadway. Guidance on selecting the radius is available in several reference documents. The American Association of State Highway and Transportation Officials' *A Policy on Geometric Design of Highways and Streets* (commonly known as the Green Book) provides general guidance on the radius of turning roadways.(5) In the Green Book, when right-turn volumes are high and pedestrian and bicycle volumes are relatively low, capacity considerations may dictate the use of larger radii, which enable higher-speed, higher-volume turns. The Green Book also notes that small turning radii, which promote low-speed right turns, are appropriate where such turns regularly conflict with pedestrians, since higher speeds have been shown to result in a decrease in yielding to pedestrians by motorists.

NACTO recommends that turning speed be limited to 15 mph or less and provides an approach to calculate assumed turning speed per radius value.(6) This approach uses the radius of curvature equation, which includes consideration of radius, side friction factor, and superelevation to determine speed. The radius of curvature equation is also known as the point mass equation or the simplified curve equation. It uses an assumed side friction factor that is a function of the radius. NACTO notes that corner radius is not the same as effective radius. The effective radius considers the actual turning path of the vehicle, which can be larger when on-street parking or a bicycle lane is present and when drivers can turn into the far lane of the cross street. Table 6 provides the calculated values for a sample of radii using the approach discussed by NACTO.

Table 6. Calculated turning speed by radius using radius of curvature equation.

Radius (ft)	Side Friction Factor	Speed (mph)
15	0.36	9.1
25	0.35	11.5
35	0.34	13.5
45	0.33	15.0
55	0.32	16.4
65	0.31	17.5
75	0.30	18.5
85	0.29	19.4

Note: $V^2 = R \times 15\ (0.01e + f)$, where V = turning speed (mph); R = centerline turning radius (ft); f = side friction factor, which is a function of the radius; and e = superelevation, which is assumed to be zero in urban conditions.

One reason for being concerned with the speed of the turning vehicle is the risk of severe injury or death to a pedestrian when struck by a vehicle. Tefft[7] notes the following:

- Average risk of severe injury for a pedestrian struck by a vehicle reaches 10 percent at an impact speed of 16 mph, 25 percent at 23 mph, 50 percent at 31 mph, 75 percent at 39 mph, and 90 percent at 46 mph.

- Average risk of death for a pedestrian reaches 10 percent at an impact speed of 23 mph, 25 percent at 32 mph, 50 percent at 42 mph, 75 percent at 50 mph, and 90 percent at 58 mph.

- Risks vary significantly by age.

Decisions on the type of vehicle used in intersection design and acceptable lane positioning are to be made based on the context of the intersection (e.g., urban, rural) and the functional class of the main and cross roadways. Corner radii should be selected to accommodate the desired design vehicles (but not necessarily to turn into the first lane on a multilane roadway) and with appropriate consideration for pedestrians and other users of the facility. For intersections with minor roadways, infrequent large trucks occupying both lanes on the minor roadway in the course of completing the turning maneuver is frequently judged acceptable. This type of design would be inappropriate for a major crossroad, of course, or where trucks are frequent users of the minor roadway. Additional discussion on intersection design is available in Fitzpatrick, Wooldridge, and Blaschke[8] and Chandler et al.[9]

Some benefits of larger radii on the operation of an intersection are the following:

- Accommodate larger vehicles without encroachment.
- Permit higher turning vehicle speed in free-flow situations.
- Allow the presence of islands for traffic control devices and pedestrian refuge areas.
- Allow larger radii to avoid having a curb that protrudes into the turning radius of the design vehicle, which can cause vehicles to drive over and damage the curb, as well as increase the potential of hitting a pedestrian standing at the curb.[10]

Some benefits of smaller radii on the operation of an intersection are the following:

- Reduce pedestrian crossing time, which decreases pedestrian exposure risk and could lead to reduced vehicular delay at signalized intersections.
- Reduce turning speeds, which can benefit pedestrians.
- Reduce pavement area.
- Expand pedestrian area, which could allow for increased opportunities to provide directional pedestrian ramps that generally shorten pedestrian crossing distance and support visually impaired pedestrians in navigating an intersection.
- Allow for better alignment of the pedestrian ramp and crosswalk with the connecting sidewalk.
- Improve visibility of drivers and pedestrians.

In general, the selected corner radius should accommodate the turning path of a design vehicle while avoiding encroaching on pedestrian facilities and preferably the opposing lanes of travel. The selection of the corner radius at an intersection affects drivers' behaviors, such as their turning vehicle speeds and their lane positioning while completing the turn, including encroachment into adjacent lanes, flush median, or opposing lanes. Factors that influence the selection of a corner radius include the following:

- Design of vehicle.
- Angle of intersection.
- Pedestrian and bicyclists.
- Geometric constraints/type of curves (e.g., multicentered or simple with tangent offsets) or use of truck apron.
- Encroachment.
- Intersection size.

PEDESTRIAN CRASHES AT SIGNALIZED INTERSECTIONS

Safety Performance Functions

In 2002, Lyon and Persaud[(11)] examined pedestrian crash frequency data for signalized intersections in Toronto, Canada. They gathered pedestrian volume and vehicle volume data for 684 four-leg intersections and 263 three-leg intersections. They used 11 yr of pedestrian crash data for each intersection to calibrate one crash prediction model for four-leg intersections and a second model for three-leg intersections. Both models predicted the expected annual pedestrian crash frequency at an intersection and included the following variables: total entering annual average daily traffic (AADT), pedestrian volume (8-h count for all approaches), and total daily left-turn volume entering the intersection. The authors noted that the models predicted the annual number of reported crashes for an intersection even though the input pedestrian volume represented only 8 h of the day.

Bonneson, Pratt, and Songchitruksa[12] used the models calibrated by Lyon and Persaud to evaluate the sensitivity of pedestrian crash frequency to daily vehicular volume and left-turn percentage. The trend lines show that pedestrian crash frequency increases with an increase in vehicular volume. A four-leg intersection with an average daily volume of 20,000 vehicles per day on each street, 20 percent left turns, and 20 percent right turns is likely to have one reported pedestrian crash each year.

In 2010, Torbic et al.[13] reported on the safety performance functions (SPFs) created for the first edition of the *Highway Safety Manual*.[14] They found AADT and annual average daily pedestrians (AADP) as significant factors at three- and four-leg signalized intersections. Other significant predictors included maximum number of lanes crossed by a pedestrian in anyone crossing maneuver, presence of bus stops, average neighborhood income, and number of commercial structures.

Schneider et al.[15] studied 81 urban signalized and unsignalized intersections in Alameda County (Oakland), CA. The significant predictors included pedestrian and traffic volumes. Other measures included the presence of a median on either the main road or cross street (decreased crashes), the presence of dedicated right-turn lanes, nonresidential driveways within 50 ft of the intersection, the number of commercial properties within 0.1 mi, and a proportion of residents within 0.25 mi under age 18 yr.

Quistberg et al.[16] used data from 2007 to 2013 to estimate the risk of pedestrian crashes at intersections and midblocks in Seattle, WA. They found that intersections had more pedestrian crashes than midblocks, nonresidential roads had higher crash rates than residential roads, and intersections with signals had about twice the crash rate as intersections without a signal. Locations with one-way roads or those with signs encouraging motorists to cede the right of way to pedestrians had fewer crashes. Crash rates were higher in locations with greater pedestrian activity (involving more bus use; more fast-food restaurants; or higher employment, residential, and population densities).

Miranda-Moreno, Morency, and El-Geneidy[17] studied the relationship of land use, demographic, and roadway factors in predicting both activity levels and pedestrian–motor vehicle crashes at 519 intersections in Montreal, Quebec, Canada. They concluded that most built environment and socioeconomic variables contribute to crash risk via their associations with pedestrian activity. However, the presence of transit stops and commercial property density contributed additionally to crash prediction, even with pedestrian flows included in crash prediction models. The presence of nearby schools was associated with reduced crashes.

In 2017, Thomas et al.[18] investigated analysis methods to identify and screen locations at risk for pedestrian crashes and injuries in Seattle, WA. They used data from the entire network to develop SPFs for two pedestrian crash types: total pedestrian crashes at intersections and a subset of intersection crashes involving through motorists striking crossing pedestrians. The AADP was estimated using manual intersection count data from 50 intersections that were adjusted using factors developed for San Francisco, CA, and included time of day, day of week, and land use. Both the natural logarithm of pedestrian volume estimate (ln_AADP_int) and the raw estimate of pedestrian volume (AADP_int) were associated with crashes with motor vehicles in both models. The combination of these variables resulted in a convex pattern where there is a critical AADP to which pedestrian safety is diminished; then pedestrian safety begins to improve with increasing numbers of pedestrians. The authors identified the value of 9,000 AADP as the point where increased number of pedestrians resulted in fewer crashes. They theorized that fewer crashes at higher pedestrian volume are due to drivers being more cautious where pedestrians are expected, or that busier roadways may contribute to slower traffic. They noted, however, that the relationship has not been firmly established in this study or previous studies. The authors found several demographic-related variables to be related to pedestrian crashes, such as total population and mean income. Other variables included transit activity, parking, number of commercial properties within 0.1 mi of the intersection, and average slope of the surrounding terrain. Geometric variables found to be significant included number of legs, number of lanes, road functional classification, and presence of traffic signal.

Xie et al.[19] identified factors contributing to pedestrian crashes at signalized intersections in Hong Kong. The database included 898 pedestrian crashes at 262 signalized intersections over a 3-yr period. They found the following variables as being positively related to pedestrian crash frequency: number of crossing pedestrians, number of passing vehicles, presence of curb parking, and presence of ground-floor shops. The presence of playgrounds near the intersection and the presence of exclusive pedestrian signals (all-red phase) for all crosswalks were associated with lower pedestrian crash frequency.

Geedipally et al.[20] developed an SPF for pedestrian crashes using data for 621 intersections in Texas. The crash data represented 3 yr (2017 to 2019), and the vehicle volume was based on 2018 average daily traffic from the Texas Department of Transportation (TxDOT) Road Highway Inventory Network Offload database or field data. The pedestrian volume counts were collected between 2015 and 2019 and were generally for 2 h and then expanded to daily equivalent values. Table 7 summarizes the modeling results for pedestrian crashes at signalized intersections.

Table 7. Calibrated coefficients for pedestrian crashes at signalized intersections from 2020 Texas study.[20]

Variable	Intersection Type	Value	Std Dev	*t*-Statistic	*p*-Value
Intercept	4-leg	−4.8428	1.0113	-4.79	<0.0001
Intercept	3-leg	−5.0672	1.0126	−5	<0.0001
Total entering vehicle volume (vehicles/day)	All	0.2272	0.09336	2.43	0.0152
Pedestrian volume (pedestrians/day)	All	0.1955	0.03172	6.16	<0.0001
Protected signal phasing	All	−0.1881	0.1016	−1.85	0.0646
Number of lanes	All	0.06504	0.04067	1.6	0.1103
Bus stop presence	All	0.3897	0.1598	2.44	0.015
Inverse dispersion parameter	All	0.4018	0.1063	3.78	0.0002

Std Dev = standard deviation.
Note: Observations = 621 intersections (4-leg = 582; 3-leg = 39).

Pedestrian Injuries

Mooney et al.[21] looked for a correlation between the built environment and pedestrian injuries at 532 New York City intersections. They found more injuries associated with marked crosswalks, traffic islands, signals, nearby billboards, and bus stops. They found fewer injuries associated with higher pedestrian volumes.

Safety Impacts of Pedestrian-Related Countermeasures

Kang[22] evaluated the safety benefits of changes to vehicle–pedestrian crashes for 11 street design elements installed between 2007 and 2015 at 118 intersections in New York City. Two treatments resulted in reductions in pedestrian crashes: pedestrian refuge islands and pedestrian plazas. Pedestrian refuge island installations had a larger reduction in pedestrian crashes when combined with lane removal or narrowing.

Several researchers focused on pedestrian crashes and left-turn vehicles. Lord[23] reviewed several research reports on the topic of left-turn-related pedestrian–vehicle crashes. The research found that left-turn maneuvers account for 20 to 30 percent of all pedestrian crashes at intersections. Left-turn-related pedestrian crashes are exceeded in number only by collisions between pedestrians and through vehicles (51 percent). Lord found that three-leg intersections (T-intersections) have a higher traffic conflict rate than four-leg intersections (X-intersections) and suggested that the finding is related to when pedestrians enter the intersection in relation to the start of the green phase.

Pratt et al.[24] showed similar correlations by developing the pedestrian–vehicle conflict model for left-turn vehicles. They developed guidelines for pedestrian safety in the left-turn operational mode at signalized intersections. Others who explored pedestrian safety at intersections and analyzed conflict between pedestrians and left-turn vehicles include Sayed and Zein,[25] Brosseau et al.,[26] Hussein et al.,[27] and Kumar, Madhumita, and Ghosh[28] examined the interactions using traffic conflict techniques such as post encroachment time. The authors developed a binary logistic regression model to identify significant contributing factors to the risk-taking behavior of pedestrians at four intersections. The model's results showed that pedestrians' age, gender, waiting time, and walking speed; type of crossing—whether a pedestrian crosses in a single stage (single gap for all lanes) or via rolling gaps (multiple gaps/different gaps per lane); number of pedestrians in the group; occurrence of conflicts in different quarters of the green interval (conflict is in first, second, third, or fourth quarter of green interval); and turning vehicle volume have a significant effect on the risk-taking behavior of pedestrians. The authors recommended a leading pedestrian interval countermeasure to address the greater number of conflicts that occur in the first and second quarters of the green interval.

The benefits of leading pedestrian intervals, along with protected/permissive left-turn phasing, were documented in a 2018 FHWA study.[29] The study showed that the provision of protected left-turn phasing reduced vehicle–vehicle injury crashes but did not produce statistically significant results for vehicle–pedestrian crashes overall. A disaggregate analysis of the effect of protected or protected/permissive left-turn phasing on vehicle–pedestrian crashes indicated that this strategy may be more beneficial when there are higher pedestrian and vehicle volumes, particularly above 5,500 pedestrians per day. The evaluation of leading pedestrian intervals showed that the countermeasure reduced vehicle–pedestrian crashes (CMF of 0.87).

Several studies have supported the use of a pedestrian refuge island or a raised median. The Schneider et al.[15] study, which found a decrease in crashes when the median was present on either the main road or cross street, included urban signalized and unsignalized intersections. Two previous studies focusing on locations with a pedestrian hybrid beacon found fewer pedestrian crashes when a raised median was present on the major roadway.[30,31] FHWA includes raised medians as a proven countermeasure and notes that a previous study[32,33] found a 39 percent reduction in pedestrian crashes for raised medians with unmarked crosswalks and 46 percent reduction for raised medians with marked crosswalks. A more recent study for uncontrolled pedestrian crossing treatments found a 31.5 percent reduction in pedestrian crashes after the installation of a raised median.[3] The study sites were a combination of intersection and midblock locations.

PEDESTRIAN CMFs AT SIGNALIZED INTERSECTIONS

Several CMFs related to pedestrians and signalized intersections are included in the CMF Clearinghouse.[1] The majority are related to the timing and phasing of the traffic control signal, such as using all-red clearance interval, changing permissive left-turn phase to protected only or protected/permissive phasing, proving split phases, installing adaptive traffic signal control, modifying the signal clearance interval, implementing an exclusive phase with diagonal crossings (e.g., Barnes Dance), increasing the cycle length for pedestrian crossing, and adding leading pedestrian interval. With regard to geometry, a CMF is available for installing left-turn lanes; however, the factors are available for all crash types including head-on crash type but excluding pedestrian crash types.

CMFs are also available for the installation of the pedestrian hybrid beacons and signing and marking treatments, such as advance yield or stop markings and signs, high-visibility crosswalk markings, and right-turn-on-red movement prohibitions.

RIGHT-TURN CRASHES AT SIGNALIZED INTERSECTIONS

Right-turn vehicle volume affects intersection capacity and delay. The interactions between pedestrians and right-turn vehicles also contribute to pedestrian delay and exposure. Various treatments have been implemented to address delay, such as installing a channelized right-turn lane or adding a dedicated lane downstream of the end of an exclusive right-turn lane. These treatments generally focus on vehicle operations rather than safety or pedestrians. A growing trend is not installing or removing or modifying the channelized right-turn lane geometry. For example, the installation of a smart channel right turn results in a more perpendicular angle of channelization (approximately 70 degrees), which widens the cone of vision of the driver toward the pedestrians as well as the cross traffic. The result from an Austin, TX, study showed that smart channel right turns can reduce overall right-turn crashes by 47 percent and severe right-turn crashes by 40 percent.[34]

A few studies have identified safety concerns for pedestrians at channelized right-turn locations, including work by Fitzpatrick, Schneider, and Park[35] and Muley et al.[36] The study by

Fitzpatrick, Schneider, and Park[37] found that variables that affect the vehicle turning speed at a channelized right-turn lane include corner radius, lane length, and island size at the beginning of the turn; and corner radius, lane length, and turning roadway width near the middle of the turn. Researchers for a Georgia study concluded that treatments that had the highest number of crashes were right-turn lanes with raised islands.[38] This type of intersection had the second highest number of crashes of the treatments evaluated in the Texas study.[35] In both the Texas and Georgia studies, the shared through with right lane combination had the lowest number of crashes. A study by Potts et al.[39] that used crash data from 1999 to 2005 found channelized right turns do not increase crash risk. Jiang et al.[40] noted that several factors may increase risks for pedestrians, including uncontrolled crosswalks on channelized right-turn lanes, where pedestrian right-of-way relies on the compliance of drivers, and increased turning radius, which may lead to higher vehicle turning speeds.

Jiang et al.[40] investigated the impact of channelized right turns on pedestrian safety using surrogate safety measures. Video data were collected at 12 signalized intersections in the city of Zunyi, China, that included three types of right-turn designs: nonchannelized right-only lanes, nonchannelized right-through lanes, and channelized right-turn lanes. Results indicate that the use of channelized right-turn lanes increases pedestrian risks at signalized intersections. The authors concluded that cities should be cautious when installing channelized intersections as a safety countermeasure and that treatments are needed to improve pedestrian safety if channelized right turns are implemented.

In a 2017 study, Muley et al.[36] investigated factors influencing the behavior of 235 pedestrians crossing at a marked crosswalk located on dedicated right-turn lanes for a study site in Doha, Qatar. Gender, distraction, and group size significantly affected the pedestrian crossing speed. Distracted pedestrians and pedestrians crossing in groups waited for significantly larger gaps compared to undistracted and individual pedestrians. Only about 15 percent of drivers yielded to the pedestrians.

RIGHT-TURN CMFs

Several CMFs related to right turns at signalized intersections (geometry features) are in the CMF Clearinghouse,[1] including the following:

- Change right-turn lane geometry to increase line of sight (approach level), also known as smart right turn or smart channel.
- Install right-turn lane on minor road of a signalized T-intersection (motorcycle crashes).
- Install right-turn lane on major road of a signalized T-intersection (motorcycle crashes).
- Provide an exclusive left or right turn on either approach (transit-serviced locations).
- Provide an exclusive right-turn phase at diamond interchange ramps.
- Provide a right-turn lane on arterial with signal coordination.
- Provide a right-turn lane on both major road approaches.
- Provide a right-turn lane on one major road approach.

Most of the CMFs are related to the addition of a right-turn lane. Some of the CMFs are focused on crash types other than pedestrians, such as for motorcycle crashes. Typically, the CMFs are for all crash types or the right-turn crash type, with none of them having a CMF uniquely for the pedestrian crash type.

In 2002, Harwood et al.[41] reported on a major study on the benefits of turn lanes. They noted that right-turn crashes are typically less frequent than left-turn crashes. When a right-turn lane was added on a road approach or on two approaches at a traffic signal, a CMF of 0.96 or 0.92, respectively, was reported. The CMFs were for all crash types and all severity levels for both urban and rural conditions.

A study on the impact of arterial signal coordination examined the impact on frequency and severity of rear-end and right-angle crashes.[42] The study found that the presence of a right-turn lane was associated with a large reduction in rear-end crashes (CMF of 0.06) and right-angle crashes (CMF of 0.32).

CMFs are also available for right turn on red and permitted or prohibited signal phasing.

CORNER RADIUS DESIGN

The selection of a large radius for a corner permits higher turning vehicle speeds in free-flow situations. The higher vehicle speeds may result in smaller speed differentials with following vehicles and thus less severe rear-end conflicts in the through lanes. While the potential increased vehicle speed through the right-turn lane is more efficient for the driver, tradeoffs exist for this design. Increased vehicle speeds create more challenges for pedestrians attempting to cross the roadway. Some of these challenges, in the authors' opinion, include evaluating vehicle gaps, managing the driver's expectation that he or she does not have to stop since a "free-flow" right-turn lane is present, and anticipating the potential increased severity of vehicle–pedestrian crashes. While it is commonly accepted that a larger corner radius is associated with higher turning speed, few studies have attempted to quantify that relationship.

Right-Turn Speeds

An objective of a 2004 TxDOT research effort was to determine which right-turn lane design elements affect free-flow speeds of vehicles in an exclusive right-turn lane.[43,44] A complete description of the technique used to collect and reduce the free-flow speed data is contained in the TxDOT report, *Turn Speeds and Crashes within Right-Turn Lanes*.[43] The authors of the report evaluated 17 exclusive right-turn lane approaches. All intersections were located in urban/suburban areas with traffic control signals present. The smallest radius was 27 ft and the largest radius was 86 ft. There were seven radii less than 40 ft, three radii between 40 and 50 ft, and eight radii greater than 50 ft.

Road tube classifiers were used to collect speeds at the beginning of the turn and near the midpoint of the turn. Video cameras located at each intersection provided additional information on the behavior of the vehicle traveling through the lane. A minimum of 30 free-flow vehicles per approach for the study period was desired. At two of the sites, drivers would either turn into the near lane (following the radius of the curb return) or turn into the second lane of the cross street, therefore using a larger radius. For these two sites, the corner radius value used for a particular car in the analysis depended on whether the vehicle turned into the near lane or the far lane.

The final sample size per approach varied from 4 (due to equipment malfunction) to 174 vehicles. For the analysis, the speeds per site were not summarized into an average or 85th percentile value, but speed measurements for each individual vehicle along with the associated intersection geometry (such as corner radius) were used in the analysis. This approach permitted the consideration of each unique vehicle rather than the collapse of the variability of a site into one value (frequently the 85th percentile value). Free-flow speed for this study was defined as the speed at which a vehicle traveled with a minimum 5-s headway from the vehicle in front of it and 3-s tailway from the vehicle behind it.

Site characteristics considered in the evaluation included:

- Corner radius.
- Channelization.
- Right-turn lane length.
- Right-turn lane width.

An analysis of the covariance model was selected to determine which of the predictor variables had a significant effect on turning speed. In the analysis, channelization was a discrete factor (either island or line), while radius, right-turn lane length, and right-turn lane width were continuous factors. In addition to these variables, all possible two-way interactions were checked. The results showed significant interaction effects between channelization and other factors, suggesting that the effects of radius, right-turn lane length, and right-turn lane width are different for each type of channelization. Therefore, a separate model was fitted for sites with an island and sites with a lane line dividing the right-turn lane from the through lane.

When examining the speed near the middle of the right turn, the researchers found radius and right-turn lane length to be significant. The effect of right-turn lane width was statistically significant at the 0.05 significance level for sites where the right-turn lane was separated from the through line with a lane line, but not for sites with an island.

An additional analysis was conducted with the data for the 13 approaches with raised islands. In addition to the variables used in the previous evaluations (radius, right-turn lane length, right-turn lane width), this evaluation also included island size and turning roadway width. The significant variables for a right-turn vehicle on an approach with a raised island included:

- Radius.
- Right-turn lane length.
- Turning roadway width.

Research on Operational Effects of Right-Turn Vehicles

A few more studies are available on the operational effects of right-turn vehicles. Some studies investigated deceleration on the approach to the right turn,[45,46,47] the location upstream where right-turn vehicles affect operations,[48] and the amount of delay caused by right-turn vehicles.[49,50,51] These studies, however, did not report or discuss the turning speed of the right-turn vehicles.

Urban Smart Channel/Improved Right-Turn Slip Lane

An alternative to the conventional channelized right-turn lane design is a design that decreases the angle of the right-turn channelization to approximately 70 degrees. The change of the angle would also be accompanied by a change in the design of the radius for the corner. Figure 3 and figure 4 show a roadway in Austin, TX, before and after the urban smart channel design was implemented. This type of design has been described in different ways, including as an urban smart channel, a modified right-turn lane design, and an improved right-turn slip lane.

Figure 3. Photo. Lamar and Palmer intersection (southeast corner) in Austin, TX, before the installation of an urban smart channel.

Figure 4. Photos. Lamar and Palmer intersection (southeast corner) in Austin, TX, after the installation of an urban smart channel.

The design brings the turning vehicle closer to 90 degrees of the cross traffic and widens the cone of vision of the driver toward the pedestrian and to the cross traffic. Benefits can include shorter total pedestrian crossing distance, pedestrians crossing at closer to a right angle to traffic, the presence of the crosswalk in an area where the driver is still looking ahead, improved visibility to pedestrians, and slower right-turn vehicle speeds.

The *Handbook for Designing Roadways for the Aging Population*(52) describes the design as having the "tail" pointing to approach traffic. The "Pedestrian Safety Guide and Countermeasure Selection System"(53) discusses several key features, including graphics that provide suggested island design dimensions (2:1 length-to-width ratio) and corner complex radii dimensions (150- to 275-ft initial radius followed by a 25- to 40-ft radius depending on design vehicle).

