North Texas Bicycle and Pedestrian Crash Analysis
Final Report

Technical Report 0-6983-1

Cooperative Research Program

CENTER FOR TRANSPORTATION INFRASTRUCTURE SYSTEMS
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16. Abstract

The scope of this project involves a holistic investigation of the causes of pedestrian and bicycle crashes in the 12-county North Central Texas area. An extensive review of literature assesses the state-of-art knowledge in crash reporting and analysis, safety countermeasures, safety target setting, as well as crash databases and tools. Five years of North Central Texas crash data from TxDOT's Crash Records Information System (CRIS) Texas Peace Officer's Crash Reports (Form CR-3) are coded according to the FHWA's Pedestrian and Bicycle Crash Analysis Tool (PBCAT) methodology. Other existing readily available databases are considered for supporting information in order to gain a better understanding of the conditions surrounding the crashes. Geospatial statistical modelling is employed to determine the roadway elements, conditions, and actions contributing to severity crash, and high-incidence crash corridors are identified within the study area. A comprehensive list of countermeasures is assembled, including the effectiveness of each countermeasure for each evaluated crash type and crash attribute. A pilot version of an on-line application has been developed to visually present the results of this project and to communicate the safety needs in North Central Texas. This on-line application includes a database with data gathered during this project, a query builder that allows users to easily identify crash locations based on multiple parameters, as well as a list of high-incidence crash locations and their potential countermeasures.

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Final Report

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Abstract

The scope of this project involves a holistic investigation of the causes of pedestrian and bicycle crashes in the 12-county North Central Texas area. An extensive review of literature assesses the state-of-art knowledge in crash reporting and analysis, safety countermeasures, safety target setting, as well as crash databases and tools. Five years of North Central Texas crash data from TxDOT’s Crash Records Information System (CRIS) Texas Peace Officer's Crash Reports (Form CR-3) are coded according to the FHWA’s Pedestrian and Bicycle Crash Analysis Tool (PBCAT) methodology. Other existing readily available databases are considered for supporting information in order to gain a better understanding of the conditions surrounding the crash. Geospatial statistical modelling is employed to determine the roadway elements, conditions, and actions contributing to severity crash, and high-incidence crash corridors are identified within the study area. A comprehensive list of countermeasures is assembled, including the effectiveness of each countermeasure for each evaluated crash type and crash attribute. A pilot version of an on-line application has been developed to visually present the results of this project and to communicate the safety needs in North Central Texas. This on-line application includes a database with data gathered during this project, a query builder that allows users to easily identify crash locations based on multiple parameters, as well as a list of high-incidence crash locations and their potential countermeasures.

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CHAPTER 1. INTRODUCTION

This research project involves the investigation of causes of pedestrian and bicyclist[1] crashes in the 12- county North Central Texas area, including the following counties: Wise, Denton, Collin, Hunt, Parker, Tarrant, Dallas, Rockwall, Kaufman, Hood, Johnson, and Ellis. This Research Report includes concepts, models, analytical methods, analysis, and results of the study with a summary of key findings and recommendations for implementation.

1.1 Technical Objectives

The technical objectives are:

1. Code five years of bicycle and pedestrian crash reports for the 12-county North Central Texas Metropolitan Planning Area using the methodology developed by the National Highway Traffic Safety Administration for the Pedestrian and Bicycle Crash Analysis Tool.

2. Conduct an analysis to identify corridors with highly concentrated bicycle and pedestrian crashes and the unsafe actions that are contributing to the crashes.

3. Provide safety countermeasures and recommendations for further study for these corridors.

4. Review the crash narrative/diagram as part of the coding process to understand the true nature concerning the cause of the crash.

1.2 Online Application to Present Study Results

A pilot version of an on-line application was developed to visually present the results of this project and tell a story about the safety needs in North Central Texas. Its features include:

- A Crash Database & Query Builder in the Crash Data Analysis and Visualization Application (CDAVA) tool that includes not only PBCAT crash types that were assigned based on information in CR-3 crash report forms but also other data collected from various datasets, such as the CRIS Automated Crash Data Public Extract files, 2017 Roadway Inventory Annual Data, NCTCOG Regional Data Center, Strava Metro, U.S. Census Bureau American Community Survey, U.S. Census Longitudinal Employer-Household Dynamics, as well as Pedestrian Fatality Risk and the Social Vulnerability Index. Users can easily identify locations of crashes based on multiple parameters using the online query builder.

[1] In this document, the terms 'bicyclist', 'bicycle', and 'pedalcyclist' are used interchangeably and are meant to include any rider of a non-motorized vehicle propelled by pedaling.

- An interactive map of high-incidence crash corridors that were identified based on 2014-2018 crash data. Information about the crashes and corridors is summarized in a report card which includes information about what city and county the corridor is located in, its length, crash history based on 2014-2018 data, roadway elements, impairment, surrounding conditions, identified PBCAT crash groups and related potential countermeasures.
- A list of potential countermeasures for each corridor. The countermeasures gathered during this project are based on recommendations from FHWA PEDSAFE, FHWA BIKESAFE, Proven Safety Countermeasures, Countermeasures that Work, Urban Bikeway Design Guide, and others.

1.3 Organization of the Report

The Research Report is a comprehensive document of all the research efforts during the development of the study, and it is organized into seven main chapters and eight appendices.

Chapter 1. Introduction: Presents the research project technical objectives and describes the organization of the chapters in the Research Report.

Chapter 2. Literature Review: Summarizes the current knowledge on topics relevant to bicycle and pedestrian crash analysis. It gathers available information from federal agencies, state departments of transportation, metropolitan planning organizations, municipalities, and other non-profit organizations. The Chapter addresses safety performance target setting, the state-of-art knowledge about methods for coding and analyzing crashes that involved pedestrians and bicyclists, and notable safety management practices with emphasis on proven countermeasures.

Chapter 3. Pedestrian and Bicycle Crash Database: Explains how the crash database was created based on data gathered from existing datasets. It also describes the crash narratives and diagrams in the Texas Peace Officer's Crash Report Form (CR-3) in order to answer PBCAT crash typing logic questions. Additionally, it summarizes the outputs from the PBCAT analysis, including the assigned PBCAT crash types and groups, crash locations, pedestrian/pedalcyclist position, motorist maneuver, and intersection scenarios.

Chapter 4. **Statistical Analysis to Identify High-Risk Incidence Crash Corridors Factors:** Describes the overall pedestrian and bicyclist crash patterns and trends in North Central Texas. It includes crash statistics by injury severity for various roadway elements, conditions, and actions prior to crash. The most common crash types that result in fatal and serious injuries are also identified. It also explains the statistical modelling concepts, methods and summarizes the results of the multinomial logit (MNL) model used to identify the factors that contribute to the severity of a crash.

Chapter 5. Guidelines for Safety Countermeasures: Provides a list of countermeasures with the objectives and effectiveness of each countermeasure based on crash type and attribute. PBCAT, FHWA PEDSAFE and FHWA BIKESAFE are the main references for the countermeasures recommended in these guidelines. This Chapter includes a case study to illustrate how to apply the guidelines to enhance safety for pedestrians and bicyclists exposed in high-risk incidence crash locations.

Chapter 6. Pilot Online Application: Includes an overview of the Crash Data Analysis and Visualization Application (CDAVA) tool that was developed to visually present the results of this project.

Chapter 7. Conclusions and Recommendations: Summarizes key findings as a result of the research study and provides recommendations for implementation and further enhancements.

Appendix A: Pedestrian crash model analysis.

Appendix B: Pedalcyclist crash model analysis.

Appendix C: Pedestrian significant crash modeling factors.

Appendix D: Pedalcyclist significant crash modeling factors.

Appendix E. PBCAT location, crash groups, and crash types.

Appendix F: Countermeasures by crash type.

Appendix G: Countermeasures for high-risk incidence corridors.

Appendix H: High-Risk incidence corridor report cards.

An overview of the process that was followed during this research projects is shown in Figure 1.1 where each step refers to a corresponding section of this Research Report.

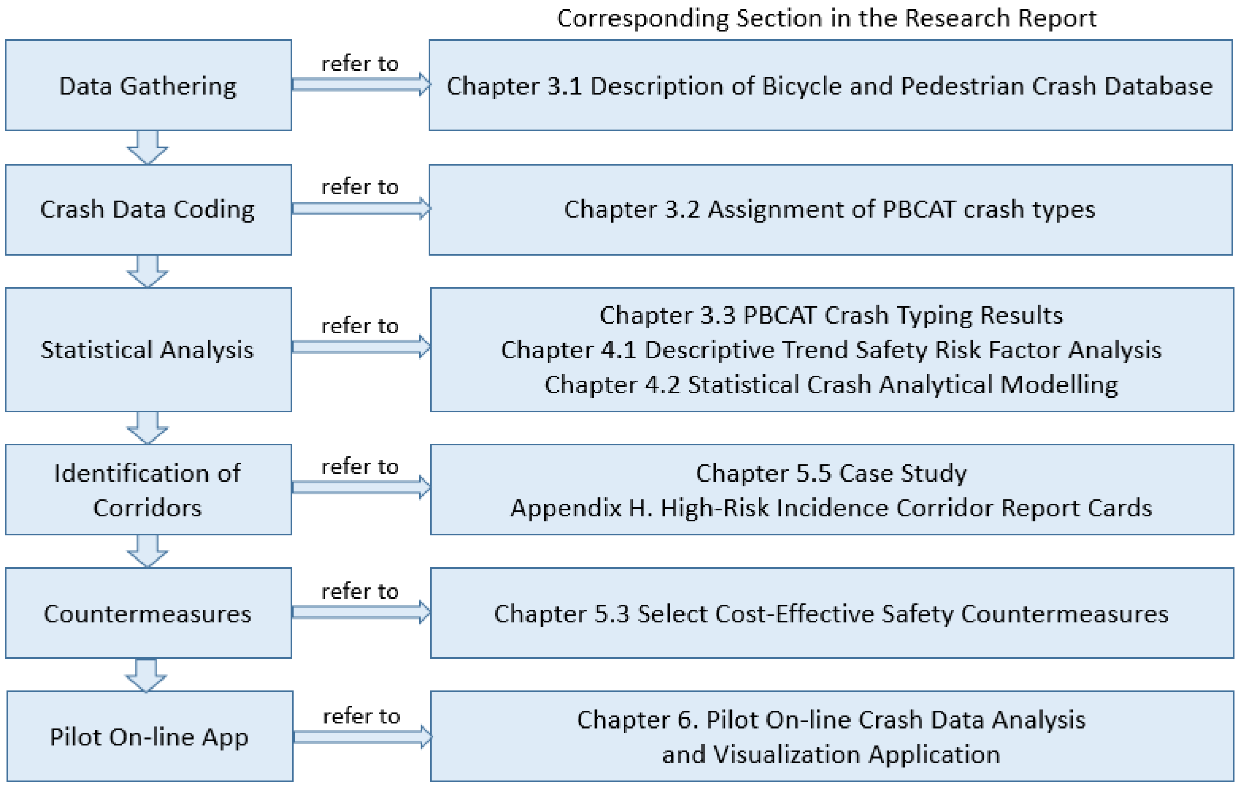

Figure 1.1 Research Steps and Their Corresponding Sections in the Research Report.