A study of a site in Austin, TX, examined the change in number of crashes; however, speed of turning vehicles before and after such an improvement was not reported.(54) A study in Peoria, IL, included the observation of driver behavior along with evaluation of the change in crashes due to the modifications of the right-turn approaches.(55) Field observations of driver behavior at the right-turn lanes at 10 test sites and 10 control sites were collected. The authors concluded that drivers traveling through the modified right-turn lane design (test sites) used safer driving behaviors compared with the traditional design (control sites). They found that drivers at the test sites exhibited the following behaviors:

- Used fewer exaggerated head turns.
- Performed fewer roll-and-go stops.
- Stopped on or before the stop bar more frequently.

The authors concluded that drivers at the modified right-turn lane design would travel at slower speeds based on their observed driving behavior; however, turning speeds were not collected.

CHAPTER 4. DATA COLLECTION AND INTEGRATION FOR CORNER-LEVEL ANALYSIS

SITE SELECTION

The primary goal of the safety data analysis for this study was to investigate the influence of the corner radius on pedestrian or right-turn crashes at signalized intersections. The analysis sought to account for pedestrian exposure and right-turn radii at urban signalized intersections. Thus, it was necessary to identify sites where pedestrian volume counts had been collected at signalized intersections. With the assistance of the project stakeholder engagement working group and other contacts, the research team identified the cities of Richmond, VA; Bellevue, WA; and Portland, OR, as data sources. Richmond, VA, had hired a consultant within the past few years to conduct turning movement and pedestrian counts at many of its signalized intersections for use in updating traffic signal timing plans. The city provided a copy of the counts to the research team. The City of Portland maintains a website that includes traffic volume, traffic speed, and turning movement data.(56) The research team reviewed the turning movement counts and selected sites with at least one pedestrian counted. These sites were later reviewed, and intersections that did not have a traffic control signal were removed. Bellevue, WA, provided vehicular turning movement and pedestrian counts.

OVERVIEW OF DATABASE DEVELOPMENT

In addition to the volume (exposure) data, the research team collected or obtained geometric data and crash data. These three datasets merged together created the database used in the analysis. Preliminary reviews indicated a potential approach for assigning crashes to a corner that would allow the specific corner radius to be considered in the evaluation model. In addition, the roadway conditions on the approach leg and on the receiving leg could be uniquely considered in the analysis. After reviewing the crash data, the approach of assigning crashes to a corner was appropriate for the Virginia and Washington crash data but not the Oregon crash data. Therefore, two crash databases were created—a corner-level database and an intersection-level database. Figure 5 shows the flowchart of how merging the data streams created the databases used in the corner-level analysis.

The research team obtained geometric data for the corners and intersections of interest using aerial photographs. The crash data were obtained through requests to the States. The following section describes the research team's efforts to assemble the component datasets and develop the merged databases for statistical analysis.

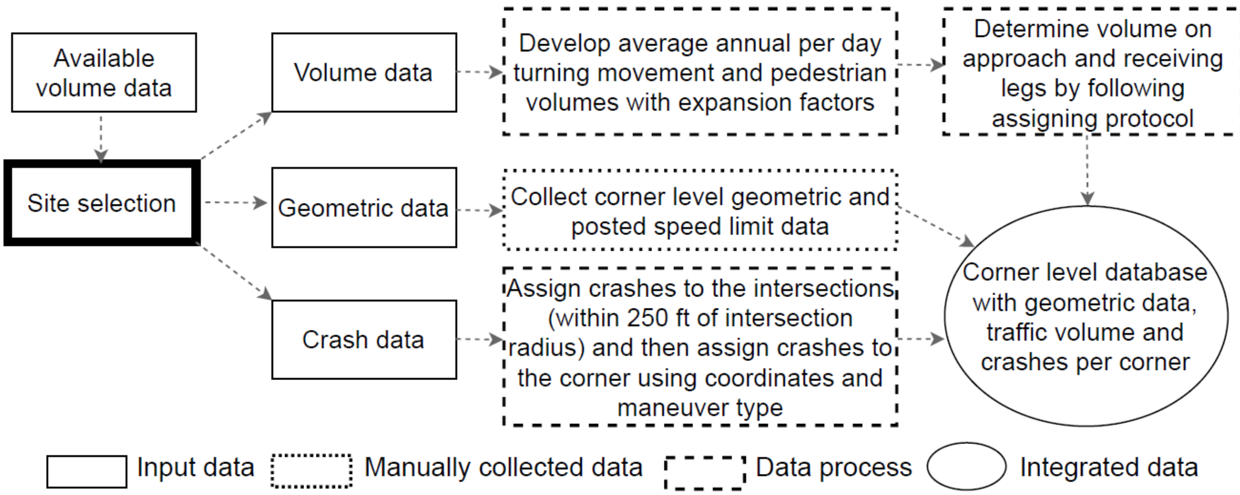


Figure 5. Flowchart. Corner-level data preparation.

CRASH DATA

Sources for Crash Data

The research team requested crash data records for 5 to 7 yr for the three cities from their respective States[1] and received data from:

- Washington for 2011 to 2017 (7 yr).
- Virginia for 2013 to 2018 (6 yr).
- Oregon for 2012 to 2017 (7 yr).

The crash records were assigned to intersections using the latitude and longitude coordinates for each crash and the centers of the intersections in the geometric database. Relevant crashes included all crashes that occurred within 250 ft of an intersection center.

The research team aggregated the crashes by severity using the KABCO scale, where:

- K = fatal.
- A = incapacitating injury.
- B = non-incapacitating injury.
- C = possible injury.
- O = no injury, property damage only.

The research team also identified if the crash involved a pedestrian or a right-turn vehicle.

[1]Data files were obtained by the research team via personal communication with the states of Washington, Virginia, and Oregon.

For the Virginia crash data, the research team used the following variables to examine the crash details:

- Drivervehiclenumber: to determine the number of vehicles involved in the crash.
- Ped_Nonped: to determine if the crash involved a pedestrian.
- Vehicle_Maneuver_Type_Cd: to determine each vehicle's maneuver type (left turn, through, right turn, or stopped).
- Driver_Action_Type_Cd: to determine if the crash involved a wrong-way movement.
- Collision_Type: to categorize the crashes as rear end, right angle, and so on.
  Direction_Of_Travel_Cd: to determine each vehicle's cardinal direction of travel.

For the Washington crash data, the research team used the following variables to examine the crash details:

- TOTAL_VEH: to determine the number of vehicles involved in the crash.
- Ped_ind: to determine if the crash involved a pedestrian.
- FIRST_COLL_TYPE_OBJ_STRUCK and SECOND_COLL_TYPE_OBJ_STRUCK: to determine if the crash was right-turn related.
- VEH_1_ACTION, VEH_2_ACTION, and VEH_3_ACTION: to determine each vehicle's maneuver type (left turn, through, right turn, or stopped).
- VEH_1_DIR_FROM, VEH_1_DIR_TO, VEH_2_DIR_FROM, VEH_2_DIR_TO, VEH_3_DIR_FROM, and VEH_3_DIR_TO: to determine each vehicle's cardinal direction of travel.
- FIRST_COLL_TYPE_OBJ_STRUCK and SECOND_COLL_TYPE_OBJ_STRUCK: to categorize the crashes as rear end, right angle, and so on.

For the Oregon crash data, the research team used the following variables to examine the crash details:

- CRASH_SVRTY_CD: to determine the injury type.
- COLLIS_TYP_SHORT_DESC: to determine if the involved party is a pedestrian or bicyclist.
- CRASH_TYP_SHORT_DESC: to determine the collision type (rear end, head on, turn, and so on).
- LAT_DD: to determine the latitude of the crash (to assign the crash to the related intersection or corner).
- LONGTD_DD: to determine the longitude of the crash (to assign the crash to the related intersection or corner).
- TOT_VHCL_CNT: to determine the number of involved vehicles in a crash.

The crash type variable available for the Oregon crash data allowed for the identification of a turning vehicle ("turn-related only"); however, whether that vehicle was turning right or turning left was not available.

Assigning Crashes to Intersection Corner

The crashes were initially assigned to intersection corners using coordinates (Corner_Coor). The variables that described vehicle maneuver types and travel directions were then used to adjust the assignment (Corner_VehManTyp). The crash databases from the States included latitude and longitude coordinates for each crash location. The research team obtained coordinates for the center of each intersection and then used trigonometry to compute the heading of a line drawn from the intersection center to the crash location. The research team used these headings and measurements of the intersection's orientation with respect to the cardinal directions to assign crashes to intersection sides (north versus south and east versus west). For example, if both intersecting streets were perfectly aligned to the cardinal directions, a crash would be assigned to the east side of the intersection, if the heading of the line drawn from the intersection center to the crash location was 0 to 180 degrees, and it would be assigned to the south side of the intersection if the heading was 90 to 270 degrees. The research team initially assigned the crashes to corners based only on the intersection sides. For example, if the crash were on the east side and the north side, its corner would be designated as northeast.

After conducting this preliminary corner assignment, the research team further examined the crash details, such as the direction of travel for each vehicle, maneuver type (left turn, through, right turn, or stopped), and number of vehicles involved. The research team revised some corner assignments if the preliminary assignment was not consistent with the crash details. For example, any of the following crashes would be assigned to the northeast corner, provided no wrong-way movements occurred:

- Crashes involving a westbound right-turn vehicle.
- Crashes on the north side of the intersection with the first vehicle proceeding northbound, if the crash type was one of the following:
  - Single vehicle.
  - Two-vehicle rear end involving left-turn and/or through vehicles.
  - Two-vehicle, same-direction sideswipe.
  - Vehicle–bicycle.
- Crashes on the east side of the intersection with the first vehicle proceeding westbound, if the crash type was one of the following:
  - Single vehicle.
  - Two-vehicle rear end involving left-turn and/or through vehicles.
  - Two-vehicle same-direction sideswipe.
  - Vehicle–bicycle.
- Two-vehicle, right-angle crashes involving two through vehicles with one vehicle proceeding northbound and the other proceeding westbound.
- Two-vehicle, right-angle crashes involving a westbound left-turn vehicle and a northbound through vehicle. (In this case, the driver's side of the left-turn vehicle is impacted.)

- Two-vehicle, right-angle crashes involving an eastbound left-turn vehicle and a northbound through vehicle. (In this case, the passenger's side of the left-turn vehicle is impacted.)
- Two-vehicle, left-turn-opposed crashes involving a westbound through vehicle and an eastbound left-turn vehicle.

Any crash types not included in the preceding list would be assigned to corners based on their coordinates alone. The research team identified analogous combinations of the variables for the other three corners and reassigned crashes to those corners accordingly. Figure 6 shows the corner labeling convention, and figure 7 through figure 15 illustrate the various crash combinations. The figures show four-leg intersections. In the case of three-leg intersections, the research team used the same corner assignment process but excluded crashes that were assigned to an intersection quadrant that did not include a right-turn movement.

If the north leg was not present, any crashes assigned the northwest or northeast quadrants were not included in the analysis because the intersection did not have westbound or southbound right-turn movements and, thus, did not have corners in those quadrants.

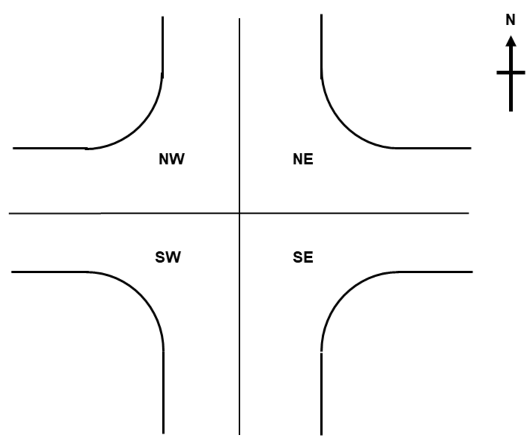


Figure 6. Sketch. Crash assignments to corners based on crash characteristics: corner labeling convention.

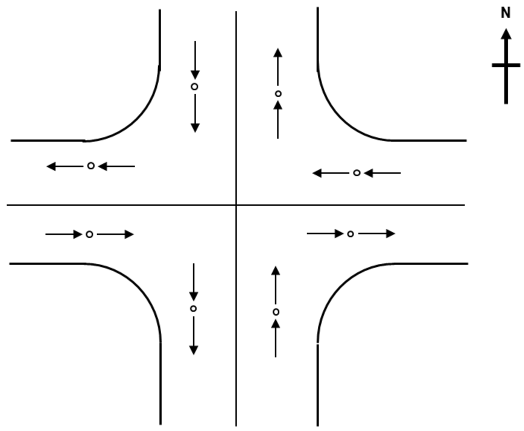


Figure 7. Sketch. Crash assignments to corners based on crash characteristics: through-through rear end.

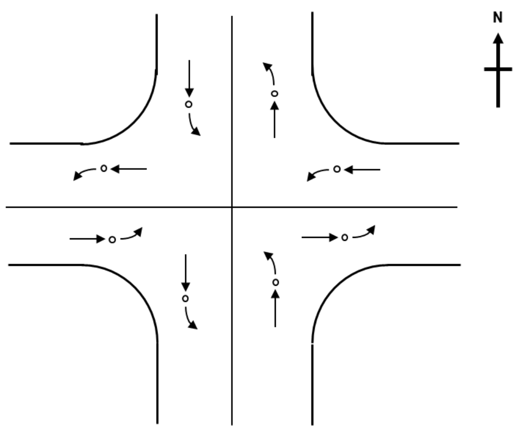


Figure 8. Sketch. Crash assignments to corners based on crash characteristics: through-left rear end.

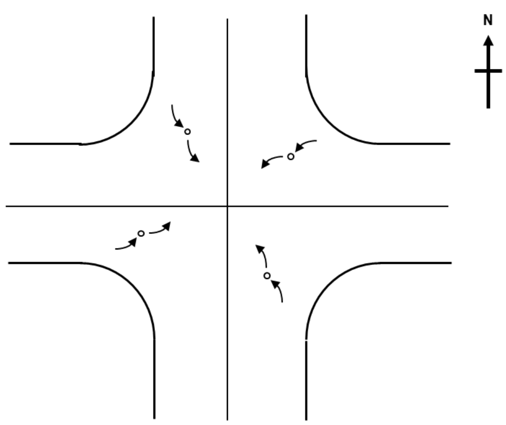


Figure 9. Sketch. Crash assignments to corners based on crash characteristics: left-left rear end.

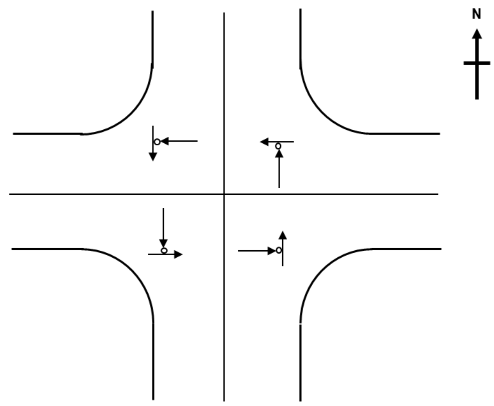


Figure 10. Sketch. Crash assignments to corners based on crash characteristics: right-angle, two throughs, driver's side impacted.

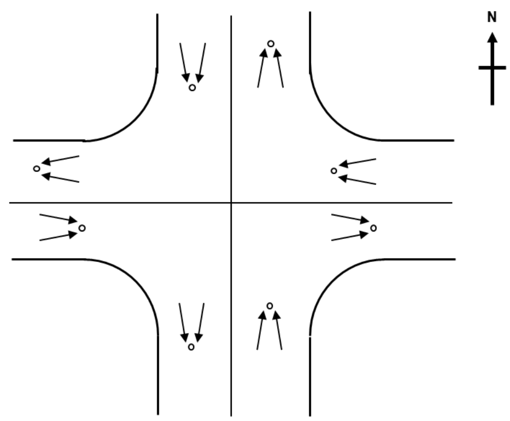


Figure 11. Sketch. Crash assignments to corners based on crash characteristics: same-direction sideswipe, two throughs.

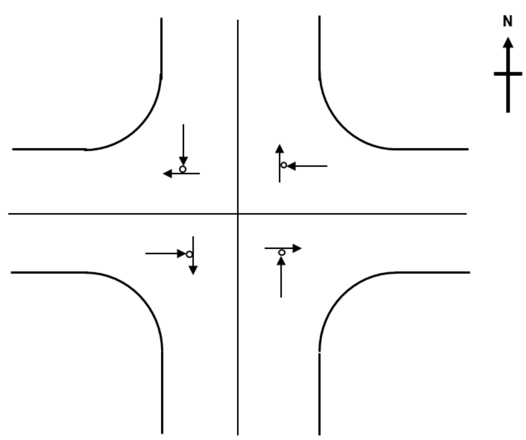


Figure 12. Sketch. Crash assignments to corners based on crash characteristics: right-angle, two throughs, passenger's side impacted.

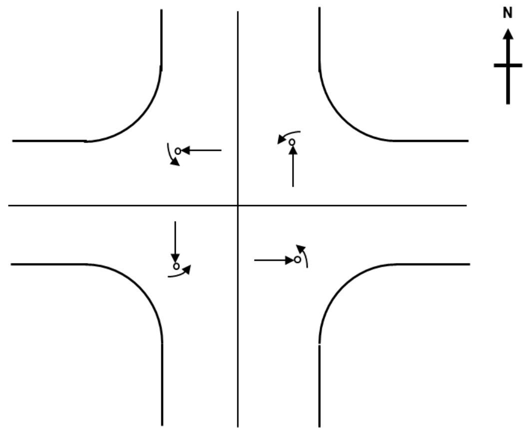


Figure 13. Sketch. Crash assignments to corners based on crash characteristics: right-angle, through and left, driver's side impacted.

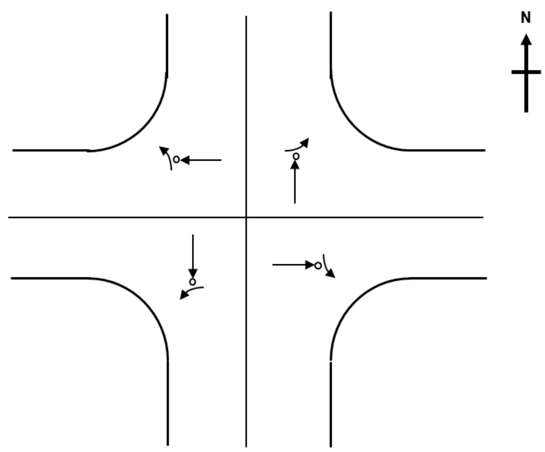


Figure 14. Sketch. Crash assignments to corners based on crash characteristics: right-angle, through and left, passenger's side impacted or same-direction sideswipe, through and left.

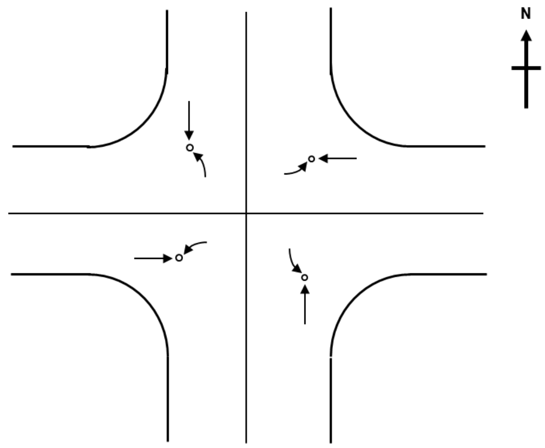


Figure 15. Sketch. Crash assignments to corners based on crash characteristics: left-turn opposed.

An examination of the distribution of crashes and volumes by assigned corners revealed that a disproportionate number of crashes in Oregon were located at the southeast corner. As table 8 shows, 49 percent of KABC crashes and 61 percent of pedestrian KABCO crashes are associated with the southeast corner; however, the average pedestrian volume for that corner is similar to the average for the other three corners. The average vehicle volumes are also similar for all four corners. This finding suggests that many Oregon crashes had been assigned to the southeast corner by default because their precise location was not known. Thus, corner-based analyses were conducted only for the Virginia and Washington sites.

Table 8. Distribution of Oregon crashes by corner.

Values	Northeast	Northwest	Southeast	Southwest
Number of corners	139	139	133	129
KABC crash distribution (percent)	19	13	49	19
KABCO crash distribution (percent)	19	14	47	20
Ped_KABCO crash distribution (percent)	12	7	61	21
Average of corner pedestrian volume (no.)	576	557	521	532
Corner pedestrian volume distribution (percent)	27	26	23	23
Average of corner vehicle volumes (no.)	15,737	15,676	14,838	15,398
Corner vehicle volume distribution (percent)	26	26	24	24

KABC = all crashes with injury levels of K, A, B, or C; KABCO = all crashes with any severity level; Ped_KABCO = pedestrian-involved crashes for any severity level.

Corner-Level Crash Data

Table 9 provides the number of corners by the number of legs present at the intersection for the corner-level database. The corner-level analysis considered 1,285 corners, with most being from Virginia. Table 10 provides the number of crashes assigned to an intersection corner for the Virginia and Washington intersections, including all crashes (KABCO) and severity levels (KABC), right-turn-related crashes with injury levels of K, A, B, C, or O (RT_KABCO), right-turn-related crashes with injury levels of K, A, B, or C (RT_KABC), and pedestrian-related crashes with injury levels K, A, B, C, or O (Ped_KABCO).

Table 9. Number of corners considered in statistical analysis.

Intersection Legs	Virginia	Washington	Grand Total
3	78	17	95
4	939	251	1,190
Grand total	1,017	268	1,285

Table 10. Per-year crash data descriptive statistics by intersection corner for Virginia and Washington.

State	Measure	KABCO/ yr	KABC/ yr	RT_KABCO/ yr	RT_KABC/ yr	Ped_KABCO/ yr
VA	Average	1.20	0.36	0.10	0.03	0.04
WA	Average	1.70	0.46	0.10	0.03	0.05
VA	Std Dev	1.34	0.47	0.19	0.07	0.10
WA	Std Dev	2.33	0.68	0.21	0.08	0.11
VA	Min	0.00	0.00	0.00	0.00	0.00
WA	Min	0.00	0.00	0.00	0.00	0.00
VA	Max	14.00	4.17	2.83	0.67	1.00
WA	Max	11.14	4.57	1.43	0.57	0.57
VA	75 percent	1.50	0.50	0.17	0.00	0.00
WA	75 percent	2.43	0.71	0.14	0.00	0.00
VA	50 percent	0.83	0.17	0.00	0.00	0.00
WA	50 percent	0.57	0.14	0.00	0.00	0.00
VA	25 percent	0.33	0.00	0.00	0.00	0.00
WA	25 percent	0.14	0.00	0.00	0.00	0.00

VA = Virginia; WA = Washington.
Note: Per-year crashes for Washington reflect crashes between 2011 and 2017 (7 yr). Per-year crashes for Virginia are between 2013 to 2018 (6 yr).

Quantifying the Uncertainty of Conflicting Information in Linking Crashes to Corners

Because uncertainty inevitably rises when different pieces of information indicate conflicting conclusions about the crash corner match, the research team decided to develop a scale to assess the level of certainty linked with each match. The scale ranges from low to high, and the levels were assigned according to the conditions listed in table 11.

Using the appropriate crash codes for both Washington and Virginia in combination with the definitions in table 11, the research team assessed the match of each crash to a corner. Table 12 shows the summary statistics of this exercise.

The table shows that the certainty about the corner assignment is slightly higher for Virginia than Washington. While Virginia has 68.6 percent of crashes assigned with high certainty, Washington has 61.1 percent. On the other end of the scale, while Virginia has only 1.9 percent of its crashes assigned with low confidence, Washington has 8.2 percent.

The intent of assessing the certainty level as just described is to develop a set of weights for the analysis so that the results reflect the level of certainty of the corner crash assignment: crashes with a high-certainly level will influence the result to a larger degree than crashes with a low-certainty level. The development of weights is further described in the section Weights Development.

Table 11. Certainty levels for crash corner assignments.

Condition	Certainty Level	Rationale
The two methods of assignment agree (i.e., Corner_Coor = Corner VehManTyp).	High	No evidence of methods contradicting each other.
The initial and revised method disagree, and the crash involved a right- or left-turn crash.	Medium–High	Anecdotal evidence indicates that this condition inflates the count of right-turn crashes where there should not have been any.
There are more than four vehicles in the crash.	Medium	With that many vehicles, the crash probably involves vehicles from/at more than one leg.
The crash type is angle, but the directions of travel for the first two vehicles involved are equal.	Medium	Angle crashes typically involve vehicles with different travel directions.
The crash type is sideswipe, but the directions of travel for the first two vehicles involved are neither equal nor opposite.	Medium	Sideswipe crashes typically involve vehicles traveling in the same or opposite directions.
The crash type is rear end, but the directions of travel for the first two vehicles involved are different.	Low	Rear-end crashes typically involve vehicles traveling in the same direction.
Corner_Coor does not equal Corner_ VehManTyp and is not covered in one of the above conditions.	Medium	For conditions not covered elsewhere.

Table 12. Certainty level descriptive statistics per State.

	Certainty Levels in Corner Crash Assignment							
	High		Medium–High		Medium		Low	
	Count	Percent	Count	Percent	Count	Percent	Count	Percent
Virginia	6,713	68.6	331	3.4	2,562	26.2	182	1.9
Washington	2,525	61.1	49	1.2	1,220	29.5	337	8.2

IDENTIFYING DAILY EXPOSURE DATA

The vehicle turning movement and pedestrian count data files contained a tabulated turning movement and pedestrian count for one signalized intersection as either a spreadsheet or a scanned data form. The research team initially attempted to use software to convert the scanned traffic count data sheets into an electronic spreadsheet format, but too many errors were introduced. Therefore, the research team retyped the data that were only available as PDFs. A spreadsheet macro was then used along with manual checks and adjustments as needed to assemble the source files into one master volume file for each State.