CHAPTER 2. LITERATURE REVIEW

2.1 Safety Target Setting

This section contains a review of legislation efforts in improving non-motorized user safety. National safety performance management and regional safety targets are discussed.

2.1.1 National Safety Performance Management and Target Setting

Over the last 27 years there has been an increasing emphasis on funding pedestrian and bicycle infrastructure through the Federal-aid highway program, as these non-motorized modes are an important part of a modern multimodal transportation system.

- 1991-1998: The ***Intermodal Surface Transportation Efficiency Act (ISTEA)*** "provided the first significant federal transportation funding that could be made available for alternate transportation forms such as bicycling and pedestrian walkways. In the six years of ISTEA, more than $1 billion has been directed to bicycle and pedestrian projects compared to less than $42 million in the 18 years before its enactment" (Fazzalaro, 2003).

- 1998-2005: The ***Transportation Equity Act for the 21st Century (TEA-21)*** mandated the inclusion of bicycling and walking as it called for "bicycle transportation facilities and pedestrian walkways shall be considered, where appropriate, in conjunction with all new construction and reconstruction of transportation projects, except where bicycle and pedestrian use are not permitted" (FHWA, 2000).

- 2005-2012: The ***Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)*** targeted investments towards safety, equity, innovative finance, congestion relief, mobility and productivity, efficiency, environmental stewardship, and environmental streamlining (FHWA, 2005). Key provisions for improvements in pedestrian and cyclist safety in SAFETEA-LU included establishment of the ***Highway Safety Improvement Program (HSIP)*** and the ***Safe Routes to School Program (SRTS)*** (PBIC, n.d.).

- 2012-2015: The ***Moving Ahead for Progress in the 21st Century Act (MAP-21)*** 21 established seven National Performance Goals that focus on improving safety, maintaining infrastructure condition, reducing congestion, improving system reliability and freight movement, promoting environmental sustainability, and reducing project delivery delays (FHWA, 2012a). With a goal to "achieve a significant reduction in traffic fatalities and serious injuries on all public roads" (FHWA, 2012a), MAP-21 doubled funding in the ***Highway Safety Improvement Program (HSIP)***. It also created a ***Special Rule for Older Drivers and Pedestrians*** (FHWA, 2016a), which applies to States where fatalities and serious injuries of drivers and pedestrians over the age of 65 increased during the most recent 2-year period. These States are then required to include in their next ***Strategic Highway Safety Plan (SHSP)*** specific strategies that improve safety of older drivers and pedestrians as recommended in ***FHWA's Handbook for Designing Roadways for the Aging Population*** (Harkey, et al., 2014). Also, the ***Identifying Countermeasure Strategies to Increase Safety of Older Pedestrians*** (NHTSA, 2013) is a useful resource to be considered.

- 2015-now: The latest transportation bill, the ***Fixing America's Surface Transportation Act (FAST Act)*** was passed into law in December 2015. The FAST Act is mandated through the fiscal year 2020 with a total amount of $305 billion and maintains focus on performance-based planning and programming along the seven National Performance Goals established in MAP-21 (FHWA, 2016b).

Following the performance-based focus of the MAP-21 and FAST Act, the FHWA published several Final Rules that establish performance measures aimed to track progress towards national performance goals. The ***Safety Performance Management Measures Final Rule (PM1)***, effective April 2016, requires State DOTs to assess five performance measures as 5-year rolling averages on all public roads regardless of functional classification (23 CFR Part 490):

(1) Number of Fatalities
(2) Rate of Fatalities per 100 million Vehicle Miles Travelled (VMT)
(3) Number of Serious Injuries
(4) Rate of Serious Injuries per 100 million VMT
(5) Number of Non-motorized Fatalities and Non-motorized Serious Injuries

The fifth safety performance measure—the 'number of combined non-motorized fatalities and non-motorized serious injuries'—directly applies to pedestrians and bicyclists. State DOTs established performance targets in August 2017 and are required to revisit them on annual basis. Metropolitan planning organizations must adopt targets established by the State DOT or establish their own regional targets within 180 days after the State DOT announces their targets. FHWA will assess the targets and performance to determine whether the State has met its performance targets or made significant progress towards meeting them. "At least 4 out of the 5 safety performance targets must be either met or the actual outcome for the target is better than baseline performance to make significant progress. [...] If a State has not met a target, FHWA will determine if the actual outcome for the target is better than the baseline performance for that target. The baseline performance is the 5-year rolling average for the target ending the year prior to the establishment of the State's target" (FHWA, 2016c). Table 2.1 shows the five performance measures and the data sources that will be used to make the determination whether a State has met its targets or made significant progress.

Table 2.1 National Safety Performance Measures and Data Sources.

Performance Target	Data Source(s) Used to Make Determination
Number of Fatalities	Final FARS (FARS Annual Report File (ARF) may be used if Final FARS is not available)
Rate of Fatalities	Final FARS (FARS ARF may be used if Final FARS is not available) and Highway Performance Monitoring System (HPMS) data
Number of Serious Injuries	State motor vehicle crash database
Rate of Serious Injuries	State motor vehicle crash database and HPMS data
Number of Non-Motorized Fatalities and Serious Injuries	Final FARS (FARS ARF may be used if Final FARS is not available) and State motor vehicle crash database

Note: Table from FHWA (2016c).

If FHWA determines that a State DOT did not meet or did not make significant progress toward its targets, then ***Highway Safety Improvement Program (HSIP)*** funding is affected and HSIP Implementation Plan is required to be submitted.

2.1.2 TxDOT Safety Performance Measurement and Target Setting

To comply with the federal requirements, TxDOT develops the following safety planning and programming documents:

- ***Strategic Highway Safety Plan (SHSP):*** updated at least every 5 years, approved by the FHWA.
- ***Highway Safety Plan (HSP)***: updated annually, approved by the NHTSA.
- ***Highway Safety Improvement Program (HSIP)***: updated annually, approved by the FHWA.

Texas Strategic Highway Safety Plan 2017-2022: The SHSP "provides a comprehensive framework for reducing highway fatalities and serious injuries on all public roads" (FHWA, 2017). The long-term vision of the SHSP is to reduce the severity of injuries in motorized crashes and achieve zero fatalities and serious injuries on Texas roadways. This plan is structured around seven safety emphasis areas: (i) pedestrian safety, (ii) older road user safety, (iii) intersection safety, (iv) speeding, (iv) impaired driving, (vi) distracted driving, and (vii) roadway and lane departures. It identifies seven strategies for the pedestrian safety emphasis area: "(1) improve driver and pedestrian safety awareness and behaviour, (2) reduce pedestrian crashes on urban arterials and local roadways, (3) improve pedestrians' visibility at crossing locations, (4) improve pedestrian networks, (5) improve pedestrian involved crash reporting, (6) establish vehicle operating speeds to decrease crash severity, (7) develop strategic pedestrian safety plans tailored to local conditions" (TxDOT, 2017a). The SHSP also describes the methodology and approach for projecting fatal and serious injuries, and the targets adopted by TxDOT for the five national safety performance measures.

Highway Safety Plan FY 2018: This annual statewide coordinated safety plan that identifies safety problems, countermeasure strategies, objectives, performance measures and targets set each year. The HSP defines fifteen core performance measures, out of which three directly assess non-motorized user safety: (C-5) non-motorized fatalities and serious injuries (one of five national safety performance measures), (C-10) pedestrian fatalities, and (C-11) bicycle fatalities. Tables 2.2 and 2.3 show the targets adopted by TxDOT for FY2018-2022. Over the next 5 years the target will be achieved by reducing each intermediate year by 0.4%, as follows: a 0.4% reduction in 2018, a 0.8% reduction in 2019, a 1.2% reduction in 2020, a 1.6% reduction in 2021, and finally reaching a 2% reduction from the original 2022 projection trend line (TxDOT, 2017b). TxDOT makes separate projections for pedestrians and bicyclists, because "bicyclist fatalities have been relatively stable, but bicyclist serious injuries have been increasing, though not as much as pedestrian serious injuries" (TxDOT, 2017a). These separate projections are then combined into a single measure, as per FHWA reporting requirements.

Table 2.2 TxDOT Trend Line Projections and Adopted Safety Targets for Pedestrian Fatalities and Serious Injuries.

Year	Pedestrian Trend Line Projections		Reduction Target	Pedestrian Targets	
	Fatalities	Serious Injuries		Fatalities	Serious Injuries
2017	569	1,274	0.0%	569	1,274
2018	591	1,377	0.4%	589	1,332
2019	613	1,401	0.8%	608	1,389
2020	635	1,464	1.2%	628	1,447
2021	657	1,528	1.6%	647	1,503
2022	680	1,591	2.0%	666	1,559

Note: Table from TxDOT (2017b).

Table 2.3 TxDOT Trend Line Projections and Adopted Safety Targets for Bicyclist Fatalities and Serious Injuries.

Year	Bicyclist Trend Line Projections		Reduction Target	Bicyclist Targets	
	Fatalities	Serious Injuries		Fatalities	Serious Injuries
2017	51	330	0.0%	51	330
2018	52	338	0.4%	52	337
2019	52	347	0.8%	52	344
2020	53	355	1.2%	53	351
2021	53	364	1.6%	53	358
2022	53	372	2.0%	53	365

Note: Table from (TxDOT, 2017b).

Figure 2.1 shows the trend line of projected non-motorized fatalities and injuries (in black) and the 2% reduction target (in green). Baseline year 2017 shows 2,224 non-motorized fatalities and injuries, determined from Tables 2.2 and 2.3 as a sum of 589 pedestrian fatalities, 1,274 pedestrian serious injuries, 51 bicyclist fatalities, and 330 bicyclist serious injuries.