The master files contained a worksheet that provided data records for each 15-min period for each intersection approach leg studied in each turning movement count. Each record included the source study name and number; study date; starting time of the 15-min period; number of intersection legs; street name and travel direction for the approach leg; count of left-turn, through, and right-turn vehicles on the approach leg; and count of pedestrians crossing the approach leg. Washington data sheets included a unique count of bicyclists along with a unique count of pedestrians that also included bicycles in the crosswalk. The turning movement counts in Oregon and Virginia included a column for pedestrians but not a column for bicyclists. Hourly volumes were computed for left-turn, through, right-turn, and total approach leg vehicles, and for pedestrians for each study hour at each site.

Expanding Short-Term Counts to Daily Counts

Because the count data generally only reflected several hours within a day for the leg, the counts needed to be expanded to represent a daily count and then an annual value for both vehicles (AADT) and pedestrians (AADP). Several resources were reviewed and considered when developing the adjustment factors. The two sources that influenced the adjustment factors used in this project included National Cooperative Highway Research Program (NCHRP) Report 841[57] for pedestrians, and the *2019 Urban Mobility Report*[58] for vehicles. An average of the morning and afternoon data for nonfreeway moderate congestion available in the *2019 Urban Mobility Report* was used to obtain the hourly adjustments (figure 16). A monthly adjustment was not used for the vehicle counts. For the pedestrian counts, values available in NCHRP Report 841 were utilized. The data are based on counts made in Charlotte, VA, which has weather comparable to that of Richmond, VA. A similar rich database of daily and seasonal pedestrian counts for other regions was not identified; therefore, the adjustment factors used for Virginia were also used for the Oregon and Washington pedestrian counts. NCHRP Report 841 also includes seasonal adjustments for winter (December to February), spring (March to May), summer (June to August), and fall (September to November), and these values were used to generate an adjustment factor for each hour of the day and each month of the year. Table 13 lists the pedestrian count adjustment factors used in this project. The expansion factors were used to estimate daily vehicular and pedestrian volumes for each study hour at each site.

The mean, standard deviation, and minimum and maximum daily vehicular and pedestrian volumes at each site were determined. The research team used the standard deviation and the minimum and maximum values to check for outliers in the volume data. When multiple hours of counts were available for a site, the adjustments were applied to each hour, and then an average of the available counts was used to identify the annual vehicle or annual pedestrian counts to be used in the statistical evaluation.

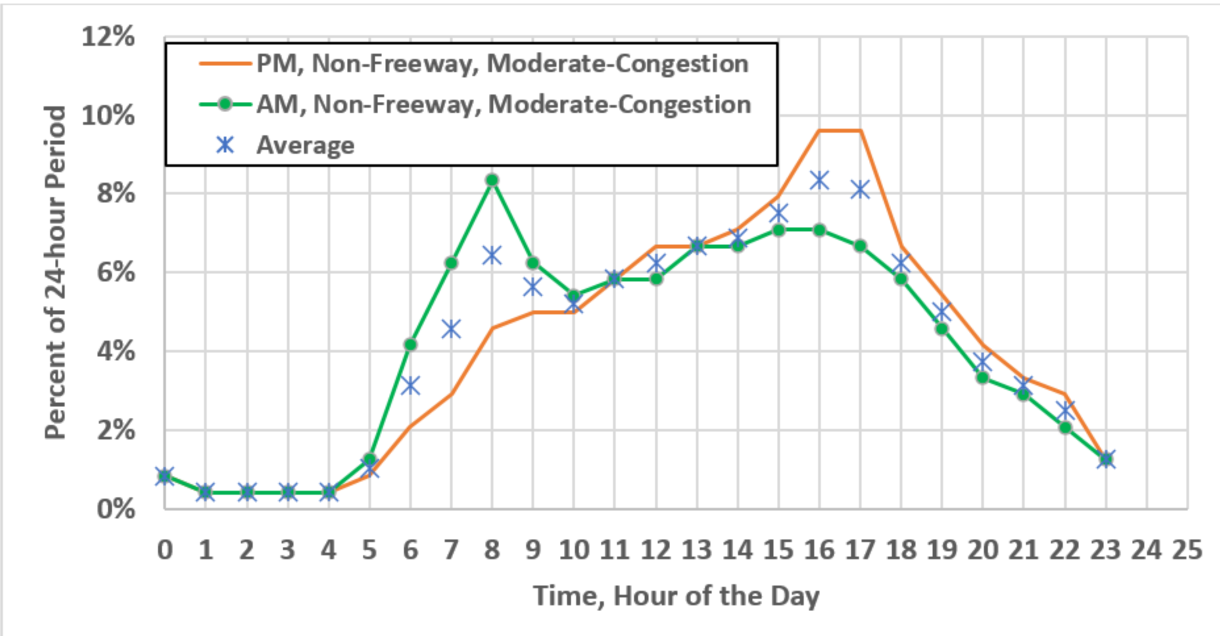


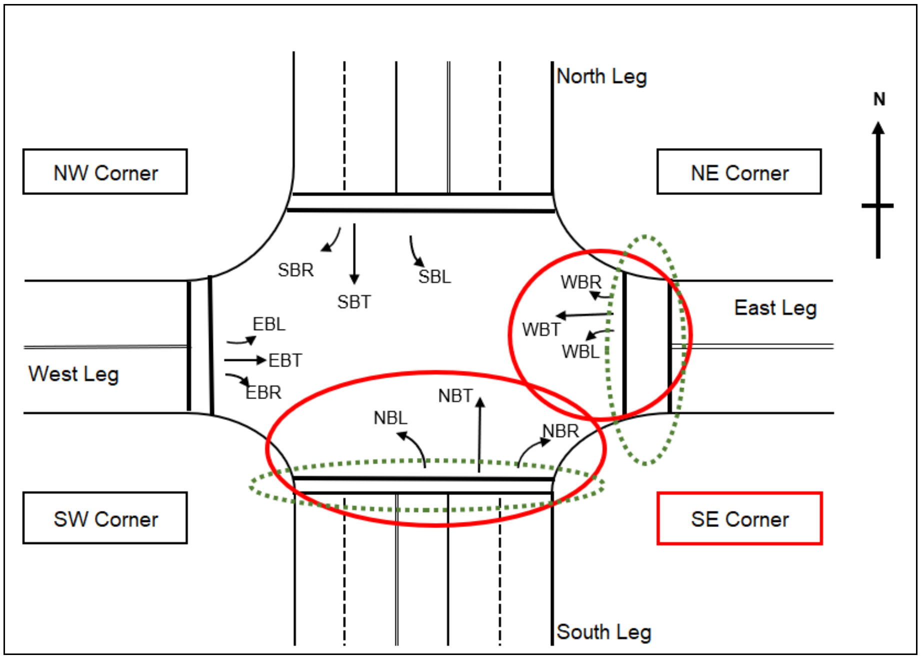
Figure 16. Graph. Daily vehicle distribution used for adjusting vehicle counts.

Table 13. Daily and monthly adjustment factors for pedestrian counts.

Hr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	17.42	17.42	17.95	17.95	17.95	17.83	17.83	17.83	19.05	19.05	19.05	17.42
7	14.95	14.95	15.38	15.38	15.38	15.27	15.27	15.27	16.34	16.34	16.34	14.95
8	13.07	13.07	13.46	13.46	13.46	13.37	13.37	13.37	14.29	14.29	14.29	13.07
9	14.95	14.95	15.38	15.38	15.38	15.27	15.27	15.27	16.34	16.34	16.34	14.95
10	17.42	17.42	17.95	17.95	17.95	17.83	17.83	17.83	19.05	19.05	19.05	17.42
11	13.07	13.07	13.46	13.46	13.46	13.37	13.37	13.37	14.29	14.29	14.29	13.07
12	11.61	11.61	11.98	11.98	11.98	11.88	11.88	11.88	12.71	12.71	12.71	11.61
13	11.61	11.61	11.98	11.98	11.98	11.88	11.88	11.88	12.71	12.71	12.71	11.61
14	13.07	13.07	13.46	13.46	13.46	13.37	13.37	13.37	14.29	14.29	14.29	13.07
15	14.95	14.95	15.38	15.38	15.38	15.27	15.27	15.27	16.34	16.34	16.34	14.95
16	10.72	10.72	10.27	10.27	10.27	9.62	9.62	9.62	9.77	9.77	9.77	10.72
17	8.92	8.92	9.36	9.36	9.36	8.59	8.59	8.59	8.31	8.31	8.31	8.92
18	12.92	12.92	10.03	10.03	10.03	12.79	12.79	12.79	8.26	8.26	8.26	12.92
19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
21	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
22	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
23	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Identifying Exposure Data (Pedestrian and Vehicle) for Analyses

The relevant vehicular and pedestrian volumes were identified for the analysis focused on pedestrian crashes associated with the intersection corner. The volumes included any vehicle or pedestrian that entered the approach and the receiving legs that connected to the subject corner. Figure 17 illustrates the areas included in the approach volume on the leg or the receiving volume on the leg. The pedestrian counts reflected any pedestrian within the crosswalk. Counts for crosswalks that both accessed and left the corner of interest were included in the pedestrian crashes at corner analyses. Table 14 shows the volumes that would be included in each corner illustrated in figure 17.



NB = northbound; SB = southbound; EB = eastbound; WB = westbound; R = right; L = left; T = through.
Note: Solid circle shows the vehicle volumes included, while the dotted circle shows the pedestrian volumes that would be included.

Figure 17. Sketch. Source of vehicle and pedestrian volumes for pedestrian-related crash analysis, illustrating volumes that would be included in the analysis of the southeast corner.

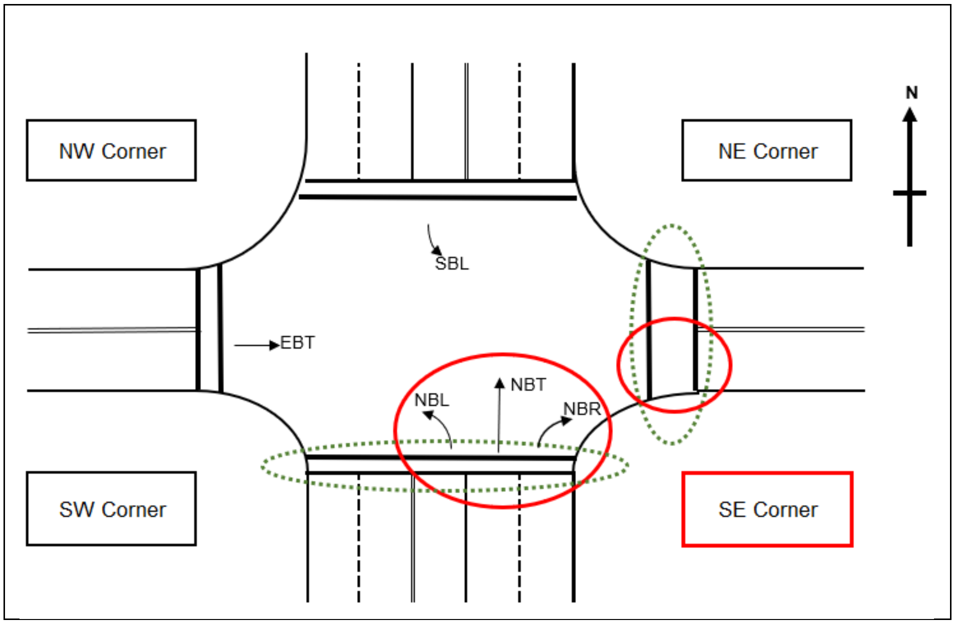
Table 14. Volumes that would be included for each corner in the pedestrian-related crash analysis as illustrated in figure 17

Corner	Vehicle Volume on Approach Leg, AppVol_OnLeg	Vehicle Volume on Receiving Leg, RecVol_OnLeg	Pedestrian Volume, AppLegPed	Pedestrian Volume, RecLegPed
Southeast	NBL+NBT+NBR+ SBT+EBR+WBL	SBL+EBT+NBR+ WBL+WBT+WBR	South leg	East leg
Southwest	EBL+EBT+EBR+ WBT+SBR+NBL	WBL+SBT+EBR+ NBL+NBT+NBR	West leg	South leg
Northwest	SBL+SBT+SBR+ WBR+NBT+EBL	NBL+WBT+SBR+ EBL+EBT+EBR	North leg	West leg
Northeast	WBL+WBT+WBR +SBL+EBT+NBR	EBL+NBT+WBR+ SBR+SBT+SBL	East leg	North leg

AppVol OnLeg = vehicle volume on approach; RecVol OnLeg = vehicle volume on receiving leg; AppLegPed = pedestrian volume on approach; Leg.RecLegPed = pedestrian volume on receiving leg.

For the right-turn crash analysis, the approach volume included the vehicular volumes (left, through, and right) on the approach leg approaching the intersection, along with the vehicular volumes entering the receiving leg that was next to the corner of the intersection. Figure 18 provides the areas included. For example, for a southeast corner, the receiving leg would have the southbound left-turn vehicles, the eastbound through vehicles, and the northbound right-turn vehicles. The pedestrian counts reflected any pedestrian within the crosswalk. Counts at crosswalks that both accessed and left the corner of interest were included. The diagram in Figure 18 illustrates the southeast corner (analogous aggregations can also be made for the other three corners), and Table 15 provides the tabulation of the included volumes for each corner.

Table 16 provides the descriptive statistics for the volumes considered in the corner crash analysis.



Note: Solid circle shows the vehicle volumes included while the dotted circle shows the pedestrian volumes that would be included.

Figure 18. Sketch. Source of vehicle and pedestrian volumes for right-turn-related crash analysis at the corner level, illustrating volumes that would be included in the analysis of the southeast corner.

Table 15. Volumes that would be included for each corner in the right-turn-related crash analysis as illustrated in figure 18.

Corner	Vehicle Volume on Approach Leg, AppVol_RtTurn	Vehicle Volume on Receiving Leg, RecVol_RtTurn	Pedestrian Volume, AppLegPed	Pedestrian Volume, RecLegPed
Southeast	NBL+NBT+NBR	SBL+EBT+NBR	South leg	East leg
Southwest	EBL+EBT+EBR	WBL+SBT+EBR	West leg	South leg
Northwest	SBL+SBT+SBR	NBL+WBT+SBR	North leg	West leg
Northeast	WBL+WBT+WBR	EBL+NBT+WBR	East leg	North leg

Table 16. Aggregated vehicle and pedestrian volumes considered for pedestrian-related crash analysis at the corner level.

State	Variable	Min	Max	Ave	Std Dev	25th Percentile	50th Percentile	75th Percentile
VA	AppLegPed (AADP)	0	6,839	341	538	56	156	386
WA	AppLegPed (AADP)	0	3,294	237	431	47	91	208
VA	AppVol_OnLeg (AADT)	56	54,125	9,666	8,459	3,369	7,700	12,499
WA	AppVol_OnLeg (AADT)	14	205,536	19,690	20,506	9,555	15,710	24,843
VA	AppVol_RtTurn (AADT)	0	27,406	4,149	4,895	0	2,135	7,485
WA	AppVol_RtTurn (AADT)	5	110,784	9,804	10,624	4,337	8,147	12,084
VA	CornerRight (AADT)	0	8,555	598	918	2	284	764
WA	CornerRight (AADT)	1	14,784	1,855	2,044	661	1,286	2,323
VA	RecLegPed (AADP)	0	6,839	347	559	57	157	396
WA	RecLegPed (AADP)	0	3,294	238	431	46	91	212
VA	RecVol_OnLeg (AADT)	10	54,125	9,602	8,464	3,213	7,683	12,477
WA	RecVol_OnLeg (AADT)	14	205,536	20,106	20,474	9,910	16,982	24,893
VA	RecVol_RtTurn (AADT)	0	27,028	4,143	4,945	0	2,013	7,393
WA	RecVol_RtTurn (AADT)	9	104,064	10,018	10,277	4,908	8,224	12,360

Min = minimum; Max = maximum; Ave = average.

ROADWAY GEOMETRIC DATA

The research team used the volume data files available from the three States to identify potential sites. The research team selected intersections with the following characteristics:

- At least a full 2-h turning movement count of vehicles and pedestrians.
- Traffic control signal presence.
- Typical intersection geometric configurations (including three- and four-leg intersections), removing intersections with five legs or a large skew.
- No road or sidewalk construction visible during the years matching the crash data.

The research team assembled a spreadsheet with one record for each intersection corner (i.e., a four-leg intersection would be described by four records) and variables to describe the approach and receiving legs in relation to the right-turn movement at the corner. For example, the southeast corner's record would include variables to describe the south (approach) and east (receiving) legs. The research team used aerial and street-level photography sources available online to extract the following observations to describe each corner:

- Location (latitude and longitude coordinates of the intersection center).
- Number of lanes on each leg.
- Traffic configuration of each leg (two-way, one-way with traffic approaching intersection, or one-way with traffic departing intersection).
- Corner radius for the right-turn movement.
- Lane and shoulder widths (or presence of curb) on each leg.
- Right-turn lane presence and type on the approach leg.
- Presence of curb extension.
- Presence of right-turn channelizing island.
- Presence of bicycle lane.
- Development type (residential, commercial/retail/industry, or rural/parks).
- Distance to nearest driveways, if within 300 ft of the corner.
- Median type on each leg (none, left-turn lane without pedestrian refuge island [LTLwoR], raised, or flush paved).
- Presence and type of on-street parking on each leg (none, parallel, angle, or perpendicular).
- Posted speed limit on the approach leg.
- Pedestrian crossing distance across each leg of the intersection.

The variables in the above list were refined during the preliminary analyses to develop the variables used in the final analysis. Table 17 provides the descriptions of the variables considered in the corner-level analyses.

A total of 1,285 corners were available for the statistical analysis. Table 18 shows the number of corners for variables with specified levels, while table 19 provides the descriptive statistics for those variables with a dimension.

Table 17. Geometric variable descriptions.

Variable	Description
AppLegType or RecLegType	Direction of traffic on the approach (or receiving) leg: two way, 1w-T = one way toward the corner, 1w-A = one way away from the corner.
BikeLnApp_1yes or BikeLnRec_1yes	Bicycle lane on approach (or receiving) leg: 1 = yes or 0 = no.
CorBulb_1yes	Value of 1 if the specified corner has a bulb/curb extension (e.g., curb extends into a parking lane), 0 otherwise.
CorIsland_1yes	Value of 1 if the specified corner has a corner island (or right-turn channel), 0 otherwise.
CorRtTurnRadius	Radius determined from deflection angle and length (ft).
Develop	Development: Residential, Rural/Parks, or Com/Ret/Ind (for commercial, retail, or industry).
DrvDisApp or DrvDisRec	Approach (or receiving) leg, distance between nearest driveway and crosswalk edge nearest to driveway (ft); any intersection creating a conflict counts, another intersection, merging lanes, and so on, if greater than 300 ft = 9,999.
IntLegs	Number of legs at the intersection.
LanesApp or LanesRec	Number of lanes on the approach (or receiving) leg including exclusive lanes for left- or right-turn drivers as well as bus lanes.
LaneWidth	Typical or average lane width on the approach leg (ft).
ParkApp_1yes or ParkRec_1yes	On-street parking (either marked or unmarked) on approach (or receiving) leg: 1 = yes or 0 = no.
Ped.cr.distA or Ped.cr.distB	Pedestrian crossing distance for direction A (to left of pedestrian at corner looking into the center of intersection) or direction B (to right of pedestrian at corner looking into the center of intersection); edge of pavement to edge of pavement distance (ft) along the center of the pedestrian crosswalk (Note: If the pedestrian reaches a median refuge prior to the far curb, the measurement omits the distance within the median refuge).
PSL_App	Posted speed limit on the approach leg, assumed to be 15 mph for driveways (mph).
ShoulderWidthApp or ShoulderWidthRec	Shoulder width on the approach (or receiving) leg, 0 when not present (ft).
Tot.Ped.cr.dist	Ped.cr.distA + Ped.cr.distB.
UnequalLanes (LanesApp ≠ LanesRec)	Is the number of lanes on the approach leg different than the number of lanes on the receiving leg? (1 = yes, 0 = no).
RtTurnLnType	RTL = exclusive single right-turn lane, SRTL = shared right-turn lane, R2TL = exclusive double right-turn lane, NRT-OW = no right turn at corner due to one-way street approaches, NA3Legs = no approach since the intersection only has three legs.

Table 18. Number of corners for specific levels within the corner-level geometric variables for Virginia and Washington.

Variable	Level	Number of Corners, VA	Number of Corners, WA	Number of Corners, VA and WA
CorBulb_1yes	0	1,016	260	1,276
CorBulb_1yes	1	1	8	9
CorIsland_1yes	0	1,017	265	1,282
CorIsland_1yes	1	0	3	3
Develop	Com/Ret/Ind	910	192	1,102
Develop	Residential	67	60	127
Develop	Rural/Parks	40	16	56
IntLegs	3	78	17	95
IntLegs	4	939	251	1,190
ParkApp_1yes	0	440	257	697
ParkApp_1yes	1	577	11	588
ParkRec_1yes	0	422	253	675
ParkRec_1yes	1	595	15	610
UnequalLanes	0	421	55	476
UnequalLanes	1	596	213	809
Grand total	All levels	1,017	268	1,285

Table 19. Descriptive statistics of corners for Virginia and Washington.

State	Variable	Min	Max	Ave	Std Dev	25th Percentile	50th Percentile	75th Percentile
VA	CorRtTurnRadius	3	116	15.1	8.37	11	14	17
WA	CorRtTurnRadius	5	74	28.4	7.90	24	27	31
VA	DrvDisApp	0	299	142.7	76.22	87	137	187
WA	DrvDisApp	0	299	152.8	77.44	98	150	213
VA	DrvDisRec	0	299	140.1	78.87	80	136	183
WA	DrvDisRec	0	298	136.5	75.21	85	128	188
VA	LaneWidth	8	42	13.1	3.84	11	12	15
WA	LaneWidth	9	20	11.3	1.33	11	11	12
VA	PSL_App	15	55	24.4	6.45	25	25	25
WA	PSL_App	15	40	30.4	4.19	30	30	35
VA	ShoulderWidthApp	0	12	0.3	1.65	0	0	0
WA	ShoulderWidthApp	0	11	0.2	1.21	0	0	0
VA	ShoulderWidthRec	0	14	0.3	1.70	0	0	0
WA	ShoulderWidthRec	0	12	0.3	1.42	0	0	0
VA	Tot.Ped.cr.dist	34	277	106.6	37.76	79	94	126
WA	Tot.Ped.cr.dist	39	234	132.9	27.87	116	134	149

CORNER-LEVEL DATABASES FOR ANALYSIS

After assembling the volume, geometry, and crash data for Virginia and Washington, the research team merged the data into a single corner-level database for statistical analysis. The merged database was organized as one record per intersection corner, with crashes aggregated by all severity levels and fatal-and-injury levels and by total, pedestrian, or right-turn crashes.

CHAPTER 5. SAFETY EFFECTIVENESS EVALUATION FOR CORNER-LEVEL ANALYSIS

This chapter presents the results of the safety effectiveness evaluation and estimated CMFs for the corner-level analysis.

EXPLORATORY ANALYSIS

The research team performed an exploratory analysis of the relationships between pedestrian crashes and variables with anticipated safety influences at the corner level. This exercise is an important step of the analysis because it can uncover trends that would suggest different treatments during the statistical evaluation. The most relevant findings from the exploratory analysis were the clear links between number of pedestrian crashes and various metrics of pedestrian and motor vehicle volumes. Several potential metrics were considered during the model selection process, as described in the next section. Ultimately, only a subset of exposure metrics was selected in the final model for pedestrian crashes.

WEIGHTS DEVELOPMENT

The research team produced the estimate for the qualitative level of the crash assignment to the corners for each individual crash (details on the qualitative levels were explained in the previous section, Quantifying the Uncertainty of Conflicting Information in Linking Crashes to Corners, and in particular table 11 and table 12). To develop weights, the four qualitive levels (from low to high) need to be considered. For this purpose, the research team used the assignment points as shown in table 20 for the conversion.

Table 20. Point conversion from qualitative certainty.

Qualitative Certainty	Assigned Points
High	4
Medium–High	3
Medium	2
Low	1

When aggregating the crashes by corner, the average number of points was computed for each corner by each of the following crash types: Ped_KABCO and RT_KABCO. This method was based on the reasoning that a separate corner analysis is anticipated for each of these crash types.

Appropriate regression weights were developed to be proportional to the average number of certainty points per corner to be applied in the maximum likelihood (ML) estimation algorithm. The purpose of the weights is to increase the influence of the corners in the results with a high level of certainty in their crash assignment while decreasing the influence of the corners with lower levels of certainty. As table 12 shows, 96.3 percent of all crashes were assigned levels of certainty from medium to high. About 69 percent of all crashes were pondered as high or medium-high.

The weights were developed to fit within the framework of generalized linear models (GLMs) of the exponential family of distributions, as shown in figure 19.

$$f(y|\theta,\phi) = exp\left[\frac{y\theta - b(\theta)}{a(\phi)} + c(y,\phi)\right]$$

Figure 19. Equation. Exponential family of distribution.

Where:

f = the probability density function of *y*, given Θ and Φ.
y = the response random variable.
Θ and ϕ = location and dispersion parameters, respectively.
a, *b*, and *c* = different functions of the parameters that define specific distributions that the GLM model can handle.