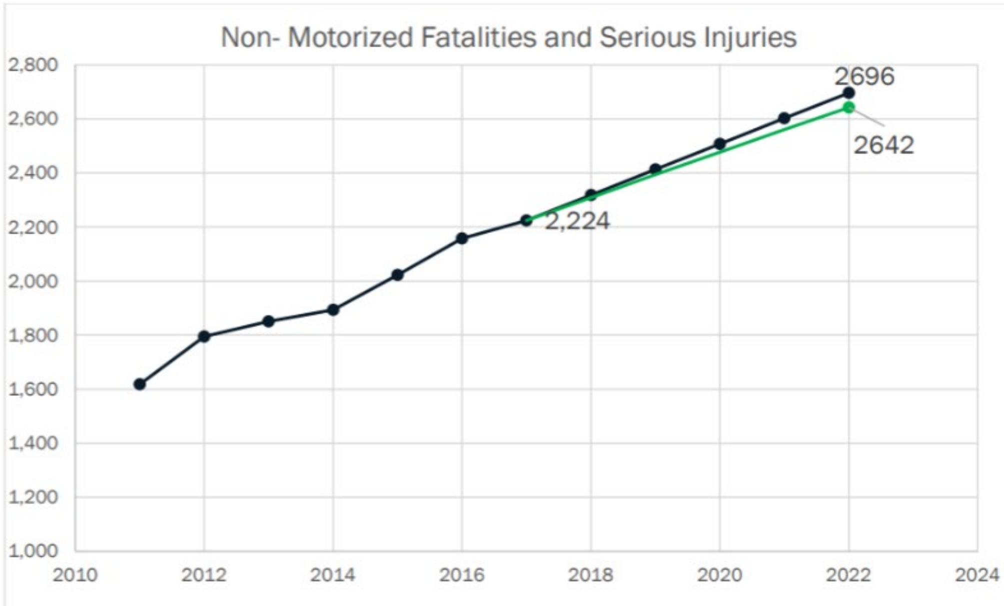

Figure 2.1 TxDOT's Trend Line Projection and Adopted Safety Targets for Non-Motorized Fatalities and Serious Injuries.
Source: TxDOT (2017a).

Texas Highway Safety Improvement Program 2017 Annual Report: This annual report summarizes the highway safety improvement projects that were programmed during FY2017 (TxDOT, 2017c). Each project description includes the improvement category and subcategory, project length, HSIP project cost, total project cost, functional classification, AADT, speed, roadway ownership, method for site selection, as well as the emphasis area and strategy as it relates to SHSP. One pedestrian safety improvement project was obligated in FY2017 (project name: STP2017(331HES), improvement category: pedestrians and bicyclists) with a total cost of $2.3 million. Therefore, out of the $250 million HSIP budget, 1% was dedicated for direct improvements in pedestrian safety.

According to the National Safety Performance Measurement Rule (23 CFR Part 490), starting FY2017 State DOTs are required to report their safety targets on annual basis in the HSIP Annual Report. "FHWA will determine whether a State has met or made significant progress toward its 2018 safety performance targets at the end of the following calendar year when target-year data is available (approximately December 2019) and report findings to States and the public by March 2020" (FHWA, 2018a). Determinations will be made annually thereafter.

TxDOT adopted its first safety performance targets in August 2017. Metropolitan Planning Organizations (MPOs) were required to establish their targets by February 2018 by either: "(i) agreeing to plan and program projects so that they contribute toward the accomplishment of the

State DOT safety target for that performance measure; or (ii) committing to a quantifiable target for that performance measure for their metropolitan planning area” (23 CFR Part 490).

2.1.3 North Central Texas Safety Performance Management and Target Setting

The North Central Texas Council of Government (NCTCOG) supports TxDOT’s safety targets in its latest long- and short-range planning documents: Mobility 2045 (NCTCOG, 2018a) and 2019-2022 Transportation Improvement Program (NCTCOG, 2018b).

Table 2.4 on the following page shows the regional 2018 target for the ‘number of non-motorized fatalities and serious injuries’, which follows the reduction percentages adopted by TxDOT and calls for a 0.4% reduction in 2018.

Table 2.4 NCTCOG Target for Non-Motorized Fatalities and Serious Injuries.

		Fatalities			Serious Injuries		
Year	Source	Projection/ Actual Data Bike & Ped (Fatal)	Target or Actual Data	Fatalities Reduced	Projection/ Actual Data Bike & Ped (Incap. Injury)	Target or Actual Data	Serious Injury Crashes Reduced
2014	FARS-CRIS	107	107	N/A	334	334	N/A
2015	FARS-CRIS	160	160	N/A	381	381	N/A
2016	CRIS	163	163	N/A	413	413	N/A
2017	Target	171	171	0	433	433	0
2018	Target	184	182	2	459	457	2
2018 target expressed as 5-year average			156.6			403.6	

Note: Table from NCTCOG (2018a).

2.2 Methods for Describing and Coding Crashes

This section describes the data commonly collected to analyze crashes that involved a pedestrian or a cyclist[2]. This process is called crash coding, and the data elements collected about crashes are used as an input for crash analysis which helps in understanding the contributing factors that lead to crashes. Quality data that describe the factors that contribute to crashes is essential to improving safety for all roadway[3] users.

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[2] In this document, the term ‘cyclist’ is considered to include any rider of a non-motorized vehicle propelled by pedaling, including electric bicycles, as per definition used by the State of Texas (TxDOT 2018).
[3] In this document, the term ‘roadway’ refers to the public right-of-way where travel lanes, bicycle lanes and sidewalks are located.

In the 1970s, the National Highway Traffic Safety Administration began systematically investigating causes of crashes that involved pedestrians (Snyder & Knoblauch, 1971) and cyclists (Cross & Fisher, 1977). These studies, based on interviews with participants and witnesses, police reports, and on-scene observations, were aimed to identify the causes of crashes and their potential countermeasures. Later during the 1990s FHWA continued research in categorizing pedestrian and bicycle crashes (Hunter et al. 1996, 1997a, 1997b), which ultimately lead to the development of a crash coding methodology titled the ***Pedestrian and Bicycle Crash Analysis Tool (PBCAT)*** (FHWA, 2006).

PBCAT is a form-based tool that helps in translating information collected through crash reports into a database and its built-in logic categorizes crashes into 56 common pedestrian crash types and 79 common cyclist crash types. PBCAT then recommends countermeasures for each crash type. Figure 2.2 shows the data elements that PBCAT version 2.0 uses for crash typing.

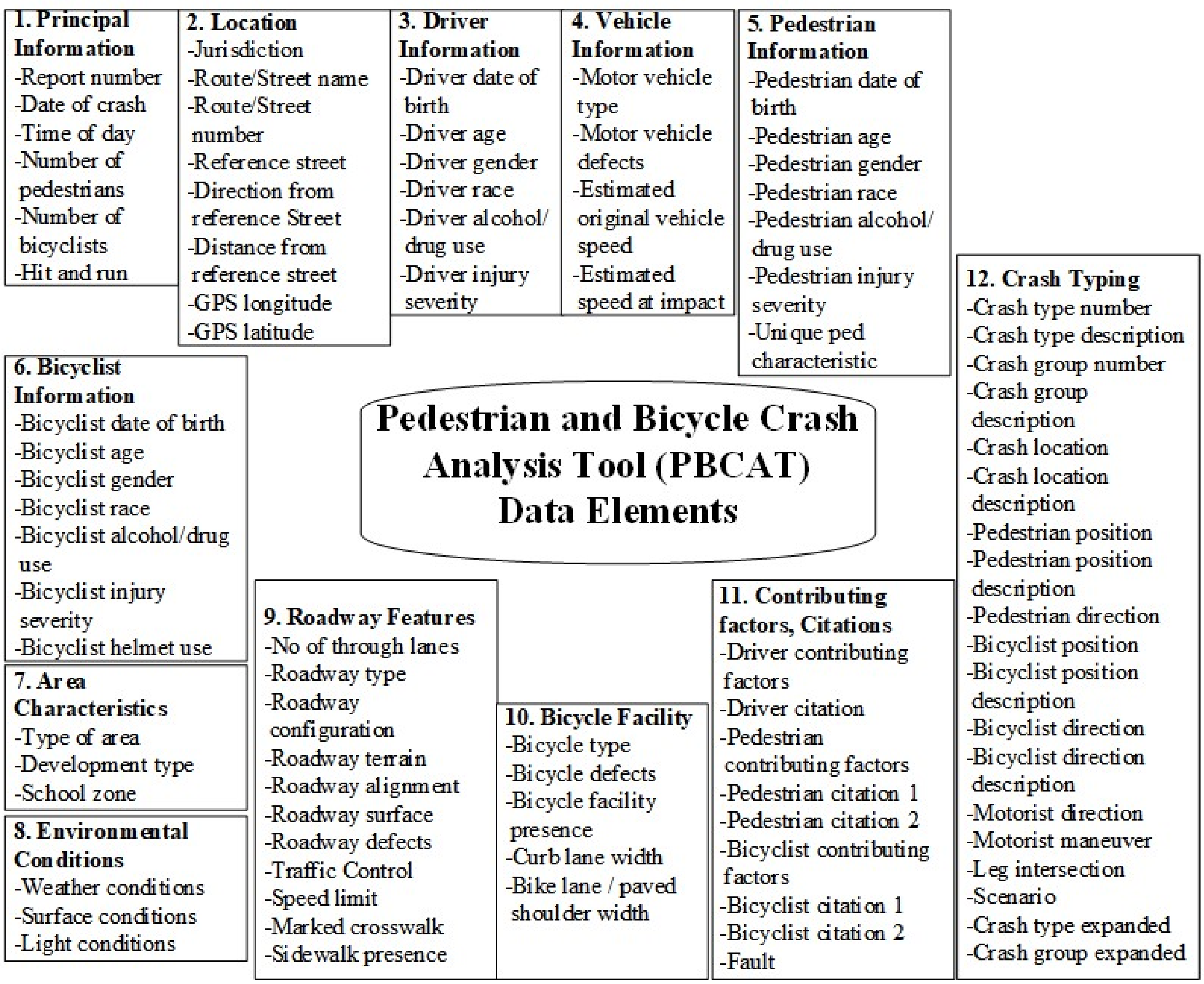


Figure 2.2 PBCAT Version 2.0 Data Elements.
Source: FHWA (2006).

PBCAT crash typing is based on data about the time and location; characteristics of the participants (motorist, pedestrian, cyclist); environmental conditions; roadway features, bikeway features; vehicle and bicycle type and defects; and the contributing factors for each of the participants, including their position, direction, and path.

State crash databases often do not provide detailed information needed for effective coding of pedestrian and cyclist crashes (FHWA, 2006). Data from police crash reports are extracted into a database maintained usually by the State DOT. However, variables that would be beneficial for pedestrian and bicycle crash analysis are either not part of the crash report form or, in some cases, are only described in a narrative or crash diagram, instead of being coded in the report and therefore easily transferable to the crash database. This leads to an increased time and cost, as reports have to be reviewed individually and obtaining relevant data for pedestrian and bicycle crash analysis becomes more difficult.

In 2017, the National Highway Traffic Safety Administration (NHTSA) published the ***Model Minimum Uniform Crash Criteria (MMUCC)*** voluntary guidelines for crash data collection. The MMUCC "identifies a minimum set of motor vehicle crash data elements and their attributes that States should consider collecting and including in their State crash data systems" (NHTSA, 2017a). Table 2.5 shows examples of states that code data about pedestrian and cyclist crashes in greater detail. Details about each of the crash report data elements are discussed later in this Chapter.

Table 2.5 Pedestrian and Cyclist Crash Coding in State Crash Reports.

Crash Report Data Element	TX	CO	FL	GA	NC	NM	OR	VA	WA
Non-motorist flag		▲			▲	▲	▲		
Non-motorist type		▲	▲		▲		▲		▲
Non-motorist safety equipment		▲			▲		▲	▲	▲
Non-motorist physical condition		▲		▲	▲	▲		▲	
Pedestrian location		▲	▲		▲	▲	▲	▲	▲
Pedestrian action / maneuver		▲	▲	▲	▲	▲	▲	▲	▲
Non-motorist contributing factors	▲*	▲				▲*	▲	▲*	▲*
Non-motorist facility type		▲							
* *only general contributing factors that apply to both motorists and non-motorists*									

Note: Compiled from CDOT (2017), FLHSMV (2018), GDOT (2018), NMDOT (2018), NCDOT (2018), ODOT (2018), TxDOT (2018), VDOT (2017), WSDOT (2014).

In Texas, any crash on a public roadway that involves a motorized vehicle and results in a death, personal injury, or property damage of at least $1,000 is investigated and reported on a Texas Peace Officer Crash Report Form CR-3 (TxDOT, 2018). While the CR-3 form includes over 140 data fields, there are 24 fields that are mandatory (as shown in Table 2.6).

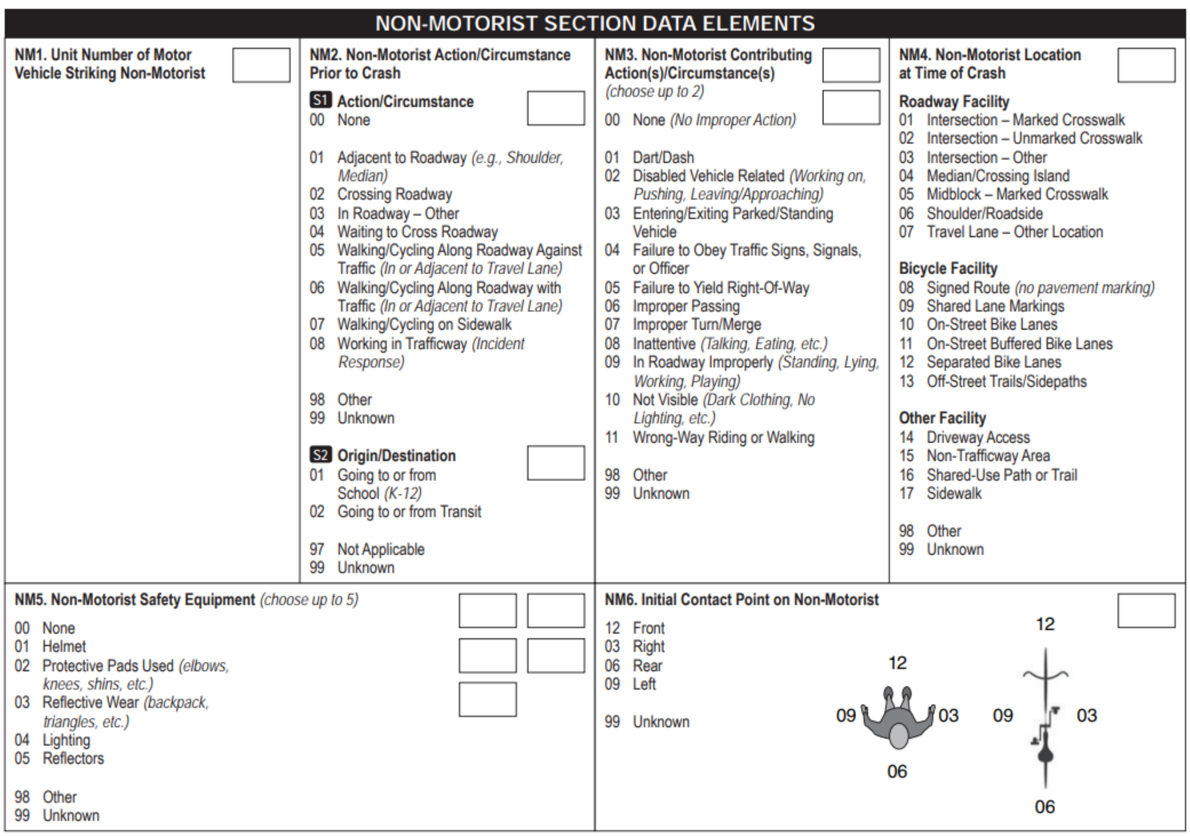
Table 2.6 Mandatory Data Fields in CR-3 Form.

Mandatory Data Fields		
Crash Date	Unit #	Traffic Control
Crash Time	Unit Description	Narrative
County	Weather Conditions	Diagram
$1000 Damage to Prop	Light Condition	Investigator Complete
Roadway Part	Entering Roads	Investigator Name
Construction Zone	Roadway Type	ID #
Workers Present	Roadway Alignment	Agency
At Intersection	Surface Conditions	

Note: Information from TxDOT (2018).

Data entries from the CR-3 form are stored in a database maintained by the Texas Department of Transportation, called the Crash Records Information System (CRIS).

According to Safe States Alliance (2017), in the U.S. "pedestrian injuries and fatalities are less meticulously or consistently monitored, recorded, documented, and linked across multiple data sources compared to other traffic-related injuries." The MMUCC (NHTSA, 2017a) recommends States to include a mandatory non-motorist section data element (Figure 2.3), whenever a non-motorized user is involved in a reportable crash.


NON-MOTORIST SECTION DATA ELEMENTS

NM1. Unit Number of Motor Vehicle Striking Non-Motorist

NM2. Non-Motorist Action/Circumstance Prior to Crash

S1 Action/Circumstance
00 None
01 Adjacent to Roadway *(e.g., Shoulder, Median)*
02 Crossing Roadway
03 In Roadway – Other
04 Waiting to Cross Roadway
05 Walking/Cycling Along Roadway Against Traffic *(In or Adjacent to Travel Lane)*
06 Walking/Cycling Along Roadway with Traffic *(In or Adjacent to Travel Lane)*
07 Walking/Cycling on Sidewalk
08 Working in Trafficway *(Incident Response)*
98 Other
99 Unknown

S2 Origin/Destination
01 Going to or from School *(K-12)*
02 Going to or from Transit
97 Not Applicable
99 Unknown

NM3. Non-Motorist Contributing Action(s)/Circumstance(s) *(choose up to 2)*
00 None *(No Improper Action)*
01 Dart/Dash
02 Disabled Vehicle Related *(Working on, Pushing, Leaving/Approaching)*
03 Entering/Exiting Parked/Standing Vehicle
04 Failure to Obey Traffic Signs, Signals, or Officer
05 Failure to Yield Right-Of-Way
06 Improper Passing
07 Improper Turn/Merge
08 Inattentive *(Talking, Eating, etc.)*
09 In Roadway Improperly *(Standing, Lying, Working, Playing)*
10 Not Visible *(Dark Clothing, No Lighting, etc.)*
11 Wrong-Way Riding or Walking
98 Other
99 Unknown

NM4. Non-Motorist Location at Time of Crash

Roadway Facility
01 Intersection – Marked Crosswalk
02 Intersection – Unmarked Crosswalk
03 Intersection – Other
04 Median/Crossing Island
05 Midblock – Marked Crosswalk
06 Shoulder/Roadside
07 Travel Lane – Other Location

Bicycle Facility
08 Signed Route *(no pavement marking)*
09 Shared Lane Markings
10 On-Street Bike Lanes
11 On-Street Buffered Bike Lanes
12 Separated Bike Lanes
13 Off-Street Trails/Sidepaths

Other Facility
14 Driveway Access
15 Non-Trafficway Area
16 Shared-Use Path or Trail
17 Sidewalk
98 Other
99 Unknown

NM5. Non-Motorist Safety Equipment *(choose up to 5)*
00 None
01 Helmet
02 Protective Pads Used *(elbows, knees, shins, etc.)*
03 Reflective Wear *(backpack, triangles, etc.)*
04 Lighting
05 Reflectors
98 Other
99 Unknown

NM6. Initial Contact Point on Non-Motorist
12 Front
03 Right
06 Rear
09 Left
99 Unknown

Figure 2.3 Non-Motorist Section Data Elements in Sample MMUCC Model Crash Report.
Source: NHTSA (2017a).

According to estimates of the Pedestrian and Bicycle Information Center, "as many as 55 percent of pedestrian crashes and even more bicyclist crashes may be missing from police-reported crash data" (FHWA, 2019). Under-reporting of crashes that involved a pedestrian or a cyclist makes effective crash analysis difficult and results in missed opportunities to improve safety of these non-motorized users. To prevent that, the MMUCC (NHTSA, 2017a) recommends linking police crash records with data from roadway databases, emergency medical services, and hospital records. Also including supplemental data sources, such as asset inventories and volume counts, can help to describe the likely chain of events and contributing factors that led to crashes (Gelinne, Thomas, Lang, Zeeger, & Goughnour, 2017).

For the purposes of this report, pedestrian and cyclist crash coding variables are organized into three categories: crash-specific factors, environmental factors, and exposure factors. As shown in Figure 2.4, there are various data sources for each of the factors. Coding variables related to crash-specific factors are identified from police crash reports. Environmental factors are likely captured in police crash reports and can be complemented with data from asset inventories. Exposure factors are identified from volume counts, travel behavior statistics, as well as other GIS data (e.g., predominant land use, proximity to transit stop or schools).

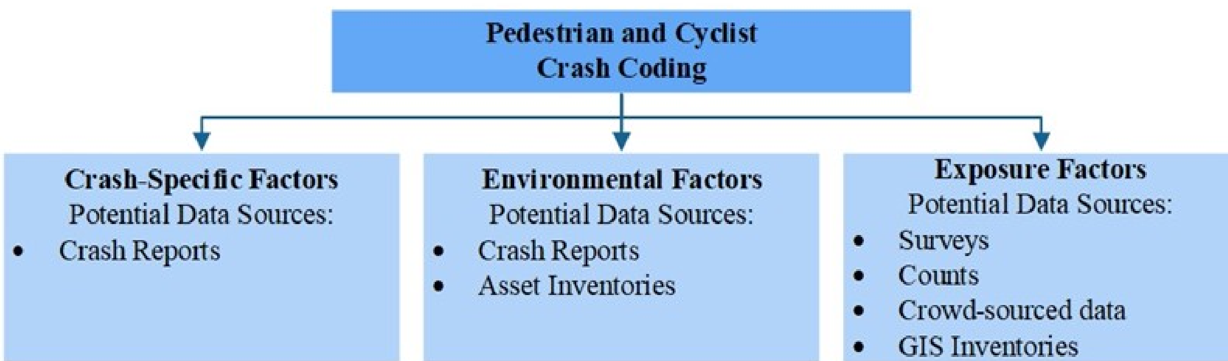


Figure 2.4 Categories for Pedestrian and Cyclist Crash Coding.