For the equation in figure 19, the function *a* can be compounded, as shown in figure 20.

$$a(\phi) = \frac{d(\phi)}{w}$$

Figure 20. Equation. Corner weights in dispersion term *a*.

Where:

d = a function of the dispersion parameter.
w = set of weights representative of the degrees of freedom available in the dataset to be passed to the estimation.

The weights, therefore, were calculated for each crash set such that they were positive real numbers, proportional to the certainty points, and the sum did not exceed the degree of freedom in the dataset. More details can be found in the statistical literature.(59,60,61)

STATISTICAL MODEL

For the corner analyses, the research team utilized generalized linear mixed-effects models (GLMMs) to perform the safety analyses. Mixed-effects models are so called because they incorporate both fixed and random effects.(62) The coefficients for key variables are generally treated as fixed effects. This treatment implies that there is a long-term underlying parameter from a latent data-generating process to be estimated for each key variable. In addition, random effects account for the effects of factors that are deemed the observed realizations of a random variable. Most often, random effects are not of interest, but their effects must be accounted for, similar to blocking in analysis of variance designs. Typically, the effect of each block is not the focus of the analysis, but the variability explained by the blocking must be accounted for to quantify the variability explained by the independent variable of interest. Mixed-effects models are suited to handle the analysis of repeated measures in otherwise cross-sectional data, as is the case of this analysis, where the unit of analysis is a corner, but they are clustered by intersection, where each intersection groups up to four corners.

Attending to the characteristics of the crash data, the research team considered two distributional alternatives for modeling the error in the models, depending on the number of crashes available for analysis: binomial log-normal for low counts, and Poisson log-normal for non-low counts.

For the statistical models, the general structure is shown in figure 21, where *N* represents the number of crashes of interest in the case of a Poisson log-normal model and the risk of crashes of interest in the case of a binomial-log-normal model. On the side of the explanatory variables, three categories were considered: exposure variables, covariates in the dataset, and corner radius, the variable of interest.

$$N \sim f(exposure, Covariates, Corner.Radius)$$

Figure 21. Equation. General structure for number of crashes associated with corner radius.

Modeling Process

After performing an exploratory analysis on the final database, the research team started the modeling process with the Virginia dataset only to avoid managing potential differences between States beyond what a single coefficient could explain. This subset was selected because of its larger size, which would produce more stable coefficients in the initial models. The smaller dataset for Washington was then used to fit a model and with comparable functional form as the most promising models in Virginia in an iterative process that would allow the research team to examine key differences between the States.

Selecting Appropriate Accounts of Exposure

As a first step in the modeling process, the research team explored multiple potential traffic volume metrics and their combinations that would better capture the exposure for the analysis of each crash type. For example, various metrics representing complementary aspects were considered in model development at the corner level for the Ped_KABCO analysis. That analysis needed to account for motor vehicle volumes—both on the approach and the receiving legs—because they are in conflict with the pair of pedestrian crossings linked to the corner. Accordingly, the pedestrian volumes at each of the two pedestrian crossings at the corner needed to be accounted for in the analysis. The modeling process then involved selecting a set of variables or combinations of variables that capture these four avenues of exposure. The four metrics most sensible were included in all the functional forms for this model: AppLegPed, RecLegPed, AppVol_OnLeg, and RecVol_OnLeg. Figure 17 illustrates the turning movements included in those metrics.

Stepwise Model Selection

As a second step, after selecting a functional structure to treat exposure explicitly, the research team performed model selection in an incremental way to consider the impact of including key variables and variables of interest one at a time. The research team informed this process using four criteria:

- The Akaike information criterion (AIC).
- The Bayes information criterion (BIC).
- The likelihood ratio test.
- Compatibility with theoretical considerations.

In the cases of essentially indistinguishable values in the above criteria, or for comparisons involving more than one model parameter, the research team utilized the likelihood ratio test as the criterion. As with any candidate model for inference, the research team flagged any alternative models that would contravene important theoretical considerations about the safety process. These types of flagged issues could include excessively large dispersion parameters, or negative coefficients for exposure terms, for example.

While the exposure terms were allowed to vary in the modeling process, the number of aggregated years was treated as an offset in the models because it was different for the two States in the analysis (7 yr for Washington and 6 yr for Virginia). This treatment effectively imposed the value of 1.0 to the coefficient of the offset variable (number of years in this case).

ANALYSIS BY CORNER

The research team performed the corner-level analysis initially using the Virginia database and then using the combined Virginia and Washington database. The research team performed checks of any differences between States through the modeling process. These checks were necessary to confirm the overarching model estimates representing the trends from each subset of data. Ultimately, significant shifts were found between the two subsets of data in the final combined models for Ped_KABCO and RT_KABCO analysis, as discussed in the following sections.

Ped_KABCO Data Analysis

Data Analysis Results

The general functional form of the fixed-effects part of the model for Ped_KABCO analysis is shown in figure 22.

$$Risk(Ped_{KABCO}) = \frac{1}{1 + exp(-\eta)}$$

Figure 22. Equation. General functional form for fixed-effects risk model for pedestrian crashes.

Where:
Risk(Ped_KABCO) = probability of Ped_KABCO crash occurrence.
η = a linear function of exposure, covariates, and corner radius.

The negative sign in figure 22 indicates the negative of the linear function is needed to use the equation correctly. In turn, the exponential of the linear function (without the negative sign) represents the odds of crashes and is very useful to estimate odds ratios (ORs) that link changes in odds and changes in the explanatory variables of interest.

The research team used ML estimation to produce coefficient estimates for the model. Because the four traffic variables and the corner radius entered the model with the restriction that they can only take positive values, the exponential of the linear function takes the form shown in figure 23 when that restriction is imposed through the use of the natural logarithm. The variables included are the following:

$$exp(\eta) = Years \cdot (AppLegPed + 0.5)^{\alpha_1} \cdot (RecLegPed + 0.5)^{\alpha_2} \cdot (AppVol.OnLeg + 0.5)^{\alpha_3} \cdot (RecVol.OnLeg + 0.5)^{\alpha_4} \cdot (CorRtTurnRadius)^{\gamma} \cdot exp(X' \cdot \beta)$$

Figure 23. Equation. Linear function form for corner-level analysis for pedestrian crashes.

Where:

η = linear predictor.
Years = number of years represented in each pedestrian crash count.
α_1, α_2, α_3, and α_4 = coefficients corresponding to exposure metrics.
γ = coefficient for CorRtTurnRadius effect (estimated only for corners where right turn is possible, 0 otherwise; for example, when the approach is a one-way street with vehicles moving toward the corner).
X = vector of covariates.
β = vector of coefficient estimates.

Other variables are as previously defined.

Adding of 0.5 in the modified exposure terms in the equation shown in figure 23 allows the estimation algorithm to include corners for which any of those exposure values are zero, which is not allowed in the functional form of the model. The research team's inclusion of these corners better reflects the uncertainty of the volume estimates because they were estimated from available short-term counts. Observing a corner with zero pedestrian traffic does not necessarily mean that no pedestrians use that corner. Rather, a zero is interpreted here as representing a very small level of pedestrian traffic, essentially undetectable in the limited period of the count. The specific value of 0.5 was selected to reflect a smaller amount of exposure than a corner with a count of one or more, yet not quite zero for the reason just explained.

Approach to Modeling

The results in table 12 show that the certainty of the crash-to-corner match is on average higher for Virginia. Those results and the significantly larger sample size for Virginia—three times larger than Washington—led the research team to perform the modeling for Virginia only and then for the dataset combining both States. The purpose of this two-step approach was to compare the impact of including Washington data to the estimation, given its larger uncertainty in the crash matching.

As reported in the following section, the model using Virginia data produced a reasonable CMF for corner radius and included other variables that support intuitive relationships between each variable and pedestrian crashes, such as volumes (pedestrian and vehicles) and presence of shoulders. The next step was to perform the modeling using a combined Virginia and

Washington database. Several models were explored, including models that used the variables listed in table 19 and variables that were created, such as by grouping all the corners that had two-way traffic on both approaches versus corners that included one-way traffic on an approach, to help improve the model fit. Even after multiple attempts, the resulting models included several variables that were not always intuitive. These models did include the key variables of pedestrian and vehicle volumes. The models generally also included as a significant variable corner radius. The estimate for the corner radius variable using Virginia and Washington data was similar to the finding for Virginia, which supports the inclusion of a corner radius CMF for the profession. The research team recommends consideration of only the Virginia model given the higher level of uncertainty with corner assignments, Washington having only about a third of the sites as Virginia, and the combined Washington and Virginia model including the State indicator variable as a significant variable (which is an indication that the State's crashes have a fundamental difference that is not captured with other variables).

Model Using Virginia Data

Table 21 provides the coefficient estimates from the best fitting model to the Virginia data only. The equation shown in

$$\begin{aligned} exp(\eta) = Years &\cdot (AppLegPed + 0.5)^{0.3626} \cdot (RecLegPed + 0.5)^{0.2482} \\ &\cdot (AppVol.OnLeg + 0.5)^{0.5151} \cdot (RecVol.OnLeg + 0.5)^{0.6122} \\ &\cdot (CorRtTurnRadius)^{0.238} \\ &\cdot exp\left(-17.0148 + 1.0551 I_{ow,ow} + 0.5908 I_{tw,ow} + 0.8574 w_s - 0.0701 I_{pk,a}\right) \end{aligned}$$

Figure 24 uses the coefficients in the functional form.

Table 21. Ped_KABCO analysis for Virginia only.

Variable[a]	Parameter	Estimate	Std Error	*z* Value	Pr(>|*z*|)	Sig[b]
AppLegPed+0.5	α_1	0.3626	0.09350	3.879	0.000105	***
RecLegPed+0.5	α_2	0.2482	0.08765	2.832	0.004631	**
AppVol_OnLeg+0.5	α_3	0.5151	0.12114	4.252	2.12E-05	***
RecVol_OnLeg+0.5	α_4	0.6122	0.11236	5.449	5.08E-08	***
CorRtTurnRadius	γ	0.2380	0.10017	2.376	0.017496	*
(Intercept)	β_0	−17.0148	1.79052	−9.503	<2e-16	***
I("w-A" and "1w-A")	β_1	1.0551	0.48193	2.189	0.028569	*
I("2way" and "1way")	β_2	0.5908	0.22574	2.617	0.008871	**
ShoulderWidthApp	β_3	0.8574	0.29759	2.881	0.003961	**
ParkApp_1yes	β_4	−0.0701	0.03291	−2.13	0.033169	*

[a] Variable description is available in table 17.
[b] Sig = significance level where: * = $p < 0.05$ (moderate evidence); ** = $p < 0.01$ (convincing evidence); and *** = $p < 0.001$x (very convincing evidence).

$$
\begin{aligned}
exp(\eta) = Years &\cdot (AppLegPed + 0.5)^{0.3626} \cdot (RecLegPed + 0.5)^{0.2482} \\
&\cdot (AppVol.OnLeg + 0.5)^{0.5151} \cdot (RecVol.OnLeg + 0.5)^{0.6122} \\
&\cdot (CorRtTurnRadius)^{0.238} \\
&\cdot exp\left(-17.0148 + 1.0551 I_{ow,ow} + 0.5908 I_{tw,ow} + 0.8574 w_s - 0.0701 I_{pk,a}\right)
\end{aligned}
$$

Figure 24. Equation. Corner-level analysis function form with coefficients.

Where:

η = linear predictor.
Years = number of years represented in each pedestrian crash count.
AppLegPed = pedestrian volume on approach leg.
RecLegPed = pedestrian volume on receiving leg.
AppVol.OnLeg = vehicle volume on approach leg.
RecVol.OnLeg = vehicle volume on receiving leg.
CorRtTurnRadius = radius (ft).
$I_{ow,ow}$ = indicator variable when both legs are one way.
$I_{tw,ow}$ = indicator variable when one leg is two way and the other is one way.
w_s = shoulder width on the approach leg.
$I_{pk,a}$ = indicator variable when on-street parking is on the approach leg.

The research team performed diagnostics on the fit of the selected model revealing no evidence of multicollinearity or unaccounted binomial overdispersion, with the expected distribution of random effects.

Discussion of Findings

This section discusses the implications of the estimates from the model shown in table 21. The coefficient for CorRtTurnRadius is not discussed in this section but rather in the following section, CMF Development, because it was the main coefficient of interest in the study. The model results provide insights into the relationship of variables to pedestrian crashes, as discussed in the following points:

- The statistical analysis found very convincing evidence of an increase in pedestrian crash risk associated with increasing pedestrian volume on the approach leg (AppLegPed). Everything else being equal, a 10 percent increase in AppLegPed was estimated to correspond to a 3.5 percent increase in odds of pedestrian crashes, or a 20 percent increase in AppLegPed was estimated to correspond to a 6.8 percent increase in odds of pedestrian crashes (estimated as an OR of $(1.10)^{0.3626} = 1.035$ and $(1.20)^{0.3626} = 1.068$, respectively). This result is not surprising since it was expected that pedestrian crash risk would increase with increasing exposure of pedestrians in the approach leg.

- The statistical analysis found convincing evidence of an increase in pedestrian crash risk associated with increasing pedestrian volume on the receiving leg (RecLegPed). With other things being equal, a 10 percent increase in RecLegPed was estimated to correspond to a 2.4 percent increase in odds of pedestrian crashes, or a 20 percent increase in RecLegPed was estimated to correspond to a 4.6 percent increase in odds of pedestrian crashes (estimated as an OR of $(1.10)^{0.248} = 1.024$ and $(1.20)^{0.248} = 1.046$, respectively). This result is also not surprising since it was expected that pedestrian crash risk would increase with increasing volume of pedestrians in the receiving leg.

- Regarding motor vehicle exposure, the results were also as expected. The statistical analysis found very convincing evidence of an increase in pedestrian crash risk associated with increasing motor vehicle volume on the approach leg (AppVol.OnLeg). Other things being equal, a 10 percent increase in AppVol.OnLeg was estimated to correspond to a 5.0 percent increase in odds of pedestrian crashes, or a 20 percent increase in AppVol.OnLeg was estimated to correspond to a 9.8 percent increase in odds of pedestrian crashes (estimated as an OR of $(1.10)^{0.5151} = 1.050$ and $(1.20)^{0.5151} = 1.098$, respectively).

- The results were also as expected regarding the motor vehicle volume in the receiving leg. Interestingly, this vehicle volume was found to have the larger magnitude in its link to pedestrian crash risk. The statistical analysis found convincing evidence of an increase in pedestrian crash risk associated with increasing motor vehicle volume on the receiving leg (RecVol.OnLeg). Other things being equal, a 10 percent increase in RecVol.OnLeg was estimated to correspond to a 6.0 percent increase in odds of pedestrian crashes, or a 20 percent increase in RecVol.OnLeg was estimated to correspond to a 11.8 percent increase in odds of pedestrian crashes (estimated as an OR of $(1.10)^{0.6122} = 1.060$ and $(1.20)^{0.6122} = 1.118$, respectively).

- The statistical analysis found moderate evidence of an increase in the odds of pedestrian crashes at locations where both the approaching leg and the receiving leg were one-way with traffic moving away from the corner. Other things being equal, it was estimated that the odds of pedestrian crashes increased by a factor of 2.87 (OR of 2.87 = *exp*[1.0551]). The research team developed the following theory of why one-way streets moving away from the intersection were associated with more pedestrian crashes. Drivers may have been more focused on the first crosswalk they encountered than the second one. Vehicles may also have been moving faster when passing over the second crosswalk for the intersection. In-field observations are needed to gain a better appreciation for the relationship between one-way streets and pedestrian crashes.

- The statistical analysis found convincing evidence of an increase in the odds of pedestrian crashes at locations where the approaches had a mix of two- and one-way traffic. Other things being equal, the odds of pedestrian crashes increased by a factor of 1.805 (OR of 1.805 = *exp*[0.5908]).

- The results provide convincing evidence of increased pedestrian crash risk at locations with shoulders. The presence of shoulders can provide additional space for turning maneuvers (e.g., increase the effective radius for turning vehicles), which can result in vehicles turning faster. Everything else being equal, the effect for shoulders was estimated as an increase in pedestrian crash risk by a factor of 2.357 for each additional foot for the shoulder (2.357 = *exp*[0.8574]).

- The results also provide moderate evidence of a reduced pedestrian crash risk at locations where on-street parking is present on the approaching leg. Everything else being equal, this effect was estimated as a reduction in pedestrian crash risk by a factor of 0.932 (0.932 = *exp*[−0.0701]). A theory for this finding is that the presence of parking is associated with a lower-speed environment and drivers are more cautious.

- Finally, table 21 shows that the estimate for the γ parameter was found statistically significant, providing convincing evidence of a link between corner radius and pedestrian crash risk. The following section discusses the implications of this finding and describes the use of the parameter estimate to develop a CMF for corner right-turn radius.

CMF Development

As explained earlier, developing a CMF for corner radius was the main focus of this analysis. For that purpose, the statistical evaluation included the parameter γ, which quantifies the variation in pedestrian crash risk linked to changes in corner radius, after controlling for other safety influential variables included in the evaluation.

The statistical model estimates can be used to estimate the OR linked to a given change in the variable that corresponds to a particular coefficient estimate. In the case of γ, it represents the OR for a continuous variable. The CMF, as defined in the *Highway Safety Manual*,[(14)] can be estimated directly from an OR when the latter represents a change in risk for a very small probability,[(63)] which is the case in this study. Therefore, the CMF is defined as shown in figure 25.

$$CMF = Odds.Ratio_{CorRtTurnRadius} = \left(\frac{CorRtTurnRadius}{CorRtTurnRadius_{Base}}\right)^{\gamma}$$

Figure 25. Equation. CMF for corner radius.

Where $CorRtTurnRadius_{base}$ = baseline condition for corner radius CMF, set to 10 ft.

For the equation shown in figure 25, a baseline condition must be selected to produce the desired CMF. The research team chose a value of 10 ft for this purpose. The function is valid over a continuous domain of radius values. Figure 26 shows the resulting CMF from the Virginia only model over the domain of 5 to 75 ft for corner radius. In addition to the 95 percent confidence envelope of the curve, specific CMF values and their corresponding 95 percent confidence intervals are shown at select points of the function domain. The corner radius CMF results for Virginia are similar to the results that used data for both Virginia and Washington; however, the research team recommends that the findings from Virginia be used as the corner radius CMF due to the greater confidence the team has in the Virginia model.

In general, the relationship between corner radius and pedestrian crashes is of direct proportionality. Thus, on average, larger corner radii are linked to more pedestrian crashes. For example, figure 26 shows that, with everything else being equal, 39 percent more pedestrian crashes are expected at a location with a corner radius of 40 ft compared to a location with a corner radius of 10 ft. The largest contrast seen in the figure is between 70-ft and 10-ft radii, with the former expected to experience about 59 percent as many crashes as the latter (from a corresponding CMF of 1.59).

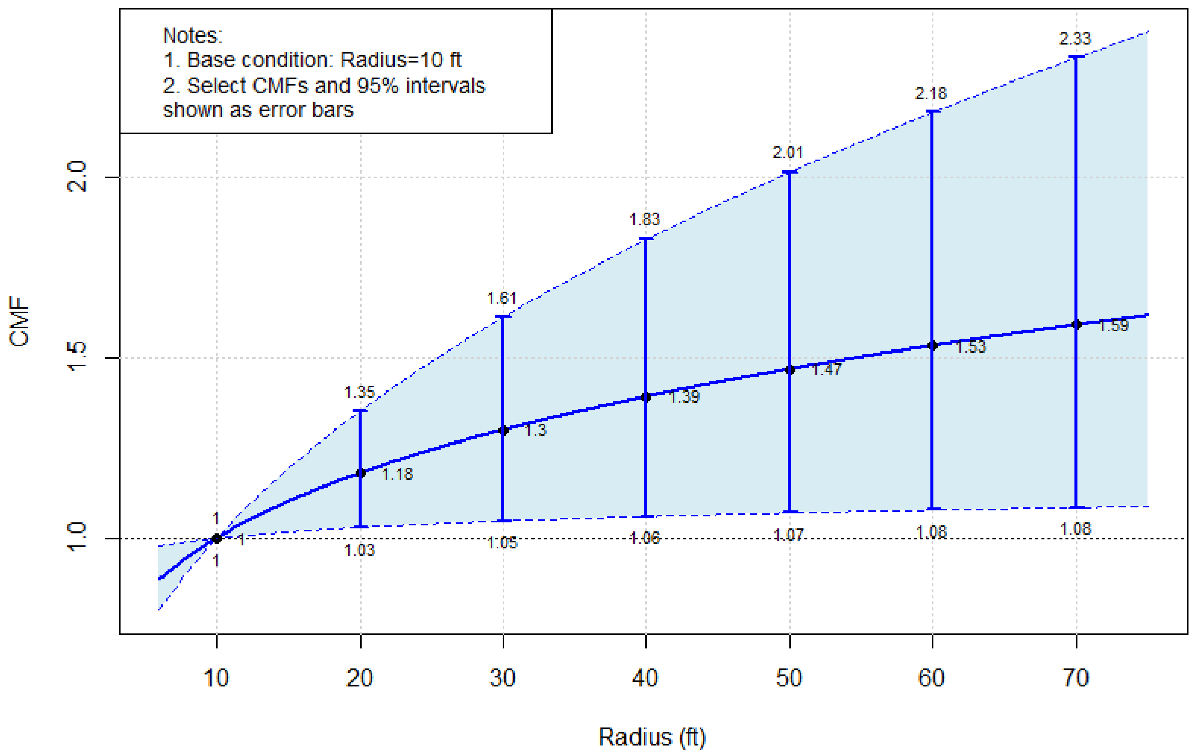


Figure 26. Graph. Corner radius CMF for pedestrian crashes based on Virginia model.

Example of Using Corner Radius CMF

The corner radius CMF is described in figure 27 for pedestrian crashes and figure 28 for right-turn crashes.

$$CMF_{R,ped} = \left(\frac{R}{R_{base}}\right)^{0.238}$$

Figure 27. Equation. Corner radius CMF for pedestrian crashes.

$$CMF_{R,rt} = \left(\frac{R}{R_{base}}\right)^{0.0731}$$

Figure 28. Equation. Corner radius CMF for right-turn crashes.

Where:

$CMF_{R,ped}$ = corner radius CMF for pedestrian KABCO crashes.

$CMF_{R,rt}$ = corner radius CMF for right-turn KABC crashes.

R = corner radius, ft.

R_{base} = base-condition corner radius (= 10 ft), ft.

If the radius is changed at an intersection corner and no other site variables are changed, the percentage change in crashes is computed using the equation shown in figure 29.

$$\Delta_{b-a} = \frac{CMF_{R,x,a} - CMF_{R,x,b}}{CMF_{R,x,b}}$$

Figure 29. Equation. Relative change in crashes.

Where:

Δ_{b-a} = percentage change in crashes between the periods before and after the change.

$CMF_{R,x,a}$ = corner radius CMF for crash type x (pedestrian KABCO or right-turn KABC) in the period after the change.

$CMF_{R,x,b}$ = corner radius CMF for crash type x (pedestrian KABCO or right-turn KABC) in the period before the change.

Figure 30 provides drawings of a signalized intersection where design changes are being evaluated for the right-turn movements. In the period before the change, all four right-turn movements have corners with 50-ft curb radii. In the period after the change, the curb radii have been reduced to 25 ft for the northeast and southeast corners to shorten the crosswalk length on the east leg of the intersection and to provide more pedestrian storage space at those corners. The before-curb radii are shown as broken lines, and the after-curb radii are shown with solid lines. The right-turn radii for the periods before and after the change are provided in the first three columns of table 22.

In the period before the change, the CMF values for all four corners were 1.467 for pedestrian KABCO crashes and 1.125 for right-turn KABC crashes. These values suggest that the large right-turn radii contribute to an increase in crashes, particularly crashes involving pedestrians. In the period after the change, the CMF values for the two treated corners (northeast and southeast) were 1.244 for pedestrian KABCO crashes and 1.069 for right-turn KABC crashes. These calculations are provided in the last six columns of table 22. The results show that pedestrian KABCO crashes and right-turn KABC crashes can be reduced by about 15 percent and 5 percent, respectively, if the corner radii are reduced and no other site characteristics are changed.

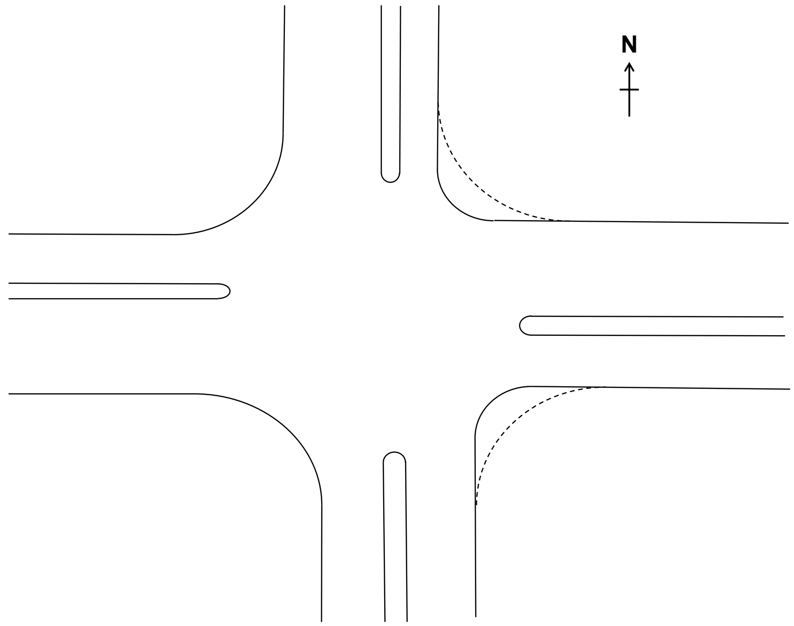


Figure 30. Sketch. Signalized intersection drawings.

Table 22. Corner radius CMF calculations.

Corner	Corner Radius		CMF Value					
			Pedestrian KABCO			Right-Turn KABC		
	Before	After	Before	After	Percent Change	Before	After	Percent Change
Northeast	50	25	1.467	1.244	−15.2	1.125	1.069	−4.9
Northwest	50	50	1.467	1.467	0.0	1.125	1.125	0.0
Southwest	50	50	1.467	1.467	0.0	1.125	1.125	0.0
Southeast	50	25	1.467	1.244	−15.2	1.125	1.069	−4.9

Right-Turn-Related Crash Data Analysis

Data Analysis Results

The general functional form of the fixed-effects part of the model for RT_KABC analysis is similar to the form used for pedestrian crashes. The research team estimated the coefficients for the dataset where Virginia and Washington data were combined. Table 23 shows the results from that exercise for the best fitting model. The research team also estimated the coefficients for Virginia only, similar to the pedestrian crash analysis. Table 24 shows the findings using Virginia-only data and includes corner radius since that variable was the focus of the study. Because corner radius is not significant when included in the model (e.g., table 23), table 25 provides the model when only significant variables are included.

Table 23. RT_KABC analysis using both Virginia and Washington data.

Variable[a]	Parameter	Estimate	Std Error	z Value	Pr(>|z|)	Sig[b]
AppLegPed + RecLegPed + 0.5	α_1	0.4325	0.09237	4.682	2.83E-06	***
RecVol_OnLeg + AppVol_OnLeg + 0.5	α_2	1.20523	0.26652	4.522	6.12E-06	***
RecLegRight_RtTurn + 0.5	α_3	0.19467	0.08481	2.295	0.02171	*
CorRtTurnRadius.eff	γ	0.0731	0.23631	0.309	0.75706	NE
(Intercept)	β_0	−18.7863	2.81901	−6.664	2.66E-11	***
I(MedianRec = "Raised")	β_1	1.14617	0.22355	5.127	2.94E-07	***
ShoulderWidthRec	β_2	0.11043	0.05334	2.07	0.03842	*
StateWA	β_3	−1.30932	0.31299	−4.183	2.87E-05	***
ParkRec_1yes	β_4	−0.72786	0.24952	−2.917	0.00353	**
I(Develop = "Rural/Parks")	β_5	−1.32488	0.63699	−2.08	0.03753	*
I(RecLegType = "2way")	β_6	−0.70929	0.33946	−2.089	0.03667	*

[a] Variable descriptions are available in table 17.

[b] Sig = significance level where: NE = $p > 0.1$ (no evidence); * = $p < 0.05$ (moderate evidence); ** = $p < 0.01$ (convincing evidence); and *** = $p < 0.001$ (very convincing evidence).

Table 24. RT_KABC analysis using Virginia only.

Variable[a]	Parameter	Estimate	Std Error	z Value	Pr(>|z|)	Sig[b]
AppLegPed + RecLegPed + 0.5	α_1	0.40256	0.10747	3.746	0.00018	***
RecVol_OnLeg + AppVol_OnLeg + 0.5	α_2	1.29201	0.30414	4.248	2.16E-05	***
RecLegRight_RtTurn + 0.5	α_3	0.2471	0.0942	2.623	0.00871	**
CorRtTurnRadius.eff	γ	−0.06276	0.25859	−0.243	0.80825	NE
(Intercept)	β_0	−18.9763	3.24218	−5.853	4.83E-09	***
I(MedianRecRA = "raised")	β_1	0.55839	0.27504	2.03	0.04234	*
ShoulderWidthRec	β_2	0.11045	0.05795	1.906	0.05663	~
I(LanesApp = 1 Or LanesRec = 1)	β_3	−0.69486	0.25962	−2.676	0.00744	**
I(IntLegs = 4)	β_4	−1.02811	0.37413	−2.748	0.006	**

[a] Variable description is available in table 17.

[b] Sig = significance level where: NE = $p > 0.1$ (no evidence); ~ = $p < 0.1$ (suggestive evidence); * = $p < 0.05$ (moderate evidence); ** = $p < 0.01$ (convincing evidence); and *** = $p < 0.001$ (very convincing evidence).

Table 25. RT_KABC analysis including only significant variables and Virginia data.

Variable[a]	Parameter	Estimate	Std Error	*z* Value	Pr(>|*z*|)	Sig[b]
AppLegPed + RecLegPed + 0.5	α_1	0.4084	0.10492	3.892	9.93E-05	***
RecVol_OnLeg + AppVol_OnLeg + 0.5	α_2	1.28868	0.30394	4.24	2.24E-05	***
RecLegRight_RtTurn + 0.5	α_3	0.22694	0.04397	5.161	2.45E-07	***
(Intercept)	β_0	−19.0103	3.24098	−5.866	4.48E-09	***
I(MedianRecRA = “raised”)	β_1	0.5528	0.27414	2.017	0.04375	*
ShoulderWidthRec	β_2	0.11052	0.05791	1.909	0.05632	~
I(LanesApp =1 Or LanesRec = 1)	β_3	−0.70072	0.25874	−2.708	0.00676	**
I(IntLegs = 4)	β_4	−1.02697	0.37399	−2.746	0.00603	**

[a] Variable description is available in table 17.
[b] Sig = significance level where: ~ = $p < 0.1$ (suggestive evidence); * = $p < 0.05$ (moderate evidence); ** = $p < 0.01$ (convincing evidence); and *** = $p < 0.001$ (very convincing evidence).

Discussion of Findings

This section discusses the implications of the estimates from the models shown in table 23, table 24, and table 25. The model results in table 23 include data from two States (Virginia and Washington); however, the inclusion of the State variable indicates that there are differences between the States. Table 24 focuses on the State with the larger dataset; however, the corner radius variable is still not significant. Table 25 provides the model that only includes significant variables for right-turn crashes.

These models provide insights into the relationship of variables to right-turn crashes, as discussed below. The coefficient for CorRtTurnRadius was found to be not significant for right-turn-related crashes when considering both States (Virginia and Washington; table 23) or the State with the largest amount of data (Virginia; table 24). This finding does not necessarily imply that there is no relationship between corner radius and right-turn crashes, only that this analysis does not provide evidence favoring such a relationship. Because the standard error of the parameter estimate was found to be 0.236 (table 25), the statistical test of the null hypothesis would indicate insignificance if there is no relationship, and the magnitude of the true parameter is smaller than roughly twice the standard error of the estimate. Therefore, this analysis is inconclusive in attempting to quantify that relationship. Further study with a larger dataset would provide more insight to differentiate between these situations on the effects of corner radius on right-turn crashes. The relationship of variables to right-turn crashes includes the following insights:

- The statistical analysis found very convincing evidence of an increase in right-turn-related crash risk associated with increasing pedestrian volume on both legs (AppLegPed + RecLegPed). Everything else being equal, a 10 percent increase in pedestrian volume was estimated to correspond to a 4.0 percent increase in odds of pedestrian crashes, or a 20 percent increase in pedestrian volume was estimated to correspond to a 7.7 percent increase in odds of pedestrian crashes (estimated as an OR of $(1.10)^{0.4084} = 1.040$ and $(1.20)^{0.4084} = 1.077$, respectively). This result is not surprising because it was expected that right-turn-related crash risk would increase with increasing exposure of pedestrians on either leg.

- Regarding motor vehicle exposure, the results were also as expected. The statistical analysis found very convincing evidence of an increase in right-turn-related crash risk associated with increasing motor vehicle volume (RecVol_OnLeg + AppVol.OnLeg). Other things being equal, a 10 percent increase in RecVol_OnLeg + AppVol.OnLeg was estimated to correspond to a 13.1 percent increase in the odds of right-turn-related crashes, or a 20 percent increase in RecVol_OnLeg + AppVol.OnLeg was estimated to correspond to a 26.5 percent increase in the odds of right-turn-related crashes (estimated as an OR of $(1.10)^{1.28868} = 1.131$ and $(1.20)^{1.28868} = 1.265$, respectively).

- Because of the assumption that right-turn-related crashes would be greatly influenced by the number of vehicles turning right, the RecLegRight_RtTurn variable was included even though that volume is also part of the RecVol_OnLeg variable. The results were also as expected regarding the motor vehicle volume turning right to the receiving leg. The statistical analysis found moderate evidence of an additional increase in right-turn-related crash risk associated with increasing right-turn vehicle volume on the receiving leg (RecLegRight_RtTurn). With other things being equal, a 10 percent increase in RecVol.OnLeg was estimated to correspond to a 2.2 percent increase in odds of right-turn-related crashes, or a 20 percent increase in RecVol.OnLeg was estimated to correspond to a 4.2 percent increase in odds of right-turn-related crashes (estimated as an OR of $(1.10)^{0.22694} = 1.022$ and $(1.20)^{0.22694} = 1.042$, respectively).

- These analyses also found very convincing evidence that sites with a raised median on the receiving leg are associated with an increased right-turn-related crash risk.

- These analyses also found moderate evidence (for both States) or suggestive evidence (when only considering Virginia data) that sites with shoulders on the receiving leg are associated with an increase in right-turn-related crash risk (1.117 OR calculated as exp[0.11043] = 1.117 using data from table 23).

- The analysis documented for both States in table 23 found convincing evidence that sites with on-street parking on the receiving leg are associated with a decreased right-turn-related crash risk (0.483 OR calculated as $exp[-0.72786] = 0.483$). The two variables with moderate evidence that the variable is associated with fewer right-turn-related crashes are rural/parks development (rather than residential or commercial) and two-way traffic on the receiving leg.

- When considering only the Virginia data, on-street parking, rural/parks development, and two-way traffic on the receiving leg were no longer significant, while having four legs (rather than three legs) and having only one lane on either the approach or the receiving leg were found to have convincing evidence of significance.

CHAPTER 6. DATA COLLECTION AND INTEGRATION FOR INTERSECTION-LEVEL ANALYSIS

SITE SELECTION/DATABASE DEVELOPMENT

The process of developing the database for the corner-level analysis provided the opportunity to also evaluate pedestrian crashes at the intersection level. The research team used the data from Richmond, VA; Bellevue, WA; and Portland, OR, as data sources. Additional information on these sources is provided in chapter 4.

Figure 31 shows the flowchart of how the data streams were merged to create the databases used in the intersection-level analysis. The research team obtained geometric data for the corners and intersections of interest using Google® Earth™. The crash data were obtained through requests to the States. The following section describes the research team's efforts to assemble the component datasets and develop the merged databases for statistical analysis.

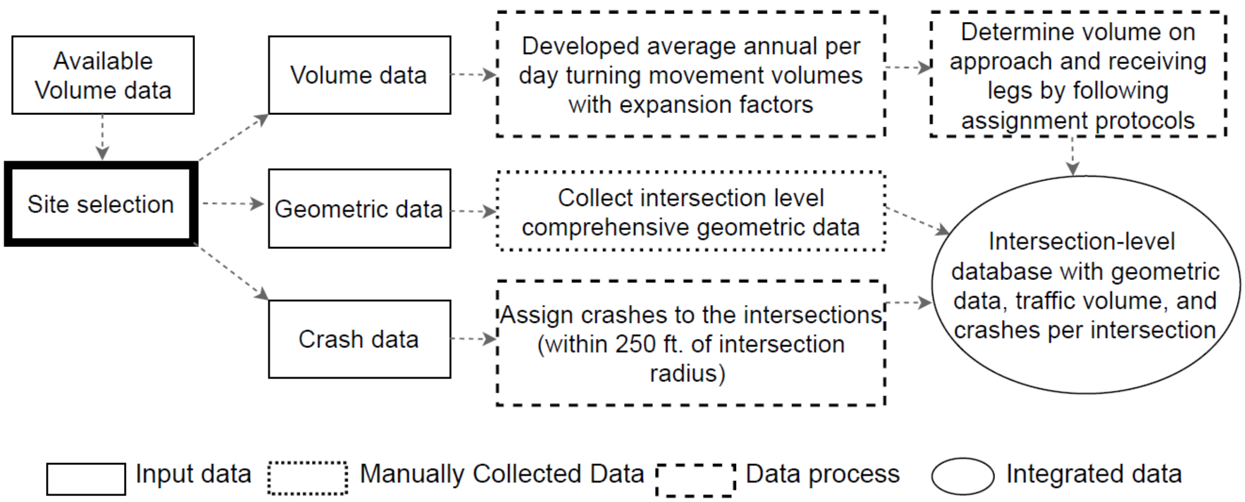


Figure 31. Flowchart. Intersection-level data preparation.

CRASH DATA

The research team requested crash data records for 5 to 7 yr from the three cities and received data from:

- Washington for 2011 to 2017 (7 yr).
- Virginia for 2013 to 2018 (6 yr).
- Oregon for 2012 to 2017 (6 yr).

Table 26 provides the number of intersections by the number of legs present at the intersection for the intersection-level database. Initially, the intersection analysis considered 531 intersections, with most being from Virginia.

Table 26. Number of intersections potentially available for statistical analysis.

Intersection Legs	Oregon	Virginia	Washington	Grand Total
3	11	39	10	60
4	141	260	70	471
Grand total	152	299	80	531

After a close examination of the intersections and their characteristics, the research team identified a significant distinction: 300 intersections between two-way roads, 36 intersections between one-way roads, and 195 intersections between one-way and two-way roads (mixed). These different configurations affect the conflict points and possible maneuvers at the intersection, as well as the manner of interactions between pedestrians and motor vehicles. As a result, the safety performance is likely to differ significantly between the intersection types. The research team recognizes that this situation potentially requires separate analyses per intersection types. In the case of one-way and one-way intersections, a sample of 36 intersections is too small to perform an analysis. A different issue exists for the 195 mixed intersections in that not all of those mixed intersections are equal: it should matter if the two-way road is the major or the minor road, as well as if the one-way section of the road is the same for opposite sides of one of the cross-streets, or where the one-way road leg or legs is located in a three-leg intersection. The research team surmises that more variables are necessary to holistically describe the nuance of mixed intersections, and a preliminary revision of this group of 195 intersections showed that the subsets resulting from further breaking down that group would result in very small subsets, similar in size to the set of 36 intersections having two intersecting roads that are one way.

Because of the reasons described above, and to ensure uniformity in the analysis, the research team decided to proceed to analyze only the set of 300 intersections between two-way roads. During the evaluation, the research team identified one of the 300 intersections to be inconsistent with the other intersection and removed that intersection from the analysis. Table 27 provides the distribution by State and number of legs for the intersections included in the intersection-level analysis. Table 28 shows the per-year crash data distribution by State summary statistics for the set of 299 intersections formed from the junction of two-way roads only.

Table 27. Number of intersections considered in statistical analysis.

Intersection Legs	Oregon	Virginia	Washington	Grand Total
3	9	13	0	22
4	86	123	68	277
Grand total	95	136	68	299

Table 28. Per-year crash data descriptive statistics of Oregon (*n* = 95), Virginia (*n* = 136), and Washington (*n* = 68) intersections.

State	Variable	Min	Max	Ave	Std Dev	25th Percentile	50th Percentile	75th Percentile
OR	KABC	0.17	13.67	3.35	3.15	1.33	2.33	3.92
VA	KABC	0.00	10.33	1.69	1.65	0.50	1.33	2.21
WA	KABC	0.00	5.43	1.87	1.27	1.00	1.64	2.46
OR	KABCO	0.17	26.67	6.31	5.56	2.58	4.50	7.42
VA	KABCO	0.17	26.50	5.31	4.46	2.33	4.17	7.04
WA	KABCO	0.00	18.86	6.87	4.60	3.54	6.21	9.32
OR	Ped_KABCO	0.00	1.17	0.22	0.27	0.00	0.17	0.33
VA	Ped_KABCO	0.00	1.33	0.14	0.23	0.00	0.00	0.17
WA	Ped_KABCO	0.00	0.71	0.21	0.22	0.00	0.14	0.32

Note: Per-year crashes for Washington reflect crashes between 2011 and 2017 (7 yr). Per-year crashes for Virginia are between 2013 and 2018 (6 yr). Per-year crashes for Oregon are between 2012 and 2017 (6 yr).

DAILY EXPOSURE DATA

The process the research team used to expand the available consultant-collected vehicle turning movement and pedestrian counts into daily exposure data is documented in chapter 4.

The research team compiled intersection-level exposure data by summing the approach volumes for each street at each intersection. For the east/west street, the vehicle volume included the vehicles on the eastbound and westbound approaches, while the pedestrian and bicyclist volume reflected the pedestrians and bicyclists using the east- and west-leg crosswalks. For the north/south street, the volumes included the vehicles on the northbound and southbound approaches, and the pedestrians and bicyclists using the north- and south-leg crosswalks. The research team converted the east/west and north/south street notations to major or minor based on vehicle volumes and lane counts. The street with the higher vehicle volume was designated as the major street, and if both streets had the same vehicle volume, the street with more approach lanes (total of both approaches) was designated as the major street.

Table 29 provides the descriptive statistics for the volumes considered in the intersection crash analysis.

Table 29. Aggregated vehicle and pedestrian volumes considered for intersection-level crash analysis.

Variable	State	Min	Max	Ave	Std Dev	25th Percentile	50th Percentile	75th Percentile
StMAJ_VolPedBike	Oregon	0	2,952	321	424	134	210	329
StMAJ_VolPedBike	Virginia	0	6,163	401	814	39	134	351
StMAJ_VolPedBike	Washington	17	2,967	420	628	107	170	453
StMAJ_VolVeh	Oregon	9,666	51,081	27,869	9,386	21,151	27,391	34,467
StMAJ_VolVeh	Virginia	3,984	107,526	36,839	21,359	21,558	35,121	46,566
StMAJ_VolVeh	Washington	14,132	101,246	47,997	18,334	36,908	47,065	59,053
StMIN_VolPedBike	Oregon	5	2,936	314	423	115	203	328
StMIN_VolPedBike	Virginia	0	3,864	411	631	87	210	435
StMIN_VolPedBike	Washington	4	3,101	389	591	100	175	398
StMIN_VolVeh	Oregon	9,640	50,681	27,495	9,360	20,747	26,906	34,061
StMIN_VolVeh	Virginia	134	40,804	10,987	9,577	3,726	8,264	14,291
StMIN_VolVeh	Washington	2,569	53,997	22,662	12,058	12,967	20,706	31,911

INTERSECTION GEOMETRIC DATA

The research team used the geometric data files developed for the Virginia and Washington corner-level analysis along with the material developed for Oregon to create the database for the signalized intersection analysis. The research team assembled a spreadsheet with one record for each intersection.

The research team generated the intersection-level geometric database by combining variables that described the intersection approaches in the corner-level database. For variables that provided counts (such as number of lanes, shoulder presence, and on-street parking presence), the combined variables in the intersection-level database represented counts for each street. For example, if the eastbound and westbound approaches each had two lanes and one shoulder, the combined lane and shoulder count variables for the east/west street would indicate four lanes and two shoulders on the street. The shoulder width variables for each street were computed as an average of the two shoulder widths for the street's approaches, and the lane width variables were computed as the average of lane widths on the street's approaches, weighted by the number of lanes on each approach. The research team computed an intersection-level, right-turn curb radius for each intersection by averaging the values of the corner radii and computed a standard deviation for the corner radii.

Table 30 provides the descriptions of the variables considered in the intersection-level analysis. For the intersection-level analysis, 299 intersections were available for the statistical analysis. Table 31 shows the number of intersections for variables with specified levels, while table 32 provides the descriptive statistics for those variables with a dimension.

Table 30. Intersection geometric variable descriptions.

Variable	Description
I_CorRtTurnRadAve	Average radius for available corners at intersection (ft).
I_CorRtTurnRadStd	Standard deviation for the radii for available corners at intersection (ft).
I_Legs	Number of legs at the intersection (either three or four).
I_TotCrossDis	Total pedestrian crossing distances for the intersection, determined by summing the pedestrian crossing distance for each leg.
StMaj_BikeLn	Major street, indicator variable for presence of bicycle lane (1 = bicycle lane is present, 0 = otherwise).
StMaj_DrvDisAppMin	Major street approach legs, minimum distance between nearest driveway/intersection and crosswalk edge nearest to driveway (ft) capped to 300 ft.
StMaj_DrvDisRecMin	Major street receiving legs, minimum distance between nearest driveway/intersection and crosswalk edge nearest to driveway (ft) capped to 300 ft.

Variable	Description
StMaj_Lanes	Major street, number of lanes including exclusive lanes for left- or right-turn drivers as well as bus lanes, average for both approaches.
StMaj_Max_CD	Major street, larger pedestrian crossing distance for the two approaches, crossing distance determined as edge of pavement to edge of pavement distance (ft) along the center of the pedestrian crosswalk (Note: If the pedestrian reaches a median refuge prior to the far curb, the measurement omits the distance within the median refuge).
StMaj_Median	Major street, type of median (none, raised, LTLwoR, mixed).
StMaj_Park	Major street, indicator variable for presence of on-street parking (1 = on-street parking is present, 0 = otherwise).
StMaj_VolPedBike	Major street, pedestrian, and bicyclist volume (vehicles/day).
StMaj_VolVeh	Major street, vehicle volume (vehicles/day).
StMin_BikeLn	Minor street, indicator variable for presence of bicycle lane (1 = bicycle lane is present, 0 = otherwise).
StMin_DrvDisAppMin	Minor street approach legs, minimum distance between nearest driveway/intersection and crosswalk edge nearest to driveway (ft) capped to 300 ft.
StMin_DrvDisRecMin	Minor street receiving legs, minimum distance between nearest driveway/intersection and crosswalk edge nearest to driveway (ft) capped to 300 ft.
StMin_Lanes	Minor street, number of lanes including exclusive lanes for left- or right-turn drivers as well as bus lanes, average for both approaches.
StMin_Max_CD	Minor street, larger pedestrian crossing distance (StMaj_Max_CD for additional details).
StMin_Median	Minor street, type of median (none, raised, LTLwoR, mixed).
StMin_Park	Minor street, indicator variable for presence of on-street parking (1 = on-street parking is present, 0 = otherwise).
StMin_VolPedBike	Minor street, pedestrian and bicyclist volume (vehicles/day).
StMin_VolVeh	Minor street, vehicle volume (vehicles/day).
T_Ent_PedBike	Total entering pedestrian and bicycle volume, determined by summing the pedestrian and bicycle volumes from each leg.

Table 31. Number of intersections for specific levels within the intersection-level geometric variables.

Variable	Level	Number of Corners, Oregon	Number of Corners, Virginia	Number of Corners, Washington	Total
Develop	Com/Ret/Ind	79	72	36	187
Develop	Mixed	0	59	24	83
Develop	Residential	13	5	7	25
Develop	Rural/parks	3	0	1	4
IntLegs	3	9	13	0	22
IntLegs	4	86	123	68	277
Maj_BikeLn	0	65	132	53	250
Maj_BikeLn	1	30	4	15	49
Maj_ParkLn	0	33	70	66	169
Maj_ParkLn	1	62	66	2	130
Min_BikeLn	0	64	130	46	240
Min_BikeLn	1	31	6	22	59
Min_ParkLn	0	33	68	62	163
Min_ParkLn	1	62	68	6	136
StMaj_Median	Mixed	46	27	18	91
StMaj_Median	None	44	43	10	97
StMaj_Median	Raised	0	66	23	89
StMaj_Median	LTLwoR	5	0	17	22
StMin_Median	Mixed	42	33	35	110
StMin_Median	None	48	88	18	154
StMin_Median	Raised	0	15	3	18
StMin_Median	LTLwoR	5	0	12	17
Grand total	All levels	95	136	68	299

Table 32. Descriptive statistics of 299 intersections used in the intersection-level geometric analysis.

Variable	Min	Max	Ave	Std Dev	25th Percentile	50th Percentile	75th Percentile
I_CorRtTurnRadAve	4.6	80.8	19.6	10.0	12.7	16.5	24.5
I_CorRtTurnRadStd	0.1	54.0	4.6	5.4	1.8	2.9	5.8
I_TotCrossDis	64.0	355.0	155.9	57.5	115.5	145.0	187.5
StMaj_DrvDisAppMin	0.0	298.0	110.5	70.6	60.0	97.0	149.0
StMaj_DrvDisRecMin	0.0	298.0	108.5	81.3	33.0	100.0	158.0
StMaj_Lanes	1.0	6.0	2.4	1.0	2.0	2.0	3.0
StMaj_Max_CD	29.0	203.0	70.7	26.3	48.0	69.0	86.0
StMin_DrvDisAppMin	0.0	296.0	108.9	69.9	52.8	101.5	149.3
StMin_DrvDisRecMin	0.0	297.0	99.9	67.5	42.0	91.0	138.8
StMin_Lanes	1.0	5.0	2.0	0.9	1.0	2.0	2.5
StMin_Max_CD	25.0	215.0	59.8	22.6	44.0	56.0	72.0

INTERSECTION-LEVEL DATABASES FOR ANALYSIS

The volume, geometry, and crash data for all three States were assembled into an intersection-level database for statistical analysis. The merged database was organized as one record per intersection, with the pedestrian-related crashes aggregated.

CHAPTER 7. SAFETY EFFECTIVENESS EVALUATION FOR INTERSECTION-LEVEL ANALYSIS

This chapter presents the results of the safety effectiveness evaluation using the intersection-level data.