The following sections (2.2.1 crash-specific factors, 2.2.2 environmental factors, and 2.2.3 exposure factors) discuss CR-3 data elements, as well as notable practices in coding pedestrian and cyclist crashes that were identified during a review of federal agencies' reports (FHWA, NHTSA), National Cooperative Highway Research Program (NCHRP) reports, as well as peer practices from eight states (Colorado, Florida, Georgia, New Mexico, Oregon, Virginia, and Washington). Section 2.2.4 then summarizes the information gathered in this Chapter.

2.2.1 Crash-Specific Factors

Crash-specific factors include data elements related to actions prior to a crash, persons, and vehicles. Figure 2.5 shows the identified potential contributing crash-specific factors that are discussed in this section.

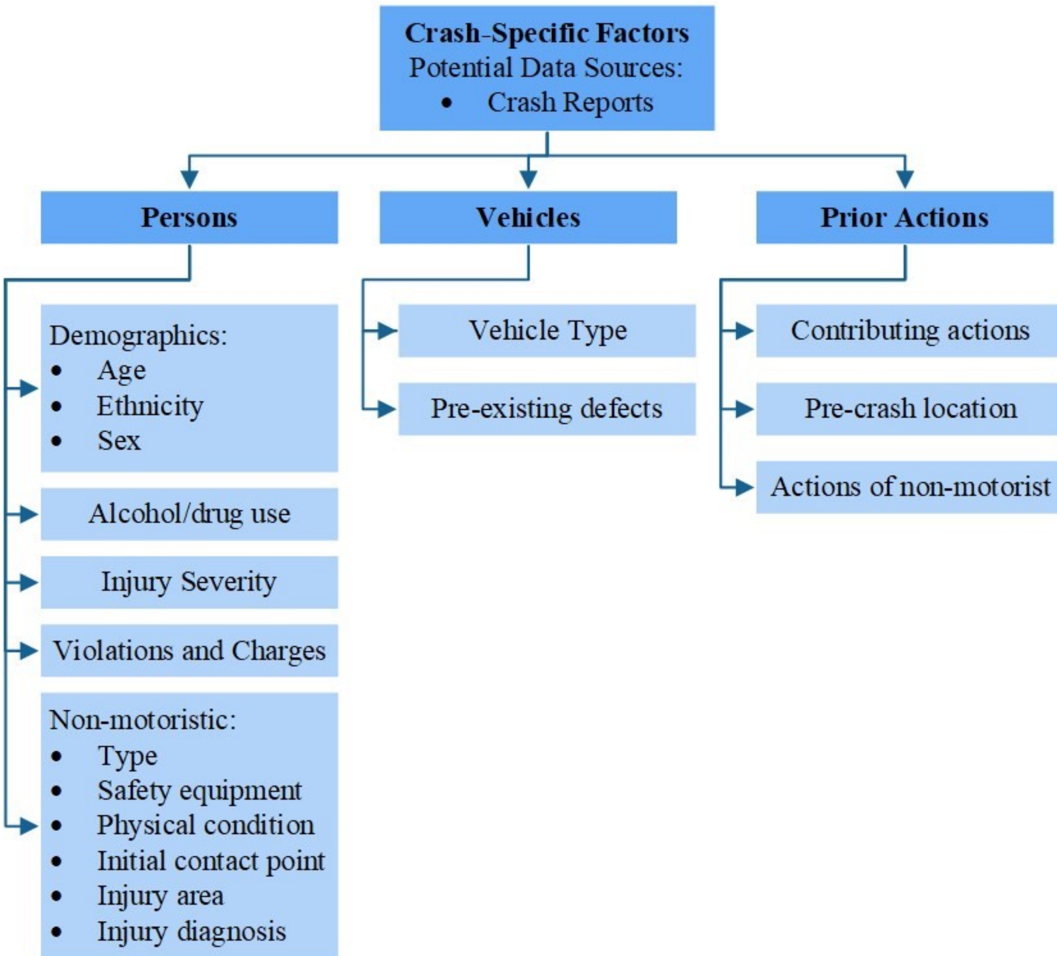


Figure 2.5 Identified Potential Contributing Crash-Specific Factors for Pedestrian and Cyclist Crashes.

Persons

Road user characteristics provide valuable information in crash analysis. The Texas Transportation Code defines a pedestrian as "any person who is not an occupant of a motor vehicle in transport [which] also includes anyone using a motorized or non-motorized wheelchair" (Transportation Code: Section: 541.201 (24)) and a cyclist (pedalcyclist) as "a non-motorized vehicle propelled by pedaling [which] also includes an electric bicycle (Texas Transportation Code: Section 542.009 (b)).

Data elements collected in form CR-3 about a person (e.g., a motorist, pedestrian, or cyclist) involved in a crash includes general demographics (age, ethnicity, sex), results of an alcohol or drug test (fatal crashes only), and any charges for violations related to the crash. Violation records "are important for evaluation of safety laws and enforcement practices" (NHTSA, 2017a).

Severity of an injury suffered in a crash is classified in police reports based on a KABCO scale developed by the National Safety Council (Greene & Jones, 1989), where K indicates a fatal injury, A represents a suspected incapacitating injury, B stands for a suspected non-incapacitating injury, C is used for a possible injury, while O is for no apparent injury (classified as N in CR-3). The KABCO scale is "designated for use by police officers who are not allowed to examine and may not even get the opportunity to see or speak to the victim" (Greene & Jones, 1989). In form CR-3 the injury severity is coded for every participant. The form also includes a flag for hit-and-run crashes.

<u>*Notable practices:*</u>

- *Non-motorist flag:* The CR-3 form includes flags for crashes that resulted in a fatality; involved a commercial vehicle or school bus; occurred within a railroad crossing or an active school; or one of the participants was taking medication, physically ill, or mentally unstable. However, in order to identify crashes that involved a pedestrian or cyclist, a search through the crash database is required. The MMUCC recommends including a flag for pedestrian and cyclist crashes, as it simplifies the use of crash data (NHTSA, 2017a). States that contain a non-motorist flag in their crash reports include Colorado, New Mexico, and Oregon (please refer to *Technical Memorandum 2A Appendix A: State Crash Reports* for details).

- *Non-motorist type*: The MMUCC (NHTSA, 2017a) recommends to the expand the pedestrian/cyclist classification into more specific types, in order to allow for analysis of countermeasures targeted to specific types of non-motorized users. For example, Colorado crash report (CDOT, 2018) includes codes for eight different types of non-motorized users: pedestrian, wheelchair, scooter, personal conveyance, other pedestrian, bicyclist, other bicyclist/cyclist, and other non-motorist. Fishman and Schepers (2018) also recommend including emerging new forms of mobility, such as bike share and scooters in police report forms. Examples of states that code a non-motorist type in their crash reports include Colorado, North Carolina, Oregon, Virginia, and Washington (please refer to *Technical Memorandum 2A Appendix A: State Crash Reports* for details).

- *Non-motorist safety equipment*: While the CR-3 collects data about helmet use, the MMUCC (NHTSA, 2017a) recommends collecting additional data elements related to non-motorist safety equipment, such as reflective clothing, lights, or reflectors. Examples of states that code a non-motorist type in their crash reports include Colorado, Oregon, Virginia, and Washington (please refer to *Technical Memorandum 2A Appendix A: State Crash Reports* for details).

- *Non-motorist physical condition:* New Mexico crash report includes information about physical condition of a non-motorist, such as hearing impairment, eyesight impairment, other physical impairment (NMDOT, 2018). These conditions are important to consider for targeted engineering, enforcement, and education countermeasures.

- *Initial contact point on non-motorist*: Knowledge of the initial contact point on non-motorists' body (front, right, rear, left) can provide insight about contributing circumstances and the infrastructure design (NHTSA, 2017a).

- *Non-motorist injury area*: The most obvious area that was injured, such as head, neck, spine, chest, lower extremity (NHTSA, 2017a) can provide additional information beyond the injury severity and be valuable in pedestrian and bicycle crash analysis.

- *Injury diagnosis*: Crash data can be linked with injury databases (e.g., National Emergency Medical Services Information Service, NEMSIS) for more precise analysis of countermeasure effectiveness (NHTSA, 2017a).

Vehicles

Vehicle characteristics are important to consider, as there is a correlation between vehicle type and injury severity – a Canadian study concluded that "the risk for pedestrians of sustaining fatal injury is 50 percent greater in collisions with LTVs [light truck vehicles] than in collisions with conventional cars" (Desapriya, et al., 2010). The form CR-3 distinguishes between 19 body styles of motorized vehicles including passenger cars, sport utility vehicles, trailers, trucks, and buses.

<u>Notable practices:</u>

- *Pre-existing vehicle defects:* The MMUCC (NHTSA, 2017a) recommends including pre-existing vehicle defects, such as brakes, steering, tires, lights, mirrors, etc. in order to identify unusual conditions that may have contributed to the crash. The CR-3 form includes codes for defective or no trailer brakes, vehicle brakes, steering mechanism, headlamps, stop lamps, trail lamps, turn signal lamps, slick tires, and trailer hitch.

Prior Actions

Crash contributing factors coded on form CR-3 and include speeding, disregarding traffic signals, failure to yield, passing violations, improper turns, wrong side driving, driving under influence, and use of mobile device. Several of these contributing factors can be applied to describe the actions prior to a crash for both motorists and cyclists, however codes for actions of a pedestrian are limited to "pedestrian failed to yield right of way to vehicle." Detailed description of the location and actions of non-motorized users prior to a crash is crucial in crash analysis.

<u>Notable practices:</u>

- *Pre-crash pedestrian location*: FHWA report ***Pedestrian and Bicycle Crash Types of the Early 1990's*** (Hunter, Stutts, Pein, & Cox, 1996) identifies seven common locations for a pedestrian prior to a crash: travel lane, shoulder, edge of lane, sidewalk, alley, driveway, or parking lot. Similarly, Colorado crash form DR 3447 (CDOT, 2018) describes the non-motorist location at the time of crash as: intersection – marked crosswalk, intersection – unmarked crosswalk, intersection – other, midblock – marked crosswalk, midblock – non-crosswalk, travel lane – other location, marked bicycle lane, protected bicycle lane, shoulder/roadside, sidewalk, median/crossing island, driveway access, or shared-use path or trail. States that code a non-motorist location in their crash reports include Colorado, Florida, New Mexico, North Carolina, Oregon, Virginia, and Washington (please refer to *Technical Memorandum 2A Appendix A: State Crash Reports* for details).