STATISTICAL MODEL

For the intersection analysis, the safety analysis process was similar to the approach used for the corner-level analysis, except that the data structure did not have repeated measures. Therefore, the research team utilized negative binomial (NB) GLMs for the analysis, where the main difference with GLMMs is that Poisson overdispersion is no longer captured as variability among the random effects, but rather by a single dispersion parameter in the NB distribution.

Ped_KABCO Data Analysis

The functional form of the NB GLM model for Ped_KABCO crash analysis effectively produces an SPF per the definitions in the *Highway Safety Manual*.(14) The functional form is shown in figure 32.

$$E\left(N_{Ped_{KABCO}}\right) = exp(\eta)$$

Figure 32. Equation. Functional form of NB GLM model for pedestrian crashes.

Where:

$N_{Ped_{KABCO}}$ = number of KABCO pedestrian crashes.
$E(x)$ = expected value (long-term average) of x.
η = a linear function of exposure and predictive covariates.

Because the resulting SPF may be intended for crash predictions in uses compatible with *Highway Safety Manual* procedures (e.g., applications of the empirical Bayes method), the NB dispersion parameter (κ) may be of interest.(14) This parameter defines the increased rate of increase in the variance of the observations (i.e., Ped_KABCO crashes) relative to the Poisson distribution. It is defined as shown in figure 33.

$$V\left(N_{Ped_{KABCO}}\right) = N_{Ped_{KABCO}} + \kappa \cdot \left(N_{Ped_{KABCO}}\right)^2$$

Figure 33. Equation. NB GLM model variance for pedestrian crashes.

Where:

κ = dispersion parameter of the NB distribution.
$V(x)$ = the variance of x.

Other variables are as previously defined.

The research team used ML estimation to produce coefficient estimates for the model. Similar to the corner-level analysis, the exponential of the linear function takes on the form shown in figure 34 (given that the traffic variables are restricted to only taking positive values).

$$exp(\eta) = Years \cdot (StMaj\_VolVeh + 0.5)^{\alpha_1} \cdot (StMin\_VolVeh + 0.5)^{\alpha_2} \cdot (T\_Ent\_Pedbike + 0.5)^{\alpha_3} \cdot exp(X' \cdot \beta)$$

Figure 34. Equation. Linear functional form for intersection analysis.

Where:
- η = linear predictor.
- *Years* = number of years represented in each pedestrian crash count.
- α_1, α_2, and α_3 = coefficients corresponding to exposure metrics.
- X = vector of covariates.
- β = vector of coefficient estimates.

Other variables are as previously defined.

Similar to the corner-level analysis, the research team added 0.5 to the exposure metrics to allow the inclusion of the intersection when an exposure value is zero. See chapter 6 for additional details on variable definitions.

Modeling Process

After performing an exploratory analysis on the final database and given the relatively small sample size (300 intersections), the research team decided to start the modeling process with the complete dataset instead of a single State, as in the corner analysis. Potential differences between States were explored in the process to include nuances beyond a single intercept-shift coefficient.

Selecting Appropriate Accounts of Exposure

As a first step in the modeling process, the research team explored multiple potential traffic volume metrics and their combinations that would better capture the exposure for the analysis of each crash type. It was determined that traditional functional forms worked best (namely, a power form of the exposure metric, as opposed to an exponential form, as other covariates are treated). However, similar to the corner-level analyses, the volumes entered in the model were slightly shifted by an additive value of 0.5 to avoid dropping locations with volumes of zero. Given that these exposure metrics are based on short time periods, the possibility of having such null values is greater (as opposed to yearly averages such as AADT).

Stepwise Model Selection

As a second step, after selecting a functional structure to treat exposure explicitly, the research team performed model selection in an incremental way to consider the impact of including key variables and variables of interest one at a time, similar to the process followed for the corner-level analyses. The research team informed this process using four criteria:

- AIC.
- BIC.
- The likelihood ratio test.
- Compatibility with theoretical considerations.

Multiple phases of model selection would drive the model selection to reduce the AIC or BIC because this effect implies a reduction in the entropy of a candidate model, compared to competitor models with larger values of AIC or BIC. However, in cases of essentially indistinguishable values in these criteria, or for comparisons involving more than one model parameter, the research team utilized the likelihood ratio test as the criterion. As with any candidate model for inference, the research team flagged any alternative models that would contravene important theoretical considerations about the safety-generating process. These types of flagged issues could include excessively large dispersion parameters, or negative coefficients for exposure terms, for example.

While the exposure terms were allowed to vary in the modeling process, the number of aggregated years were treated as an offset in the models because they were different for the two States in the analysis (7 yr for Washington and 6 yr for Virginia and Oregon). This treatment effectively imposes the value of 1.0 to the coefficient of the offset variable (number of years in this case).

ANALYSIS AT INTERSECTION LEVEL

Through the modeling process, the team ran fit and stability diagnostics through the modeling iterations. In these checks, one intersection appeared repeatedly as a source of instability for the model; on examination, the research team determined that the actual crash count at this intersection was significantly smaller than what would be expected from various models' fits. This observation, therefore, had a large influence on at least one coefficient estimate and resulted in observed positive biases on the right end of the range of predictions by the model. For these reasons, the research team removed this intersection and proceeded to model intersection-level crashes with 299 instead of the total 300 observations.

Additionally, the research team performed checks of any differences between States and between three- and four-leg intersections. These checks were necessary to confirm the overarching model estimates representing the trends from each subset of data. Ultimately, small shifts were found between the three- and four-leg intersections and were accounted for by single individual intercepts that while significantly different from zero, did not show a statistically significant difference in their value. In the case of States, the research team verified that while there were differences in intercepts, because interactions with other key variables were allowed during the modeling process, a statistically significant shift in the account of pedestrian volumes was found only for Washington, compared to the other two States (Virginia and Oregon). Despite the statistical significance of the difference, the magnitudes remained somehow comparable, as shown in table 33, which also provides the coefficient estimates from the best fitting model using the intersections where all approaches have two-way operations. The research team performed diagnostics on the fit of the selected model revealing no evidence of multicollinearity or unaccounted binomial overdispersion, with the expected distribution of random effects.

The equation using the coefficients in table 33 is shown in figure 35.

Table 33. Ped_KABCO analysis for Virginia, Washington, and Oregon.

Variable[a]	Parameter	Estimate	Std Error	*z* Value	Pr(>|*z*|)	Sig[b]
StMaj_VolVeh+0.5	α_{maj}	0.6228	0.1448	4.3020	1.69E-05	***
StMin_VolVeh+0.5(OR or VA)	$\alpha_{min\ OR\ or\ VA}$	0.4997	0.0954	5.2380	1.62E-07	***
T_Ent_PedBike+0.5	α_{Pedbik}	0.5666	0.0554	10.2320	<2e-16	***
I(State = OR or VA)	$\beta_{OR\ or\ VA}$	−4.5950	0.9722	−4.7260	2.29E-06	***
I(4 Legs)	β_{4L}	−11.9680	1.6748	−7.1460	8.95E-13	***
I(3 Legs)	β_{3L}	−12.1350	1.6981	−7.1460	8.91E-13	***
I(StMaj_Median = LTLwoR)	β_{TWLTL}	0.4470	0.1916	2.3330	0.0196	*
Dispersion[c]	κ	0.1126	0.0151	7.4777	7.57E-14	***

[a] Variable descriptions are available in table 30.
[b] Sig = significance level where * = $p < 0.05$ (moderate evidence); *** = $p < 0.001$ (very convincing evidence).
[c] Bootstrap estimate.

$$exp(\eta) = Years \cdot (StMaj_{VolVeh} + 0.5)^{0.6228} \cdot (StMin_{VolVeh} + 0.5)^{0.4967 \cdot I(State \neq WA)} \cdot (t_{entPedBike} + 0.5)^{0.5666} \cdot exp\begin{pmatrix} -4.5950 \cdot I(State \neq WA) - 11.968 \cdot I(4\ legs) \\ -12.135 \cdot I(3\ legs) + 0.447 \cdot I(StMaj_{Median} = TWLTL) \end{pmatrix}$$

Figure 35. Equation. Linear functional form for pedestrian crashes at intersections with coefficients.

Discussion of Findings

This section discusses the implications of the estimates from the model shown in table 33. The model results provide insights into the relationship of variables to pedestrian crashes for signalized intersections, as discussed in the following points:

- Similar to the corner-level analysis, the statistical analysis found very convincing evidence of an increase in pedestrian crash frequency associated with total entering pedestrian and bicycle volume (T_Ent_Pedbike). Everything else being equal, a 10 percent increase in T_Ent_Pedbike+0.5 was estimated to correspond to a 5.5 percent increase in pedestrian crashes, or a 20 percent increase in T_Ent_Pedbike+0.5 was estimated to correspond to a 10.9 percent increase in pedestrian crashes (estimated as $(1.10)^{0.5666} = 1.055$ and $(1.20)^{0.5666} = 1.109$, respectively). This result is not surprising because it was expected that pedestrian crash risk would increase with increasing exposure of pedestrians and bicyclists at the intersection.

- Regarding motor vehicle exposure on the major street, the results were also as expected. The statistical analysis found very convincing evidence of an increase in pedestrian crashes associated with increasing motor vehicle volume on the major street (StMaj_VolVeh+0.5). Other things being equal, a 10 percent increase in StMaj_VolVeh+0.5 was estimated to correspond to a 6.1 percent increase in pedestrian crashes, or a 20 percent increase in StMaj_VolVeh+0.5 was estimated to correspond to a 12.0 percent increase in pedestrian crashes (estimated as $(1.10)^{0.6228} = 1.061$ and $(1.20)^{0.6228} = 1.120$, respectively).

- The results were also as expected regarding the motor vehicle volume on the minor street for Oregon and Virginia. The statistical analysis found convincing evidence of an increase in pedestrian crashes associated with increasing motor vehicle volume on the minor street (StMin_VolVeh+0.5). Other things being equal, a 10 percent increase in StMin_VolVeh+0.5 was estimated to correspond to a 4.9 percent increase in pedestrian crashes, or a 20 percent increase in StMin_VolVeh+0.5 was estimated to correspond to a 9.5 percent increase in odds of pedestrian crashes (estimated as $(1.10)^{0.4997} = 1.049$ and $(1.20)^{0.4997} = 1.095$, respectively).

- The statistical analysis found significant differences in terms of the link of pedestrian crashes and minor street vehicle volumes between Washington and the other two States in the analysis. While the link was statistically significant for Virginia and Oregon (as described above), a log-likelihood test of a model with a single three-State estimate for this link compared to the model differentiating between Washington and the other two States significantly favored the latter model (3.66E-4 *p*-value for 12.69 log-likelihood statistic on 1 degree of freedom). A more detailed description of the differences between States is provided in the next section, Sensitivity of Results.

- Although the final model offers a differentiation between three-leg and four-leg intersections (base crash frequency in crash prediction of $exp[-12.1350]$ and $exp[-11.968]$, respectively), the statistical analysis did not find evidence of a difference in pedestrian crash frequency between three- and four-leg intersections (0.6236 *p*-value from a Wald test on the difference between coefficients−12.135−(−11.968) = 0.167 with 0.340 standard error). Unique coefficients for three-leg and four-leg intersections were provided because many *Highway Safety Manual* intersection prediction equations consider the number of legs.(14)

- Finally, the results also provide suggestive evidence of increased pedestrian crash frequencies, on average, at locations where LTLwoR are present on the major street, compared to sites without this median type, which for this dataset, would include left-turn lanes with raised median (median type = raised), no left-turn lane (median type = none), and a mix of median types. The lack of pedestrian refuge associated with major streets with a LTLwoR is a hypothesis for why more pedestrian crashes are predicted. Major streets with a median of none also lack pedestrian refuge, and a similar finding of greater pedestrian crashes was not present. Therefore, additional research may be needed to fully understand this relationship. The authors note that all the sites with an LTLwoR had four or more through lanes compared to the other intersections in the dataset, which included intersections with only two through lanes. While the number of through lanes was not significant, a larger sample size may be able to add to the understanding of how median design is associated with pedestrian crashes. Everything else being equal, this safety association was estimated as an increase in pedestrian crash frequency by a factor of 1.5636 (1.5636 = *exp*[0.4470]) for intersections with LTLwoR on the major approaches.

Sensitivity of Results

In this section, the research team provides further details on various implications of the intersection-level analysis. Figure 36 shows how multiplicative changes in the three metrics of exposure in the model (StMaj_VolVeh, StMin_VolVeh, and T_Ent_Pedbike) relate to multiplicative changes in Ped_KABCO crash frequency. The plots are normalized around the mean of each exposure metric (i.e., mean exposure value at 1.0 in the *x*-axis) for comparison. The plot shows that the relative impacts are very comparable for the three measures of exposure (which is not surprising given the similar values for the alpha coefficients in table 33). Figure 36 shows, for example, that if any of the exposure metrics drops to 50 percent of its value, a reduction of about 30 percent is expected in Ped_KABCO crash frequency. Similarly, if any of the exposure metrics doubles, the Ped_KABCO crash frequency is expected to increase by slightly less than 50 percent.

Next, figure 37 and figure 38 show the Ped_KABCO predictions by major road volume and entering pedestrian/bicyclist volume, respectively. Both plots show crash frequency results for three-leg and four-leg intersections, with three-leg intersections having fewer pedestrian crashes than four-leg intersections. Figure 38, which plots pedestrian crashes by total entering pedestrian/bicyclists, shows a wider range of Ped_KABCO crash predictions than figure 37, which plots pedestrian crashes by major road volume.

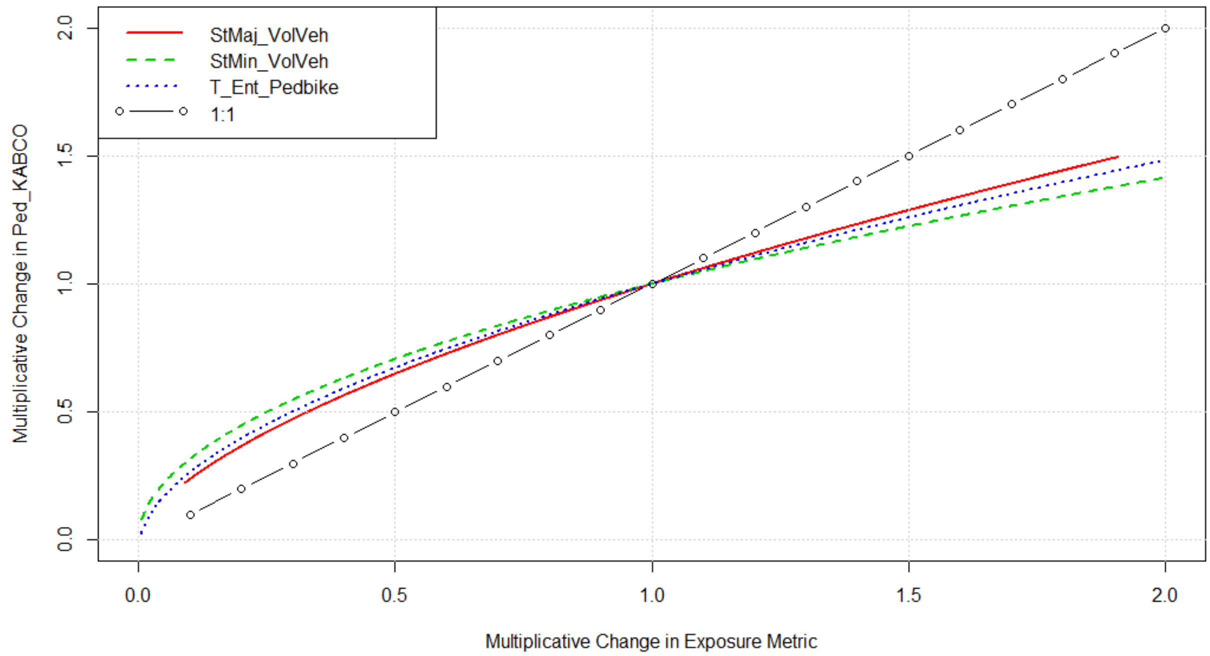


Figure 36. Graph. Multiplicative change in Ped_KABCO crashes per metric of exposure.

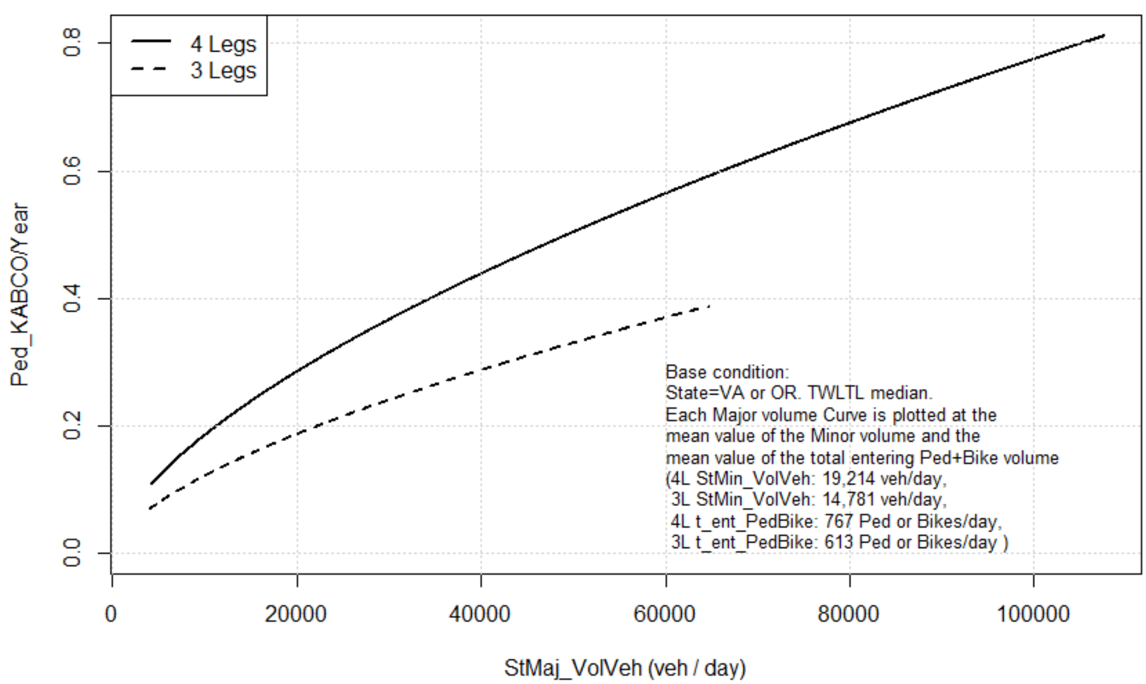


Figure 37. Graph. Ped_KABCO crash model predictions versus major vehicle volumes by number of legs.

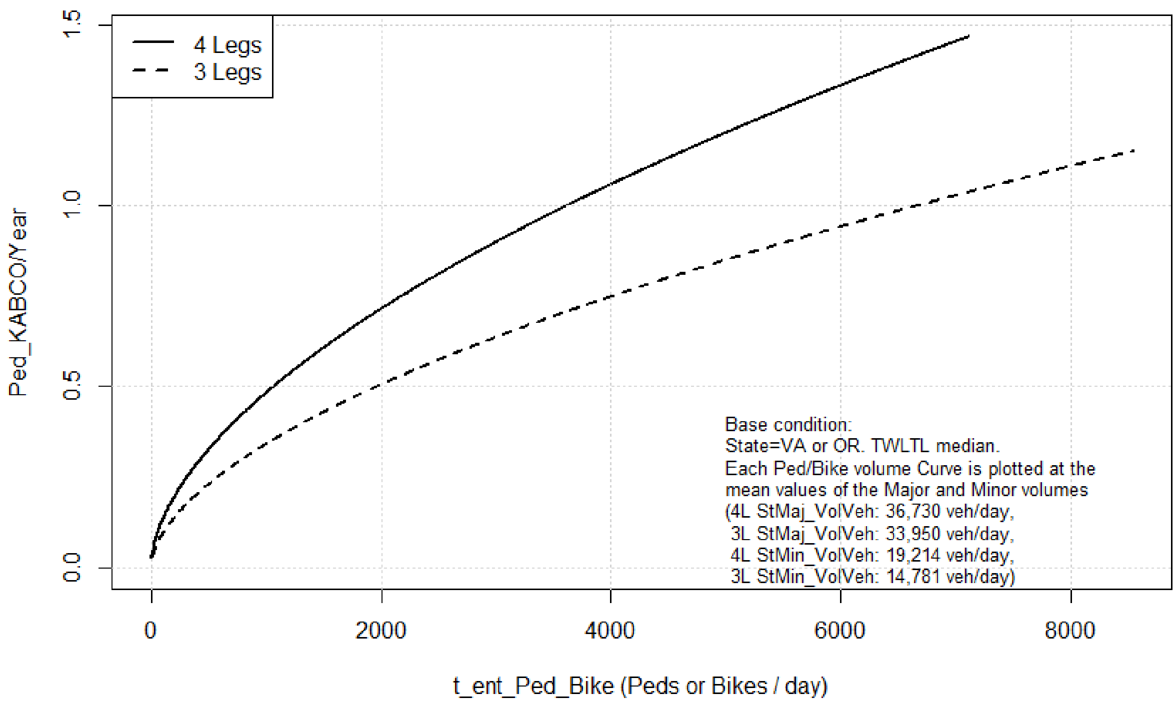


Figure 38. Graph. Ped_KABCO crash model predictions versus pedestrian/bicycle volumes by number of legs.

Figure 39 shows the marginal effect of Oregon or Virginia relative to Washington, which is equivalent to the relative change in Ped_KABCO crash frequency due to StMin_VehVol for Oregon and Virginia relative to Washington when all other variables in the model have the same value. For StMin_VehVol below 10,000 vehicles/day, the model predicts fewer pedestrian crashes for Oregon and Virginia, everything else being equal. The biggest difference between Washington and the other two States in this region is a factor of 0.51 that occurs at the smallest volume where the comparison is possible (2,595 vehicles/day). For StMin_VehVol above the 10,000 vehicles/day threshold, the model predicts more pedestrian crashes for Oregon and Virginia, with the biggest difference being a factor of 2.27 for the biggest volume where a comparison is possible (50,680). Overall, this lack of sensitivity to StMin_VehVol in Washington helps to explain the narrower range of yearly crashes in this State compared to Oregon and Virginia (table 28). The research team surmises that this finding is because the analysis showed sensitivity to three exposure metrics for Oregon and Virginia, while it showed sensitivity to only two exposure metrics for Washington.

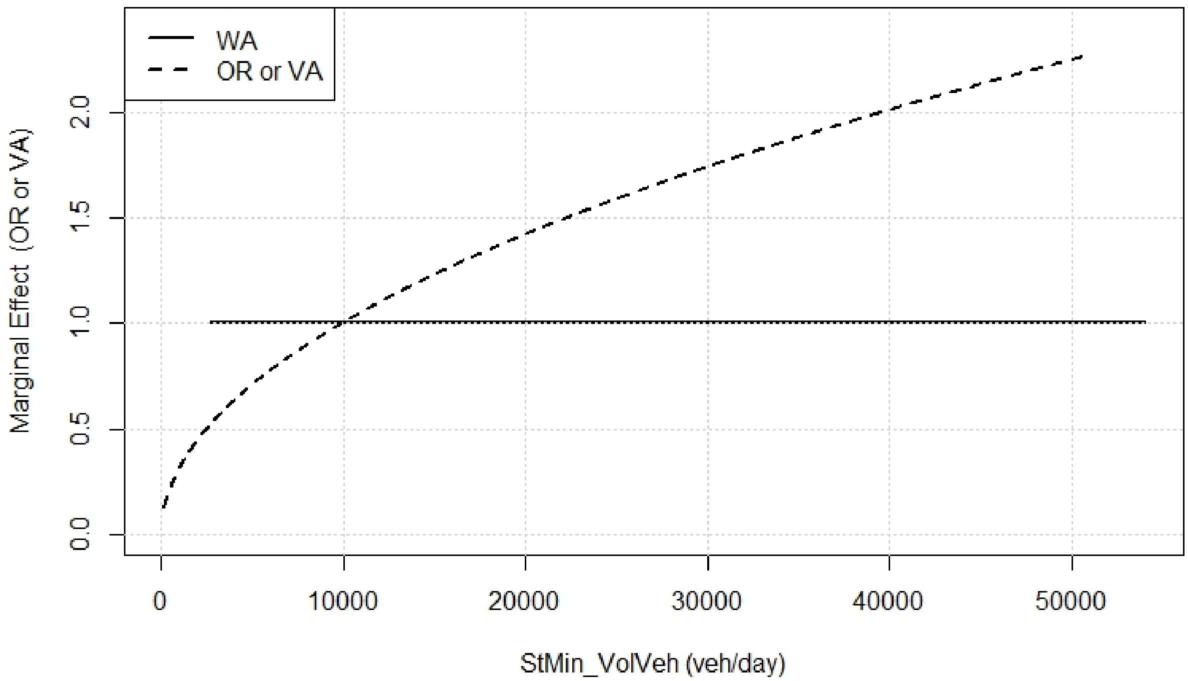


Figure 39. Graph. Marginal effect for Oregon or Virginia (relative to Washington).

CHAPTER 8. RIGHT-TURN SPEED AT SIGNALIZED INTERSECTIONS

SITE SELECTION

The research team compiled a list of signalized intersections within the cities of Dallas, Bryan, and College Station, TX. For this study, intersections were removed from consideration if one of the approaches had a posted speed limit over 55 mph, a lack of marked crosswalks, or an intersection skew. A site was defined as one corner (right-turn movement) at a signalized intersection; thus, a four-leg signalized intersection may yield up to four sites. For this study, the sites were removed from consideration if they had complex curvature for the right-turn movement or a corner island. The right-turn lane could be either a shared through right lane or an exclusive right-turn lane.