- *Actions of non-motorist prior to crash:* A crash report used in Georgia (GDOT, 2018) categorizes movements of pedestrians prior to crash as follows: crossing not at crosswalk, crossing at crosswalk, moving with traffic on roadway, moving against traffic on roadway, pushing or working on vehicle, other working in roadway, playing in roadway, standing in roadway, off roadway, darting into traffic, entering/exiting bus, entering/exiting parked or standing vehicle. Hunter at el. (1996) identified nineteen common locations of a cyclist prior to a crash: through travel lane, edge of through lane, left turn lane, two way left turn lane, right turn lane, merge lane, roadside out of through lane, on shoulder, road-related – unsure of exact location, on-street parking space/lane, bike lane, multi-use path, path beside road, on sidewalk, alley/driveway/other entering roadway, parking lot – travel lane, parking lot – other, pedestrian crosswalk – marked, pedestrian crosswalk – implied. States that code a non-motorist actions in their crash reports include Colorado, Georgia, New Mexico, Oregon, Virginia, and Washington (please refer to *Technical Memorandum 2A Appendix A: State Crash Reports* for details).

2.2.2 Environmental Factors

Environmental factors include data elements related to roadway and conditions, such as weather, and lighting and visibility. Figure 2.6 shows the identified potential contributing environmental factors that are discussed in this section.

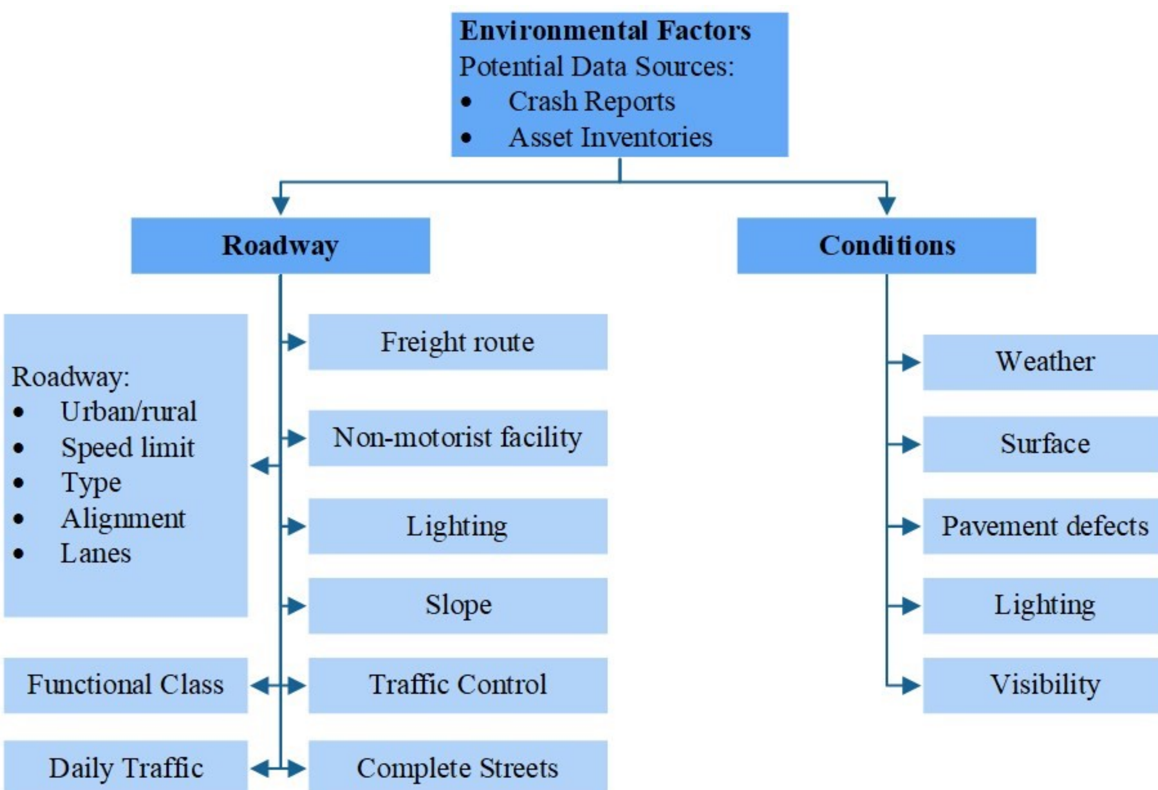


Figure 2.6 Identified Potential Contributing Environmental Factors for Pedestrian and Cyclist Crashes.

Roadway

A mix of different users share the roadway space. Consideration of roadway factors in crash analysis is useful for determining effective countermeasures. The CR-3 form includes the following data elements: whether a crash location is outside city limits (yes/no), type of roadway system (e.g. state highway, local road/street), roadway part (e.g. main/proper lane, service/frontage road), posted speed limit, construction zone (yes/no), at intersection (yes/no), number of entering roads, roadway type (two-way, not divided; two-way, divided, unprotected median; two-way, divided, protected median; one-way), number of lanes, roadway alignment (straight, level; straight, grade; straight, hillcrest; curve, level; curve, grade; curve, hillcrest), the type of traffic control (inoperative; officer; flagman; signal light; flashing red light; flashing yellow light; stop sign; yield sign; warning sign; center stripe/divider; no passing zone, railroad gate/signal; crosswalk; bike lane; marked lanes; signal light with red light running camera; none). Average daily traffic and the percentage of average daily traffic that is single-unit truck traffic is also coded in CR-3 forms.

<u>Notable practices:</u>

- *Non-motorist facility type*: While the CR-3 form features crosswalk and bike lane under the type of traffic control, the MMUCC (NHTSA, 2017a) recommends at minimum to collect information about the presence and type of bicycle facility based on *FHWA Separated Bike Lane Planning and Design Guide*'s classification (FHWA, 2015): signed bicycle route, shared lane markings, on-street bicycle lane, on-street buffered bike lane, separated bike lane, off-street trail/side path. For example, Colorado crash form (CDOT, 2018) classifies the type of designated pedestrian or bicycle facility where the crash occurred as: sidewalk, crosswalk, marked bicycle lane, shared travel way, protected bicycle lane, unmarked paved shoulder, separate bicycle path/trail, or no specific facility. Including these data elements in crash reports can potentially save time and effort during crash analysis, when otherwise this information would need to be queried from asset inventories. *NCHRP Web-Only Document 129: Pedestrian Safety Prediction Methodology* (Harwood, Torbic, Gilmore, Bokenkroger, & Dunn, 2008) recommends including the presence of raised pedestrian crosswalks and pedestrian crossing width.

- *Pedestrian-scale lighting:* Pedestrian scale lighting illuminating pedestrians in crosswalk at intersections or mid-block, can significantly improve pedestrian safety (Markowitz, 2018; Harwood, Torbic, Gilmore, Bokenkroger, & Dunn, 2008).

- *Slope:* Change in slope or grade is associated with higher crash risk for pedestrians and cyclists (Seattle DOT, 2016; Thomas, et al., 2018) A bicycle safety analysis in Seattle revealed that "downhill approaches to intersections may increase the potential for bicycle left-hook crashes" (Seattle DOT, 2016). Information about slope can be obtained from roadway inventories or from the U.S. Geological Survey's National Elevation Dataset (USGS, n.d.).

- *Traffic control device type:* Presence of elements such as signs, signals, and pavement markings is better verified during police report coding, rather than retrospectively from asset inventories. Missing and inoperative devices are also more likely to be noticed at the crash scene. Sign data elements recommended in the MMUCC (NHTSA, 2017a) include pedestrian crossing sign, school zone sign, reduce speed ahead sign, stop sign, and yield sign. Signal data elements recommended in the MMUCC (NHTSA, 2017a) include flashing school zone signal and traffic control signal. Pavement marking data elements in the MMUCC (NHTSA, 2017a) include bicycle crossing, pedestrian crossing, marked/unmarked crosswalk, and school zone. *NCHRP Web-Only Document 129: Pedestrian Safety Prediction Methodology* recommends considering the presence of right turn on red in pedestrian safety analysis (Harwood, Torbic, Gilmore, Bokenkroger, & Dunn, 2008).

- *Complete Streets:* As Complete Streets policies refer to physical changes in roadway infrastructure, an observation can be made of crashes that occurred on roadways that follow the Complete Streets standards. Including the existence of Complete Street compliance into pedestrian and bicycle crash analysis can help quantify the impact of these changes on roadway safety (Schneider, 2018).

- *Expanded functional classification*: Classification of roadways into five roadway types in five contexts, as introduced in *NCHRP Research Report 855: An Expanded Functional Classification System for Highways and Streets* (Stamatiadis, Kirk, Hartman, Jasper, & Wright, 2018) aims to help with design decisions to efficiently accommodate pedestrians and cyclists along motorists, freight, and transit.

- *Freight route overlay:* Consideration of freight route location together with truck traffic volume may provide useful insight in crashes between commercial trucks and non-motorized users. As *NCHRP Web-Only Document 230: An Expanded Functional Classification System for More Flexibility in Geometric Design* explains, "while low-order freight routes and infrequent turns may not require special accommodation, higher priority routes for freight should have smooth turning radii to minimize unnecessary delays and possibility of crashes at turns. On bike priority routes, which call for lower speeds of vehicular traffic, wider lanes used to accommodate freight may encourage higher speeds. When this occurs, increased separation of bike facilities may be imperative to avoid conflict and improve bicyclist safety" (Stamatiadis, Kirk, Hartman, Jasper, & Wright, 2018).

Conditions

Unlike the roadway elements that are result of engineering and planning decisions, these conditions are temporary. Form CR-3 includes weather conditions (clear, cloudy, rain, sleet/hail, snow, fog, blowing sand/snow, severe crosswinds), surface condition (dry; wet; standing water;

snow; slush; ice; sand; mud, dirt), and light conditions (daylight; dark, not lighted; dark, lighted; dark, unknown lighting; dawn; dusk).

<u>*Notable practices:*</u>

- *Visibility:* Factors that might have obscured the vision of the driver, pedestrian, or cyclist that contributed to the crash, include obstructed visibility of crosswalk (NHTSA, 2017a), headlights, sunlight/glare, parked/stopped vehicles, tress and or bushes, rain, snow, and ice on the windshield (GDOT, 2018).

- *Pavement defects:* Existence of unusual conditions, such as holes, bumps, or rutting in the roadway pavement can be useful in determining the need for maintenance (NHTSA, 2017a; GDOT, 2018).

2.2.3 Exposure Factors

Exposure factors are helpful in interpreting non-motorized crash trends and tracking progress (Safe State Alliance, 2017). Unlike motorized traffic volumes, pedestrian and bicyclist count data is often limited and is not coded in crash reports. Non-motorist exposure can be defined based on mode-share, pedestrian and cyclist counts, vehicle ownership, proximity to destinations (Safe State Alliance, 2017; Turner, et al., 2017).