Key roadway geometrics were gathered for the potential list of sites using aerial photography. The measurement tool in Google Earth was used to determine the corner radius. For example, the corner at the top of figure 40 has a radius of 50 ft. Table 34 lists the variables collected. No bicycle or parking lanes were present on the approach or the receiving leg for any of the sites.

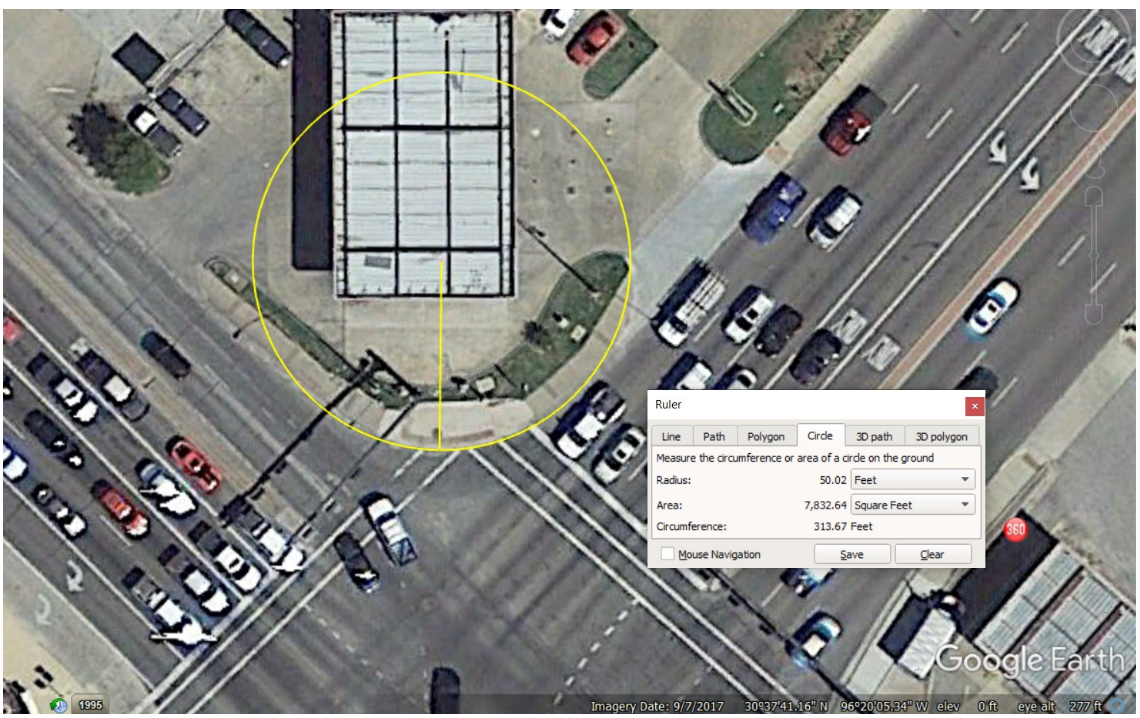


Figure 40. Photo. Corner radius measurement example.

Table 34. Geometric variable descriptions for right-turn speed study sites.

Variable	Abbreviation	Description
City	City	Metropolitan area where site is located, either Dallas or Bryan/College Station, TX.
Corner radius	R	Radius for the corner (ft).
Driveway_dist_app	Drw App	Distance to nearest upstream driveway on the approach leg (ft), measure from closest crosswalk line to driveway centerline.
Driveway_dist_rec	Drw Rec	Distance to nearest downstream driveway on the receiving leg (ft), measure from closest crosswalk line to driveway centerline.
GC_ratio	GC	Green to cycle length ratio for right-turn movement (including permissive phase plus protected overlap phase, if used), based on a typical signal cycle at the site.
Num_rec_lanes	#Rec Lns	Number of receiving lanes available for the right-turn maneuver.
Num_RT_lanes	#RT Lns	Number of right-turn lanes on the approach.
RT_lane_type	RTLT	Right-turn lane type, either exclusive (including lane drops) or shared. A right-turn lane is considered a lane drop if it extends to the next upstream intersection as a through lane but ends at the subject intersection.
Site_num	Site	Site number assigned to the site (corner).
Speed_limit_mph	PSL	Approach posted speed limit (mph).
Turn_bay_len	Bay Len	Length of right-turn bay (ft), measured from stop line to point of fully developed width or end of solid white line: zero if shared right-turn lane; drop if exclusive lane drop.

Since the goal was to identify the relationship between corner radius and right-turn speed, the research team wanted to select sites with a range of corner radii so a relationship could be derived. A goal of 30 sites (corners) was established for the study. Because of data collection efficiencies, data were collected at 32 sites. Table 35 lists the site characteristics for the corners. Most of the sites had one right-turn lane, but a few had two. The speed study included only vehicles using the curb lane. The radii for the selected sites are in the range of 25 to 115 ft, with most being between 35 and 50 ft.

Table 35. Right-turn speed data collection site characteristics.

Site	R (ft)	RTLT	#RT Lns	Bay Len (ft)	Drw App (ft)	Drw Rec (ft)	#Rec Lns	PSL (mph)	GC
1	25	Shared	1	0	129	180	2	35	0.38
2	30	Exclusive	1	106	349	272	2	40	0.39
3	50	Shared	1	0	584	722	2	45	0.21
4	50	Shared	1	0	312	333	3	35	0.13
5	45	Shared	1	0	320	362	1	45	0.50
6	45	Shared	1	0	140	395	1	45	0.49
7	55	Shared	1	0	578	1,703	1	40	0.29
8	40	Exclusive	1	Lane drop	213	214	3	40	0.30
9	40	Exclusive	1	231	226	153	2	55	0.24
10	35	Shared	1	0	462	366	2	40	0.13
11	40	Exclusive	1	Lane drop	278	515	2	40	0.43
12	70	Exclusive	2	169	212	860	2	40	0.20
13	15	Shared	1	0	197	296	2	40	0.14
14	20	Shared	1	0	234	309	2	40	0.69
15	50	Shared	1	0	93	174	2	45	0.18
16	70	Exclusive	1	149	59	45	2	40	0.19
17	50	Exclusive	1	Lane drop	131	149	3	45	0.22
18	115	Shared	1	0	150	125	3	30	0.25
19	35	Exclusive	1	165	533	602	3	40	0.42
20	40	Exclusive	1	177	93	287	3	40	0.13
21	40	Exclusive	1	220	86	122	2	40	0.52
22	35	Exclusive	1	134	163	173	3	40	0.22
23	40	Exclusive	1	219	610	195	2	45	0.23
24	30	Exclusive	2	260	391	504	2	55	0.30
25	45	Exclusive	2	140	423	77	3	45	0.33
26	45	Shared	1	0	884	1,145	2	55	0.26
27	30	Exclusive	1	161	277	238	2	40	0.46
28	65	Exclusive	2	Lane drop	301	266	2	40	0.34
29	60	Exclusive	1	153	413	284	3	40	0.23
30	50	Exclusive	1	283	4,210	225	3	55	0.40
31	50	Exclusive	1	157	340	310	3	40	0.11
32	50	Exclusive	1	Lane drop	502	246	3	55	0.38

Note: See table 34 for descriptions of column headings.

METHODOLOGY

The right-turn speed measurement methodology involved collecting video footage at signalized intersection approaches and post-processing the footage to extract speed measurements. The following sections describe the methodology for the data collection and data reduction activities.

Data Collection

At each data collection site, the research team mounted a camcorder near the right-turn approach such that the following elements were visible in the footage:

- The brake lights of the approaching right-turn vehicles.
- The crosswalk markings for both the approach and the receiving lanes.
- The traffic signal faces for the right-turn movement.
- A small portion of the receiving lanes for the right-turn vehicles.

Figure 41 shows an example camera view. Note the presence of a right-turn vehicle in figure 41 with its front-right tire on the initial edge of the approach lane crosswalk markings (called first reference line in this study) and the ending edge of the receiving lane crosswalk markings (called second reference line in this study) in figure 42. The vehicle is beginning a right turn on a green signal indication. The goal was to obtain observations of at least 50 vehicles making unimpeded right-turn movements at each site. A vehicle was determined to be unimpeded during field observations if it made the right turn on a green indication and was not part of the initial queue of stopped vehicles at the beginning of the green indication.

Figure 41. Photo. Example of a camera view for right-turn speed measurement, first reference line.

Figure 42. Photo. Example of a camera view for right-turn speed measurement, second reference line.

Data Reduction

The research team computed speeds for each right-turn movement by observing the video footage and applying geometric calculations. The right-turn travel path is approximated as a circular arc with a radius greater than the gutter's circular path. In cases where the right-turn vehicle traverses a path that does not parallel the gutter (i.e., the right-turn driver swings outward and turns into the leftmost receiving lane), the path radius will vary, and the center of the circle used to approximate the travel path will not be concentric with the gutter-path circle. Key observations from the video footage included timestamps when the vehicle's front axle crossed the reference lines (as shown in figure 41) and the pixel distances from the tire to the curb edge. Further calculations were applied to correct for camera perspective and site geometry. The calculation method provides the average speed between the two reference lines, which are the initial edge of the crosswalk markings on the approach and the trailing edge of the crosswalk markings on the receiving lanes.

In addition to being used to calculate the speed of the right-turn vehicle, the timestamps were used to determine the headway between the subject right-turn vehicle and the preceding vehicle. Also identified was whether that preceding vehicle was going straight through the intersection or was turning right.

Validation of Method

The research team tested the speed calculation methodology by conducting test runs at a data collection site. The research team obtained ground-truth speed measurements using a global positioning system (GPS) receiver that was configured to record a continuous log of position, speed, time, and heading at a rate of 10 Hz. This analysis included turn movements that occurred during green or yellow indications on the traffic signal while the receiving lanes were unimpeded by queued vehicles.

While the video footage collection was in progress, the research team collected speed data for a test vehicle using the GPS receiver. One of the team members drove the test vehicle through the sites during video footage collection and made right turns on green signal indications whenever possible.

The comparison of the speeds calculated from the video with the speeds collected with the test vehicle resulted in two adjustments to the data reduction efforts. First, if screen-pixel measurement was recorded as 0.0 pixels from the curb (indicating that the vehicle's right tire was mounting the curb), a value of 0.5 pixels was substituted. Second, to obtain an estimate of the vehicle's arc length about its center point (instead of its right tire), it was necessary to adjust the average path radius by 3 ft to account for the typical distance between a vehicle's right tire and the vertical longitudinal plane at the center of the vehicle. These changes in the data reduction efforts resulted in better speed measurements.

Figure 43 shows a comparison of the GPS-measured speeds and video-calculated speeds (by vehicle). As shown, the speed values were generally in agreement. The figure shows a simple trend line that has a slope of about 1 and overlays the $y = x$ line with no vertical shift.

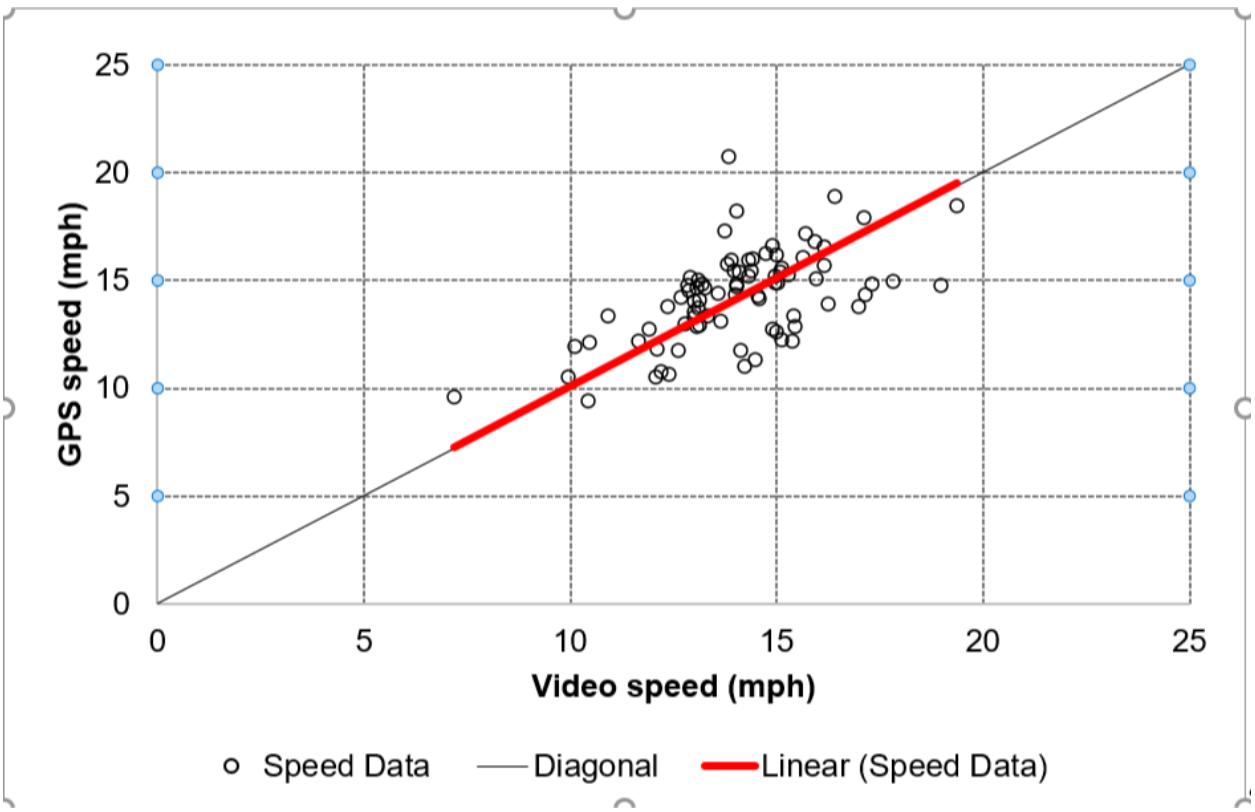


Figure 43. Graph. Comparison of GPS and video speeds by vehicle.

Sample Size

Technicians collected the needed information from the video footage and entered the data into a spreadsheet. Senior research team members reviewed and cleaned the data. Vehicles that did not turn on a green or yellow indication were removed from the database, as were observations for when the data for the preceding vehicle were not available (typically the first observed right-turn vehicle for the video at a site). The final database included data for 4,349 right-turn vehicles. Table 36 provides descriptive statistics (average and standard deviation) of the right-turn speeds by radius. Overall, the average right-turn speed was 14.4 mph. Across the range of radii in table 36, the standard deviations are within the range of 2.1 to 3.0 mph.

Table 36. Average speed by radius.

R **(ft)**	**Number of Vehicles**	**Average v_{RT} (mph)**	**Standard Deviation of v_{RT} (mph)**
15	100	13.5	2.07
20	87	13.3	2.23
25	127	15.4	2.16
30	283	12.7	2.21
35	301	13.5	2.15
40	1,110	14.6	2.46
45	585	13.7	2.07
50	686	14.0	3.00
55	380	16.3	2.33
60	188	15.6	2.14
65	165	15.9	2.96
70	260	16.1	2.99
115	77	12.5	2.09
Grand total	4,349	14.4	2.68

v_{RT} = right-turn speed.

RESULTS

Exploratory Analysis

The research team created box plots to aid in the exploratory analysis. Figure 44 shows the box plot of right-turn speeds (labeled as V_{RT} in mph) by radius (labeled as R, in ft). The width of the box reflects the quantity of data present for the given radius value. A trend of higher right-turn speeds can be seen for larger radii except for the 115-ft radius. Only one site had a 115-ft radius, which was the only site with the lowest posted speed limit in the database of 30 mph. Because the site with the 115-ft radius had a larger radius than the other sites and was the only site with a 30-mph speed limit, which was the lowest speed limit in the dataset, the site was removed from the analysis.

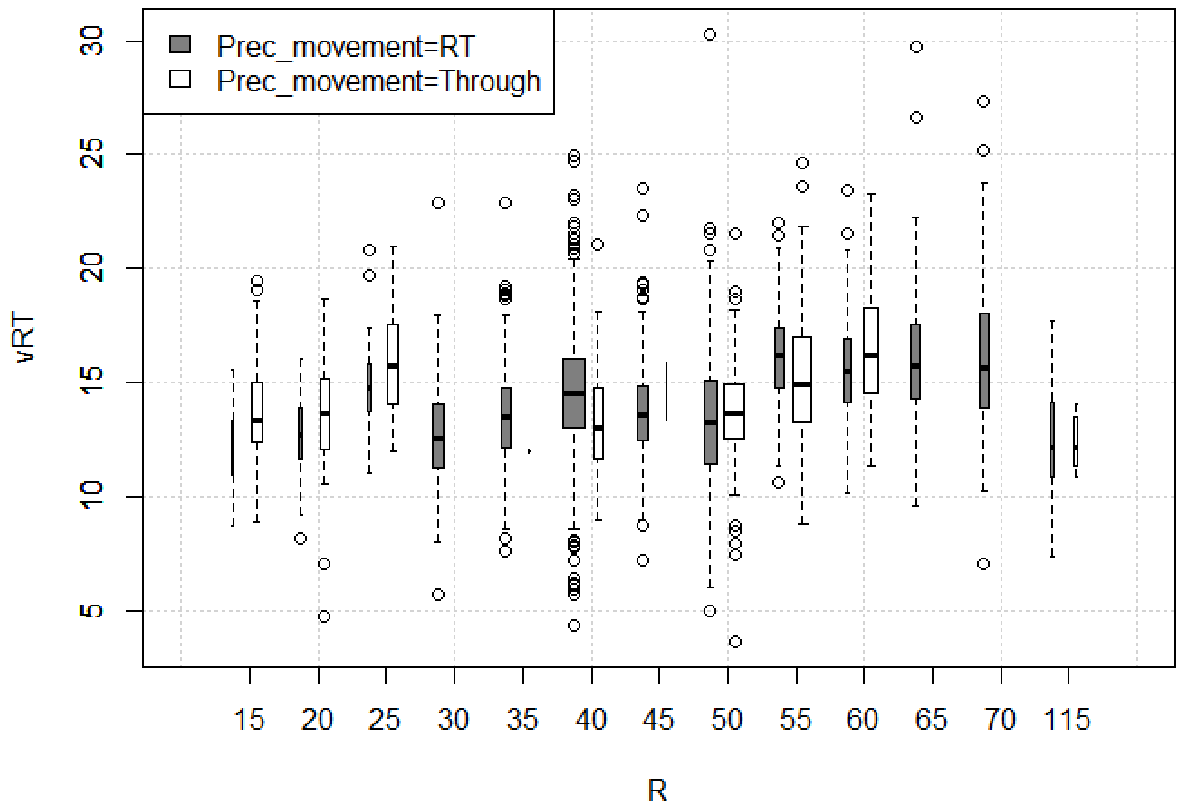
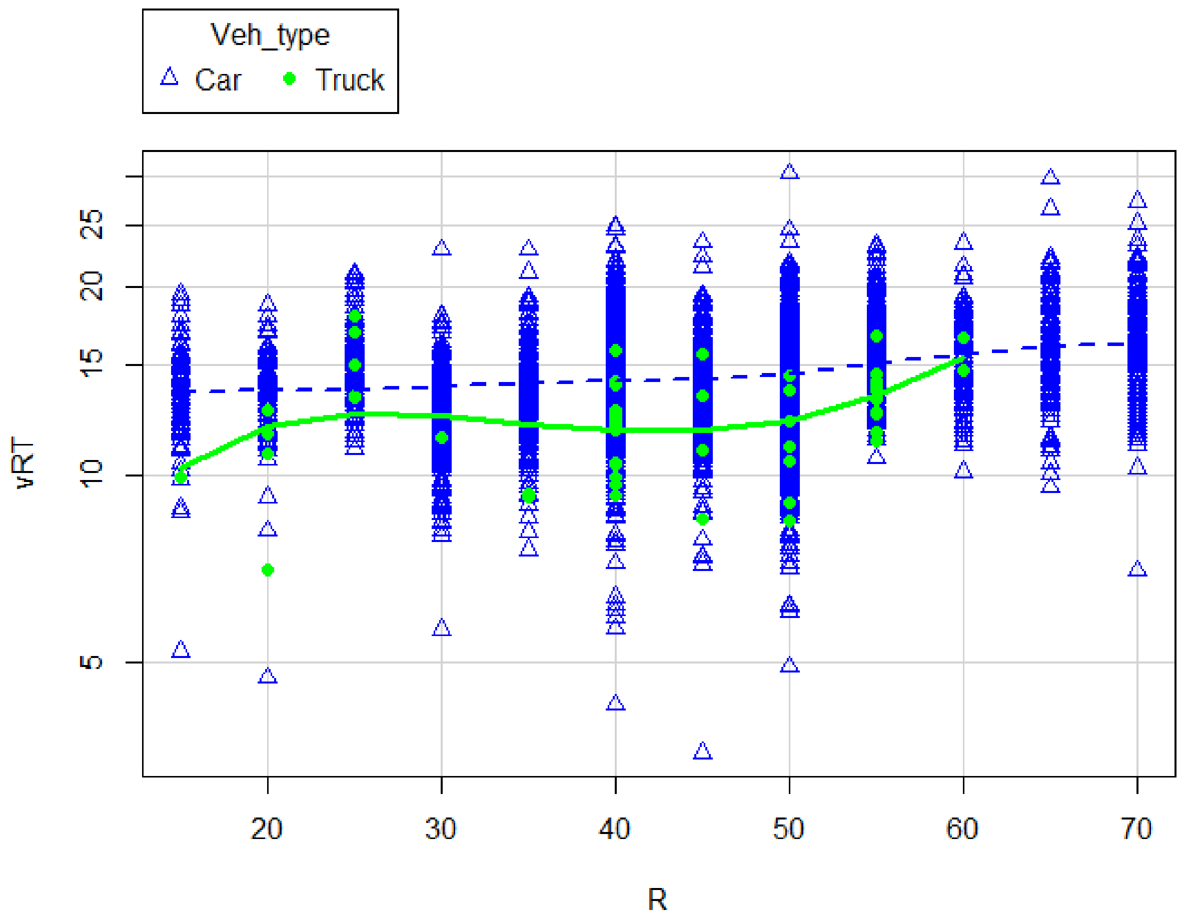


Figure 44. Graph. Speeds of right-turn vehicles by movement of preceding vehicle and radius.

Since the type of movement of the preceding vehicle could affect the turning speed of the subject vehicle, figure 44 also shows the box plot of turning speed by radius and type of movement for the preceding vehicle. In most cases, right-turn speeds were slightly higher if the right-turn vehicle was preceded by a through vehicle. Some sites had an exclusive right-turn lane, such that no right-turn vehicles were preceded by a through vehicle.

Figure 45 shows the distribution of individual speed values (labeled as v_{RT}, in mph) by radius (labeled as R, in ft), subdivided by car and truck. As shown, there is considerable variation among speeds within each radius category, but there is generally an upward trend in speed as radius increases. The magnitude of the average speed increase across radii is small—approximately 13 mph for 15-ft-radius sites to 15 mph for 70-ft radius sites. Across the range of radius values, truck speeds are about 2 mph lower than car speeds.



Note: Blue dashed line is the trend line for cars, while the solid green line is the trend line for trucks.

Figure 45. Graph. Speeds of right-turn vehicles by vehicle type and radius.

Speed Data Modeling

The research team fitted log-normal models for v_{RT} as the response variable. The use of the log-normal instead of the normal distribution was to account for the long right tail (i.e., positive skewness) clearly observable in the data. Two random parameters were included in the model: one to account for exogenous differences between sites, and another to account for speed variability due to correlation with the speed of the preceding right-turn vehicle. To account for potential interdependency between adjacent observations (given that most of the time headways were smaller than 6 s), the model included a correlation structure of the residuals. The correlation between two consecutive speed residuals increased with decreasing headways, more so for preceding right-turn vehicles than for preceding through vehicles. The model included a penalization in correlation between nonconsecutive vehicles to model those vehicle speeds as virtually independent of each other. The dynamic mixed-effects model was calibrated using the statistical language R with a log-normal distributional structure and using the ML method to produce model estimates from the data.

Several model alternatives were explored to identify the variables and the combination of variables that best predict the measured right-turn speeds. The effort included several geometric variables for the site, including those identified as being potentially influential based on findings from the literature. The variables initially considered in the modeling process included:

- GC_ratio.
- Turn_bay_len.
- Driveway_dist_rec.
- Driveway_dist_app.
- Num_rec_lanes.
- Speed_limit_mph.
- City.
- RT_lane_type.
- Corner radius (ft).
- Signal indication (green or yellow).
- Vehicle type (car or truck).
- Preceding vehicle maneuver type (through or right turn).
- Vehicle headway(s).

Preliminary models considered all variables that the literature indicated as having some relationship with turning speed and any additional variables the research team collected that could have a relationship. A reduced set of variables and the functional form of the model were updated based on the anticipated form of some of the relationships (e.g., the decaying effect of the leading vehicle as the headway increases); these candidate intermediate models were tested stepwise against alternatives based on quality of information criteria to achieve a balance between fit and parsimony. A final model was selected based on knowledge of the limitations of the available variables (e.g., number of data points and range represented by different levels in explanatory variables) and the practical interpretation of the set of variables in the final model.

This study allowed the inclusion of variables that described conditions present when the subject vehicle was turning right, including the signal indication, type of vehicle, and maneuver type of the vehicle immediately preceding the turning vehicle. The conditions during the specific turn appeared to be more influential than the site characteristics except for corner radius, which was the only site characteristic in the final selected model. The covariates found to have statistically significant links to explaining v_{RT} variability included corner radius, headway, signal indication (green or yellow), vehicle type (car or truck), and preceding movement (through or right turn). The other variables considered during the model selection were not found to significantly improve the model.

Based on the findings of the exploratory analysis, the research team calibrated a statistical model to predict right-turn speed as a function of the following variables:

- Corner radius (ft).
- Signal indication (green or yellow).
- Vehicle type (car or truck).
- Preceding vehicle maneuver type (through or right turn).
- Vehicle headway(s).

To account for potential interdependency between adjacent observations, the research team decided to include a correlation structure of the errors in the model. The mixed-effects model was calibrated using the statistical language R with a log-normal distributional structure. The fixed-effects part of the model represents the long-term median of v_{RT} for all sites and is given in figure 46.

$$v_{RT} = exp\left(\beta_0 + \beta_a I_Y + \beta_b I_{Tk} + \beta_c R + \frac{\beta_d + \beta_e \cdot I_{Thru} + \beta_f \cdot R + \beta_g \cdot R \cdot I_{Thru}}{t_H^2}\right)$$

Figure 46. Equation. Median right-turn speed functional form.

Where:

v_{RT} = predicted median right-turn speed for vehicle of interest (mph).
β_i = calibration coefficients.
R = corner radius (ft).
I_Y = indicator for yellow signal indication (= 1.0 if the signal indication is yellow when the vehicle of interest crosses the stop line, 0.0 = otherwise).
I_{Tk} = indicator variable for truck (= 1.0 if the vehicle of interest has three or more axles and is not a motorcycle, 0.0 = otherwise).
I_{Thru} = indicator variable for preceding maneuver (= 1.0 if the vehicle preceding the vehicle of interest proceeded straight through, 0.0 = if the preceding vehicle turned right).
t_H = leading headway between preceding vehicle and vehicle of interest(s).

The coefficient values for the equation in figure 46 are as shown in table 37. Coefficients *d* through *g* are shifts in the effects of two variables adjusted by inversed functions of the leading headway. This parameterization allows for the model to phase out those adjustments as the headway increases.

Figure 47 shows the model functional form with the corresponding coefficient estimate values.

Table 37. Speed model calibration results.

Coefficient	Value	Std Error	*t*-Value	*p*-Value	Significance[1]
β_0	2.465682	0.07411576	33.26798	<0.001	***
β_a	0.0471218	0.01047752	4.49742	<0.001	***
β_b	−0.1428277	0.02014032	−7.09163	<0.001	***
β_c	0.0035318	0.00163545	2.15955	0.0392	*
β_d	−0.1375053	0.03312485	−4.15112	<0.001	***
β_e	0.8183215	0.16973427	4.82119	<0.001	***
β_f	0.032	0.005	6.229	<0.001	***
β_g	−0.0076864	0.00366375	−2.09796	0.036	***

[1] Significance level where: * = $p < 0.05$ (moderate evidence); *** = $p < 0.001$ (very convincing evidence).

$$v_{RT} = exp\left(2.466 + 0.047I_Y - 0.143I_{Tk} + 0.004R + \frac{-0.138 + 0.818I_{Thru} + 0.032R - 0.008RI_{Thru}}{t_H^2}\right)$$

Figure 47. Equation. Median right-turn speed functional form with coefficients.

The equation above yields an estimate of the median (or 50th percentile) right-turn speed. If speed at a speed distribution value other than the 50th percentile is wanted, it can be obtained by including the product of *Z* (the standard normal variable) and the amount of variation in the residuals and random intercept, which is 0.19 for this dataset. For the 85th percentile, the value of *Z* is 1.0364, which amounts to approximately 23 percent faster right-turn speeds than the median speed. For other percentiles, the value of *Z* would be modified—for example, *Z* = 1.6449 for the 95th percentile, which in the equation would amount to 37 percent higher right-turn speeds than the median speed. The equation to calculate right-turn speed for a specific percentile is shown in figure 48.

$$v_{xxth\ RT} = exp\left(2.466 + 0.047I_Y - 0.143I_{Tk} + 0.004R + \frac{-0.138 + 0.818I_{Thru} + 0.032R - 0.008RI_{Thru}}{t_H^2} + Z \cdot 0.19\right)$$

Figure 48. Equation. Percentile right-turn speed functional form with coefficients.

Where:

v_{XXthRT} = predicted *xx*th percentile right-turn speed, reflecting the condition where *xx* percent of the drivers are turning at that speed or less and 1 *xx* are turning at speeds that are higher (mph).

Z = 1.0364 for 85th percentile or 1.6449 for 95th percentile.

Other variables are as previously defined.

COMPARISON OF SPEEDS

The resulting predicted right-turn speeds were compared to the speeds generated using the radius of curvature equation. The assumptions used to predict the speeds included:

- Headway is 6 s.
- Turning vehicle is a car.
- Preceding vehicle is going straight.
- Signal indication is yellow.

For the radius of curvature equation, superelevation was assumed to be zero and side friction was estimated from the values shown in table 6. As a reminder, the range of speeds and not just the average speed should be considered when evaluating how traffic is operating at an intersection, especially with respect to safety and to pedestrians. Figure 48 in this report provides the opportunity to calculate a range of expected speeds rather than just the average speed.

Figure 49 shows the comparison using calculated 50th, 85th, and 95th percentile right-turn speeds for a turning car (rather than a truck), on a yellow (rather than green) signal, and when the preceding vehicle is going straight and a headway of 6 s is present. The figure demonstrates that the speed prediction using observed right-turn vehicles has 50th percentile (median) turning speeds higher than the values calculated using the radius of curvature equation for radii up to 45 ft. For radii greater than 45 ft, the 50th percentile turning speed is slightly below the radius of curvature equation, indicating that roughly 40 percent of right-turn cars are exceeding that value, which has significant implications for pedestrians. For all radii values, the predicted 85th or 95th percentile speeds are all greater than the value generated with the radius of curvature equation.

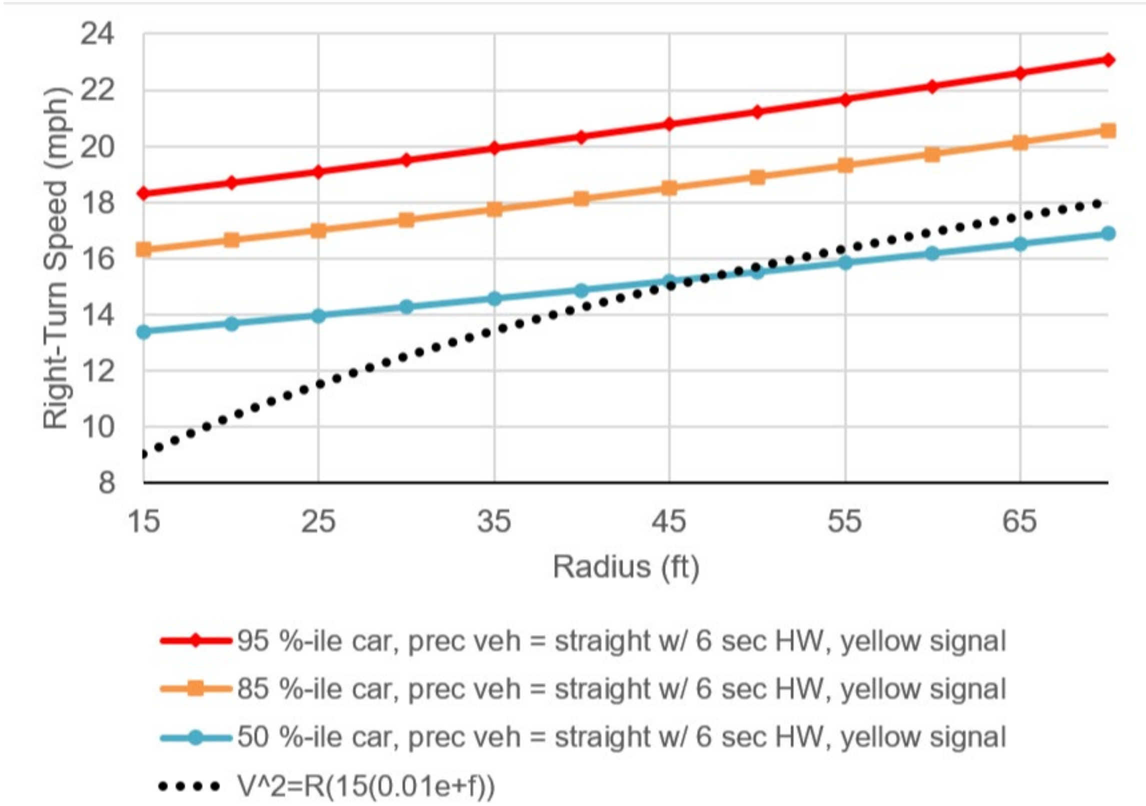


Figure 49. Graph. Comparison of predicted 50th, 85th, and 95th percentile right-turn speeds for stated conditions with calculated speed using radius of curvature equation.

OBSERVED RIGHT-TURN SPEED DISTRIBUTION

Computer simulation of vehicle operations at an intersection can consider speed distribution that may be reflective of a site or a condition. The equation in figure 48 can be used with the necessary assumptions to generate a distribution, or the field data can provide a general speed distribution for right-turn vehicles. The statistical evaluation identified only one intersection geometric variable as being significant—the corner radius. Speed distribution curves for the radii values available in the analysis were reviewed, and a visual difference was present for the larger radii values; therefore, the distribution curves were generated for all data and then by two radii groups: 15 to 50 ft and 55 to 70 ft. Figure 50 illustrates these curves. Figure 51 provides the speed distribution for a sample of corner radius values using the equation in figure 48 along with the average speed observed for comparison.

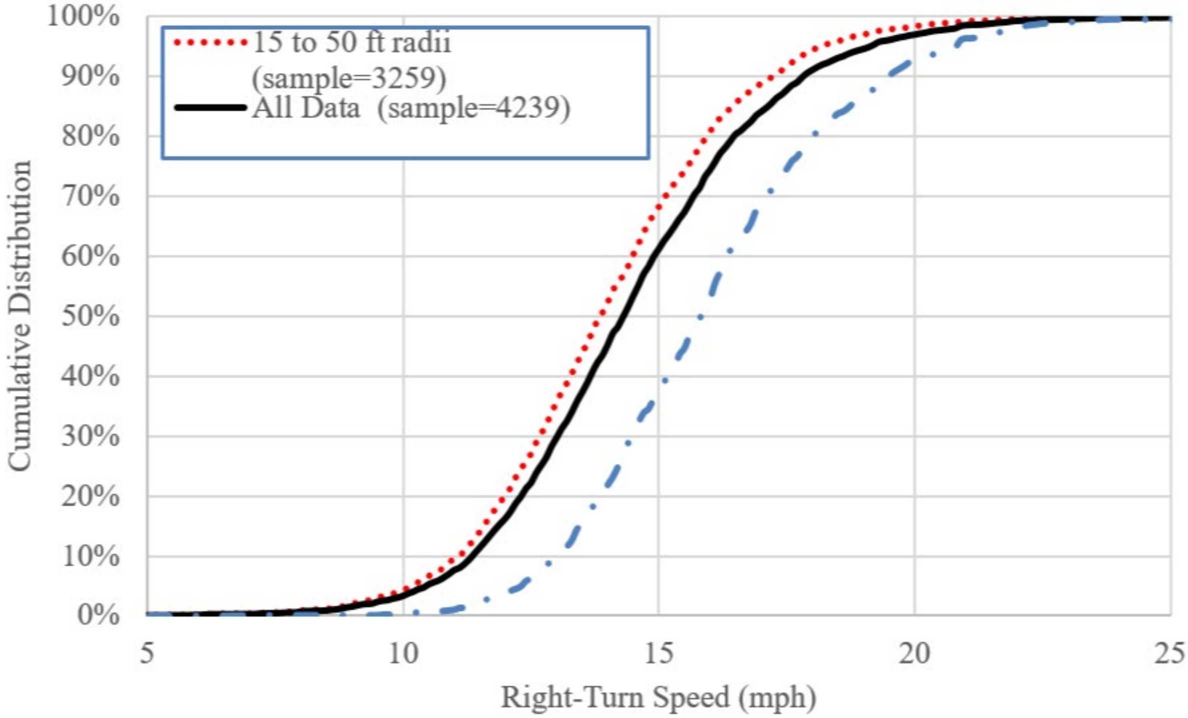


Figure 50. Graph. Passenger car right-turn speed distribution for observed field data.

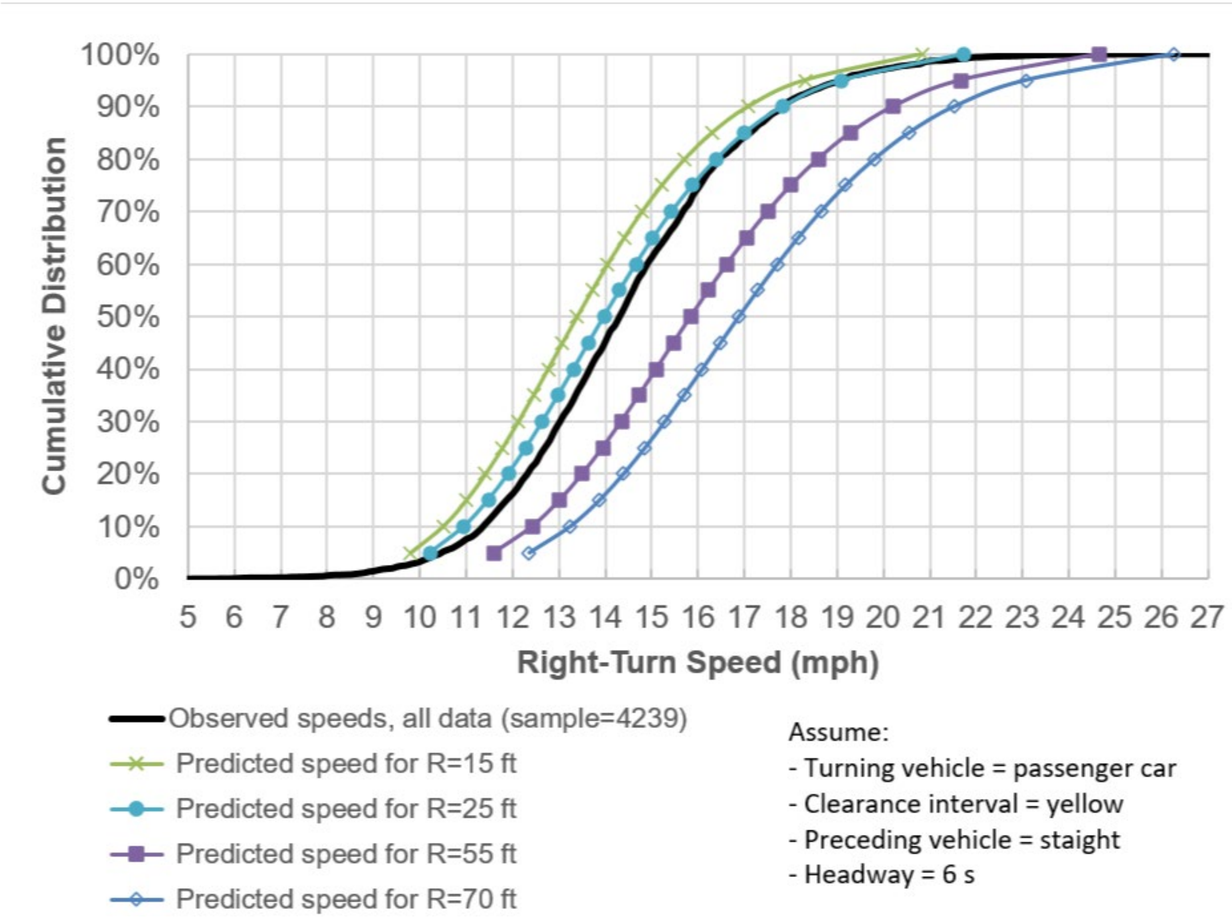


Figure 51. Graph. Passenger car right-turn speed distribution for a sample of corner radius values using prediction equation.

CHAPTER 9. SUMMARY AND CONCLUSIONS

SURVEY ON PEDESTRIAN TREATMENTS

The initial efforts for this project were to identify candidate pedestrian treatments of interest to the profession and to determine the quality of CMFs that exist for the treatment. Discussions with FHWA and the TAC resulted in intersection corner radius being selected for study, with the treatment being the focus of both a crash analysis approach and an operational analysis approach.

CORNER RADIUS CMF

The objective of this effort was to determine the safety effectiveness of intersection corner radii in reducing nonmotorist crashes at signalized intersections. The research team selected intersections with the following characteristics:

- At least a 2-h turning movement count of vehicles and pedestrians.
- Traffic control signal presence.
- Typical intersection geometric configurations (including three-leg and four-leg intersections), removing intersections with five legs or a large skew.
- No road or sidewalk construction visible during the years matching the crash data.

The research team obtained consultant-collected vehicle turning movement and pedestrian count data files for signalized intersections in three cities. Since the count data generally only reflected several hours within a day, the counts were expanded to represent a daily count and then an annual value for both vehicles and pedestrians.

The corner radius can be unique to each corner at an intersection. As a result, this study assigned crashes to an intersection corner rather than to the entire intersection using the latitude and longitude of the crash along with information on the directions the vehicles were moving and the crash type. Because the assignment to a corner did not always agree between those methods, the research team created a weighting scheme to consider the level of certainty of the corner crash assignment; crashes with higher certainly level should influence the result to a larger degree than crashes with a low level of certainty. For the Oregon dataset, the assignment showed that most of the crashes would be assigned to one corner, which was disproportionate to the distribution of vehicle or pedestrian volumes; therefore, the data for that State were not included in the corner-level analysis.

The research team considered the vehicle volumes on the legs (both directions of traffic) adjoining the intersection corner of interest for the pedestrian crash evaluation and on the same-direction lanes nearest to the corner for the right-turn analysis. The pedestrian volumes included any pedestrian counted on the two legs that connected to the subject corner. Roadway geometric data and the posted speed limit value were obtained using aerial and street view photos. Crash data for Washington reflected crashes between 2011 and 2017 (7 yr), and for Virginia between 2013 to 2018 (6 yr).

For the corner analyses, the research team utilized GLMMs to perform the safety analyses. After performing exploratory and preliminary analyses, the research team selected the modeling process using the Virginia dataset as the one with the better results to consider. The combined Virginia and Washington models included a State variable, indicating that significant shifts are present between the two subsets of data. The Virginia dataset was selected because its larger size produced more stable coefficients and because a greater proportion of the corner crash assignments had a high certainty with respect to assigning crashes to a corner.

For corner-level pedestrian crashes, the following variables were found to be positively related: pedestrian volume on the approach leg, pedestrian volume on the receiving leg, vehicle volume on the approach leg, vehicle volume on the receiving leg, corner radius, and shoulder width. The number of pedestrian crashes was higher when both legs at a corner were one-way streets with traffic moving away from the corner or when there was a mix of two-way and one-way operations present at the intersection. Fewer pedestrian crashes occurred when on-street parking existed on the approach leg.

For corner-level, right-turn crashes, pedestrian and vehicle volumes on the approach and receiving legs were found to be positively related. The number of vehicles making a right turn at the corner was also positively related. Other variables positively related to corner-level, right-turn crashes included the presence of a median or the shoulder width on the receiving leg. Variables associated with fewer right-turn crashes included when one of the legs had only one lane on the approach or when the intersection had four legs rather than three legs.

The focus of this study was to investigate the relationship of the intersection corner radius with pedestrian or right-turn vehicular crashes. The evaluation using right-turn vehicular crashes did not find a statistically significant relationship. This finding does not necessarily imply that there is no relationship between corner radius and right-turn crashes, only that this analysis did not provide evidence favoring such a relationship. For pedestrian crashes, the evaluation found a statistical relationship with corner radius. The statistical model estimate for corner radius can be used to generate a CMF. Assuming a baseline condition of 10 ft, the pedestrian crashes' CMFs for corner radius for the range of corner radii included in the evaluation were:

- 1.00 for 10-ft corner radius.
- 1.18 for 20-ft corner radius.
- 1.30 for 30-ft corner radius.
- 1.39 for 40-ft corner radius.
- 1.47 for 50-ft corner radius.
- 1.53 for 60-ft corner radius.
- 1.59 for 70-ft corner radius.

PEDESTRIAN CRASHES AT INTERSECTIONS

The analysis of the pedestrian crashes at signalized intersections considered data for 299 intersections located in Oregon, Virginia, and Washington. The database included both three-leg and four-leg signalized intersections, including streets with two-way traffic operations. The best model found very convincing evidence of an increase in pedestrian crashes with increases in pedestrian and bicycle volume, major street vehicle volume, or minor street vehicle volume for Oregon and Virginia. Overall, and using a general rule-of-thumb summary, a 10 percent increase in any of these volumes corresponded to about a 5 percent increase in pedestrian crashes. This result is not surprising because it is reasonable to assume that pedestrian crash risk will increase with increasing exposure of pedestrians and vehicles at an intersection. While several median types were represented in the dataset, only LTLwoR was included in the model. Everything else being equal, this safety association was estimated as an increase in pedestrian crash frequency by a factor of 1.5636 when the LTLwoR was present on the major street compared to all other median types (none, raised, or a mix of median types for the major street approaches). The lack of pedestrian refuge associated for major streets with a LTLwoR is a theory for why more pedestrian crashes are predicted. Major streets with a median type of none also lack pedestrian refuge, and a similar finding of greater pedestrian crashes was not present. Therefore, additional research may be needed to fully understand this relationship. The authors note that all the sites with a LTLwoR had four or more through lanes compared to the other intersections in the dataset, which included intersection with only two through lanes. While number of through lanes was not significant, a larger sample size may be able to add to the understanding of how median design is associated with pedestrian crashes. The number of pedestrian KABCO crashes estimates at a signalized intersection can be obtained from the equation provided in figure 35.

RIGHT-TURN SPEED

This study explored the relationship between in-field, right-turn vehicle speeds and roadway geometrics, especially corner radius, at signalized intersections. Because the goal was to identify the relationship between corner radius and right-turn speed, the research team selected sites with a range of corner radii so a relationship could be derived. A goal of 30 sites (corners) was established for the study. Because of data collection efficiencies, data were collected at 32 sites. The radii for the sites included in this study initially had a range of 15 to 115 ft; however, because the site with the largest radius was also the only site with the smallest posted speed limit, it was removed from the analysis. The range or radii for the analysis was 15 to 70 ft.

The right-turn speed measurement methodology involved collecting video footage at signalized intersection approaches and post-processing the footage to extract speed measurements, along with headway between the turning vehicle and the preceding vehicle. This study allowed the inclusion of variables that described conditions present when the subject vehicle was turning right, including the signal indication (green or yellow), type of turning vehicle (car or truck), and characteristics of the vehicle immediately preceding the turning vehicle (going straight or turning right). The conditions during the specific right turn were more influential than the site characteristics, except for corner radius. Noteworthy findings included the following:

- The analysis found convincing evidence that right-turn speeds are a function of corner radius, with the range of increases in turning speed for corner radii between 15 and 70 ft being about 4 mph. The larger the radius, the higher the turning speeds.

- The final selected model from this study can be used to predict turning speeds. For example, assuming the preceding vehicle went straight through the intersection with a 6-s headway to a passenger car that is turning right on a yellow indication, the range of median turning speed is 13.1 mph for a 15-ft corner radius to 16.75 mph for a 70-ft corner radius. The range of 85th percentile speed with these assumptions is 16.0 mph to 20.4 mph for corner radii of 15 to 70 ft.

- As expected, the analysis found convincing evidence that the speed of the right-turn vehicle is affected by the headway to the preceding vehicle. Smaller headways are associated with slower right-turn speeds when the preceding vehicle is a right-turn vehicle, and faster right-turn speeds when the preceding vehicle is a through vehicle. This prior maneuver-specific effect was found to dissipate at headways of 4 to 8 s and more, when it was found to have minimal impact on the turning speed. This trend is intuitive since larger time headways imply a decreased dependence between the right-turn speed and the maneuver of the preceding vehicle.
- The analysis found convincing evidence that a yellow traffic signal indication is linked with faster turning speeds (about 4.8 percent faster).
- The analysis found convincing evidence that trucks turn slower (about 13.3 percent slower).
- The analysis found convincing evidence that right-turn preceding vehicles influence turning movement by decreasing turning speed, compared to preceding vehicles that are going straight through the intersection (i.e., the random parameter estimate was negative in 26 out of the 31 sites, with a grand average effect across all sites of 0.13 percent decrease in right-turn speed for a 1-mph increase in right-turn speed for the preceding vehicle).

The findings from this study can be used to update the discussion contained in design manuals, especially with respect to designing intersections. For example, NACTO recommends that turning speeds be limited to 15 mph or less, and figure 48 can be used to check a corner radius design to determine if (or how often) the anticipated speed for the design would exceed the set criteria.(6)

Additional research could help explore other variables that would affect turning speed, such as the presence of parking or bicycle lanes. The research should consider whether vehicles are present in the parking space to understand how the additional space, which would change the effective radius, is influencing turning speeds. Future research could also explore speed differences when a shoulder is provided instead of a curb and gutter. Similarly, a truck apron can be used to accommodate large trucks at an intersection corner. Research is also needed on the effects of the truck apron design components on turning speed.

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