An FHWA report titled *Synthesis of Methods for Estimating Pedestrian and Bicyclist Exposure to Risk at Areawide Levels and on Specific Transportation Facilities* (Turner, et al., 2017) describes a standardized approach to pedestrian and bicyclist exposure to risk estimation for four geographical scales (regional, network, segment, point). (Turner, et al., 2017) also developed state-level and MPO-level non-motorized exposure rates for years 2012-2016 based on fatal crash statistics and travel surveys (American Community Survey, National Household Travel Survey, and regional surveys).

FHWA's *Guidebook on Identification of High Pedestrian Crash Locations* (Fitzpatrick, Avelar, & Turner, 2018) suggests considering surrogate indicators, such as the location of activity centers, type of land use, proximity of a grocery store, retail or population density, location of a transit stop, or number of lanes and their posted speed, to identify locations with high potential for pedestrian crashes.

Figure 2.7 shows the identified potential contributing exposure factors that are discussed in this section.

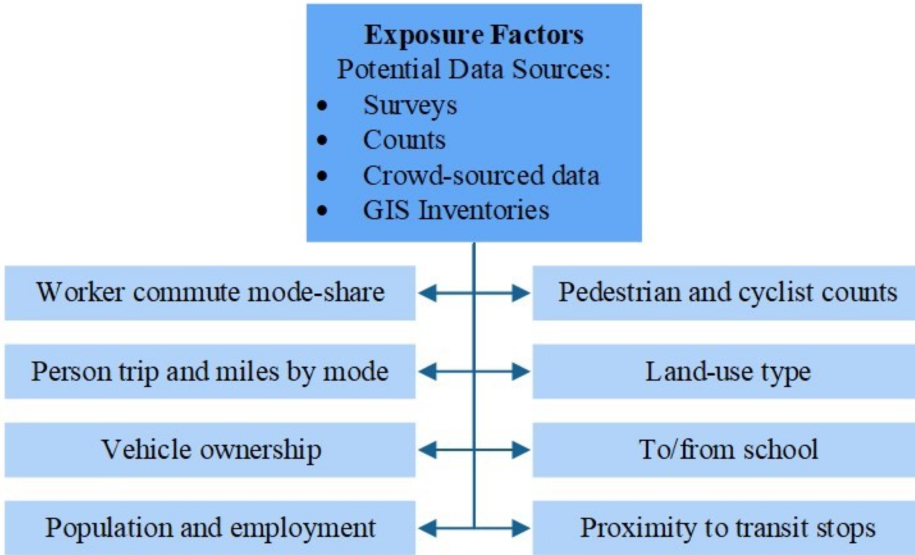


Figure 2.7 Identified Potential Contributing Exposure Factors for Pedestrian and Cyclist Crashes.

Notable practices:

- *Worker commute mode-share:* The American Community Survey (ACS) 2013-2017 (U.S. Census Bureau 2018) estimates for mode of transportation used by workers suggest that majority of work commute in Texas is driving (90.8%), walking (1.6%), transit (1.5%), bicycling (0.3%), or other means (5.8%). The ACS publishes these estimates annually for all census blocks, which are approximately size of a city block.

- *Person trips and miles by mode:* Personal and household travel trends are collected in the National Household Travel Survey (NHTS), which is administered approximately every 8 years by the U.S. Department of Transportation. Statistics approximated from national trends are available for each census tract (BTS, 2018), unless a state or local government purchases additional samples. The 2017 NHTS surveyed more than 20,000 households in Texas and 2,917 households in the North Central Texas Council of Government area (USDOT, 2018a). According to the national 2017 NHTS estimates (USDOT, 2017), majority of person trips was by driving (82.1%), followed by walking (10.5%), transit (2.5%), bicycling (1.0%), and other means (3.9%).

- *Vehicle ownership:* Various studies (Ewing, Pendall, & Chen, n.d.; Gelinne, Thomas, Lang, Zeeger, & Goughnour, 2017) suggest a possible correlation between vehicle ownership and fatality rates.

- *Population and employment:* Number of residents and employees play a role in non-motorized user risk and exposure (Wier, Weintraub, Humphreys, Seto, & Bhatia, 2009).

- *Pedestrian/bicycle counts:* Annual average daily bicycle and pedestrian traffic can be determined based on data from permanent counters that collected data throughout a year. Availability of non-motorized travel volumes varies from region to region. North Central Texas Council of Governments has been collecting pedestrian and bicycle traffic counts on shared-use paths since 2015 (NCTCOG, 2017), however no region-wide on-street counts were available at the time of this research.

- *Crowd-sourced pedestrian and bicyclist data:* Crowdsource activity apps, such as Strava Metro (Strava Metro, 2017) collect de-identified pedestrian and bicycle trip data from users who are tracking their fitness activity via a smartphone or GPS device. Counts are available for streets, as well as intersections. Strava Metro data can be compared with data from local counters in order to develop a regional multiplier and provide a more holistic picture of non-motorized travel behavior (Strava Metro, n.d.). Seattle DOT estimated pedestrian and bicyclist exposure using data such as counts, Strava Metro, transit, land use, and presence of pedestrian and bicycle facilities (Seattle DOT, 2016).

- *Land use type:* While NHTSA crash statistics (Coleman & Mizenko, 2018) distinguish only between rural and urban land use, literature indicates that also the type of land use (single-family residential, multi-family residential, mixed use development, commercial, industrial, etc.) plays a significant role in crash incidence (Dumbaugh & Rae, 2009; Ewing, Schieber, & Zegeer, 2003; Pulugurtha, Duddu, & Kotagiri, 2013). Predominant land use is also one of the variables in FHWA's pedestrian and bicyclist safety indices scoring methodology (Monsere, Wang, Wang, & Chen, 2017), along with roadway characteristics like the type of signalization, number of lanes, posted speed limit, and motorized traffic volume.

- *Proximity of transit stops:* Various research studies (Truong & Somenahalli, 2011; TTI, 1996) indicate a correlation between transit stops and crashes involving pedestrians, especially in locations without safe crossing opportunities. In a study in San Francisco, (Wier, Weintraub, Humphreys, Seto, & Bhatia, 2009) observed that arterial streets without transit had higher vehicle-pedestrian injury collision rates.

- *From/to school*: Whenever a child is involved in a crash on the way to or from school, these crashes are flagged in a crash report (CDOT, 2018; NHTSA, 2017a).

2.3 Methods for Analyzing Crashes

This section introduces crash analysis methods with a focus on pedestrian and bicyclist crashes. According to the *FHWA Guidebook on Identification of High Pedestrian Crash Locations* (Fitzpatrick, Avelar, & Turner, 2018), there are three main approaches:

- A **traditional approach** identifies locations with high crash frequency based on historical crash data.
- A **proactive approach** identifies locations for safety improvements based on a broad view of risk factors, rather than historical crashes.
- A **combination approach** is a mix of the first two approaches, as it uses historical crash data analysis to compliment the potential risk assessment a more comprehensive analysis can be achieved.

2.3.1 Traditional Approach

The traditional approach is mostly known as the reactive approach or high-crash approach. As the name suggests, this analysis approach takes into a consideration the number of crashes that have occurred in a specific system and records it. The clusters of historical crashes that happen in a specific point on a system can then be defined as a "hot spot" or a "high-crash location" and should be considered for further analysis or countermeasures (Fitzpatrick, Avelar, & Turner, 2018).

Traditional Approach: Assumptions

The traditional approach assumes that the historical crash statistics can indicate the locations where crashes will occur in the future. However, under several conditions, this assumption was found to be not plausible (Gelinne, Thomas, Lang, Zeeger, & Goughnour, 2017).

Traditional Approach: Limitations

The traditional approach utilizes information like traffic volume or pedestrian and bicycle counts but does not consider other factors to measure risk throughout the system. The approach might also be susceptible to a bias towards high volume sections and identify them as priorities while missing low volume sections with a high amount of risk but lesser traffic.

Another limitation of this approach particularly for pedestrian and bicyclist crash analysis is the insensitivity of this method to slight differences in the number of crashes. Since there are very limited amount of pedestrian and bicyclist crash reports as opposed to vehicle reports the difference between a high crash location versus a location with some crashes is slim. Severe pedestrian and bicyclist crashes mostly occur in the state and local urban streets instead of rural areas since there is more pedestrian, bicyclist, and vehicle traffic. (Gelinne, Thomas, Lang, Zeeger, & Goughnour, 2017) recognized this limitation and stated that most of the crashes of pedestrian and bicyclists are "widely dispersed, affecting the ability to perform either a high-crash or a risk-based assessment, at least based on local data."

Traditional Approach: Data Analysis

This approach uses historical crash data and basic roadway data (e.g., traffic volume) to identify locations with high crashes.

2.3.2 Proactive Approach

The proactive approach focuses on identifying priority corridors where crashes will most likely occur because of a common problem (Gelinne, Thomas, Lang, Zeeger, & Goughnour, 2017). This approach is based on certain key factors and functions which identify high-risk elements throughout an entire roadway system rather than reacting to crashes that have already occurred. There are various risk assessment methods that can proactively identify locations that need a safety improvement, including safety performance functions (SPF)[4], severity distribution functions (SDF)[5], and crash modification factors (CMF)[6].

There are several different ways to look at the area that is to be analyzed which will decide what type of proactive approach to use: systemic analysis, and systematic analysis.

Systemic Analysis

The systemic approach identifies locations with greatest risk where countermeasures are needed. Unlike the traditional approach, which would select a segment with the most crashes as a location that needs an improvement (Figure 2.8, top), the systemic analysis approach looks for similar risk factors along adjacent segments. Figure 2.8 (middle) shows an identified high crash location and locations with similar risk factors that will also receive improvements.

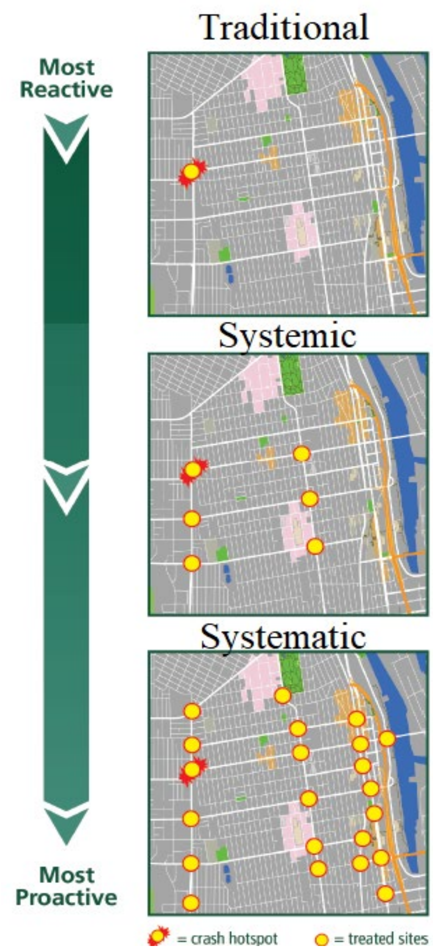


Figure 2.8 Traditional Approach, Systemic Approach, Systematic Approach.
Adapted from (Thomas, et al., 2018).

A simple ranking, sliding window and peak searching screening method can be used to identify the locations. The simple ranking method identifies intersections, segments,

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[4] SPF "is an equation used to predict the average number of crashes per year at a location as a function of exposure and, in some cases, roadway or intersection characteristics (e.g., number of lanes, traffic control, or median type)" (AASHTO, 2014).
[5] SDF is an equation that predicts the proportion of crashes in each severity category as a function of various geometric, operational, and traffic variables. (Gates, et al., 2018)
[6] CMF is "a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. A CMF reflects the safety effect of a countermeasure." (CMF Clearinghouse, n.d.)

and facilities that are most in need of improvements based on the calculated risk. The sliding window and peak searching methods are able to identify which segments in a facility are the best candidates for improvements. The difference between a sliding window and peak searching is that sliding window calculates risk for a specific length and then this window of length is moved by increments of distance and risk is recalculated. The peak searching method also uses windows but are not moved by increments as to not overlap. The risk of each window is compared to a desired risk value and if it is not a desired value then a bigger window can be used.

Systematic Analysis

The systematic analysis "makes improvements at all sites in an area, regardless of predicted crash risk or crash history" (Thomas, et al., 2018). The systematic improvements are deployed at all locations and consist primarily of low-cost countermeasures from engineering, education, or enforcement (Cottrell & In-Kyu Lim, 2018).

The selection of the type of analysis used for the proactive approach is a multicriteria decision based on type of resources, information available, and area that is going to be analyzed for planning effective countermeasures from the analysis.

A grid or polygon screening method can be used for both the systemic and systematic analysis. This can be used to identify which areas have the highest risk for by plotting risk per area instead of pedestrian crash per area. A polygon screening method shows a concentration of crashes: smaller polygon areas have the highest concentration of crashes while the lager polygons have lower concentration of crashes. The polygon screening method is used when the geographic scale analyzed is an entire system but still is able to show which intersections and segments have highest to lowest crash density.

Proactive Approach: Assumptions

The proactive approach assumes that the areas of interest can be predicted based on data that measures risk or safety problems for pedestrians and bicyclists. The approach takes into consideration an entire roadway system for evaluation instead of analyzing only certain locations. This means that the countermeasures to mitigate the problem at a certain intersection can vary based on the geographic scale analyzed. Since the proactive approach uses models based on risk (e.g., SPF, SDF, CMF) to determine the expected number of crashes (or crash frequency) for locations within a set region it is important to decide the geographic scale before analysis. *FHWA Guidebook on Identification of High Pedestrian Crash Locations* (Fitzpatrick, Avelar, & Turner, 2018) recommends using different screening methods based on the geographic scale being analyzed, as Table 2.7 shows.

Table 2.7 Screening Methods.

Screening Method	Intersection	Segment	Facility	System
Simple Ranking	✓	✓	✓	
Sliding Window		✓		
Peak Searching		✓		
Grid				✓
Polygons				✓

Note: Table adapted from Fitzpatrick, Avelar, & Turner (2018).

Proactive Approach: Limitations

A limitation for the proactive approach is that it will require more effort when it comes to modeling and the analysis of the data. Also, if any of the data required is missing then some of the factors that are used for the identification of high-risk locations will be misleading.

Proactive Approach: Data Analysis

A variety of factors, including information about the driver, pedestrian, cyclist, vehicles involved, prior actions of the participants, roadway elements, environmental conditions, as well as exposure factors, can help in crash analysis to offer a deeper understanding of why crashes occurred and what were the common characteristics.

Proactive analysis is based on safety performance factors which describe the mathematical relationship between the frequency of crashes and the most significant factors in crashes, such as pedestrian volume, bicyclist volume, roadway features, and built environment characteristics.

The expected safety performance of a roadway is in terms of crash frequency and severity. Therefore, SDFs and CMFs are also implemented to aid the predictive analysis. Severity models are used to estimate the probability, or proportion, of each severity level given the traffic, geometric, and traffic control characteristics. Crash modification factors are used to estimate the change in crashes expected after implementation of a countermeasure.The CMFclearinghouse.org, a website maintained by the FHWA, provides regularly updated CMFs and crash reduction factors.

Some of the models that are used for the identification of which corridors are of interest are the Chi-square automatic interaction detection (CHAID) (Cottrell & In-Kyu Lim, 2018), and Poisson distribution (Monsere, Wang, Wang, & Chen, 2017). The CHAID is used to identify several intersections based on focus crash types and the variables that describe it. Cottrell et al. (2018) suggest that the CAHID is useful "when looking for patterns in datasets with lots of categorical variables and is a convenient way of summarizing the data as the relationships can be easily visualized." VDOT used this by first narrowing down the crash information to intersections with highest crash frequency and showed the most potential for reduction of crashes (Cottrell & In-Kyu

Lim, 2018). They then used CHAID to identify several intersections that were directly related to the collision types based on roadway inventory and traffic count variables. The Poisson distribution is used to analyze the variables that directly influence crashes and the patterns that are associated with the crashes. The variables that can be used are pedestrian, bicycle, and driver characteristics to identify the contribution of each to risk levels.

Some of the models that are used to describe the crash frequency, or the number of crashes occurring within a specific location, are linear regression and negative binomial. The linear regression model is used to estimate the crash frequency or crash frequency rate at intersections (Monsere, Wang, Wang, & Chen, 2017). The negative binomial model is used to "estimate the pedestrian-vehicle crash frequency rate of both intersections and midblock crossings" (Monsere, Wang, Wang, & Chen, 2017). Chimba et al. (2014) used the negative binomial distribution to identify factors that had a correlation with crash frequency of pedestrians and bicyclists. Another way to depict crash frequency at intersections is by having individual diagrams for the intersections with the highest crash density as seen in Figure 2.9 below used by VDOT.

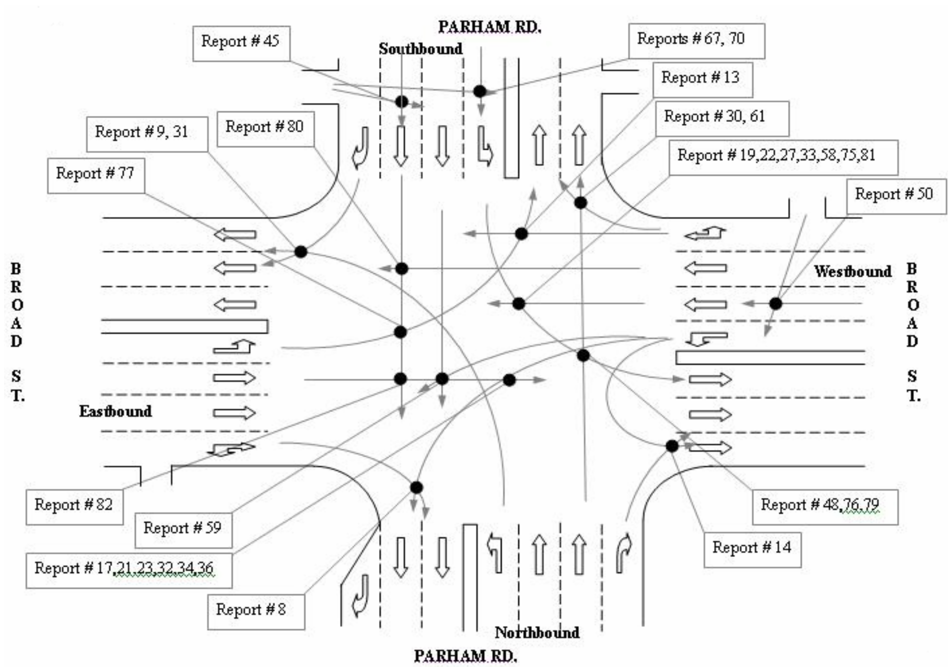


Figure 2.9 Intersection Crash Frequency Diagram.
Source: VDOT (2018)

Crash density models show the concentration of crashes per a unit area or length that has already been decided upon. The size of an area can be in square miles to align with the U.S. Census block groups or established geographic regions.

Potential for safety improvement can be modelled by potential for safety improvement factor (PSI), FHWA pedestrian and bicyclist intersection safety indices (Ped ISI and Bike ISI), logit, probit, or negative binomial models.

The PSI factor was used by the Virginia Department of transportation to prioritize intersections in accordance with a quantified safety performance measure (Cottrell & In-Kyu Lim, 2018). The PSI was calculated by using the difference between predicted and expected crash frequency. The expected crash frequency was estimated using a weighted crash frequency that considered the observed and predicted crash frequency. A positive PSI suggested a higher potential for safety improvements while a lower PSI showed lower potential for safety improvement.

The FHWA has also used the pedestrian and bicyclist ISIs to "proactively identify which intersection crossings and approach legs have the greatest priority for undergoing pedestrian and bicycle safety improvements" (Monsere, Wang, Wang, & Chen, 2017). A score was given to each leg of an intersection and the leg of the intersection with the highest score suggests it should be priority for safety improvements.

Monsere et al. (2017) used a multinomial logistic regression model at signalized and un-signalized intersections to measure crash injury severity and calculate risk factors for intersections based on crash types, intersection characteristics, and other significant variables. The negative binomial model is used to study various factors which influence bicycle risk factors at un-signalized intersections in order to prioritize safety levels. These are a few of the many models that can be used to measure pedestrian and bicycle safety according to Monsere et al. (2017).

Traffic volume is often readily available; however, the availability of pedestrian and bicyclist counts depend on the specific region, municipality, or location. Pedestrian and bike volume can be approximated by using crowd-sourced data. An example of this is Strava which is a mobile application that can track athletic activities including cycling and running through GPS (Monsere, Wang, Wang, & Chen, 2017). However, it is important to note that data from crowdsourced fitness apps is biased, as they tend to oversample recreational cyclists and runners (Roy, Nelson, Fotheringham, & Winters, 2019). Inclusion of volume eliminates the overrepresentation of crashes of a specific type in different areas of interest. For example, if there are two intersections that depict the same priority as a high-crash location for a specific crash type, but one is a high pedestrian volume intersection and the other is a low pedestrian volume intersection then the prediction will be incorrect due to over-representation.

The *Highway Safety Manual* (AASHTO, 2014) has several methods for the estimation of crash severity at varying locations. North Carolina was able to use multinomial logit model in order to predict the probability of different severity levels for bicycle-motor vehicle crashes (Monsere, Wang, Wang, & Chen, 2017). Various probit models were used to analyze crash injury severity levels at signalized and unsignalized intersections (Monsere, Wang, Wang, & Chen, 2017). Alluri et al. (2017) have used the logit model to study the injury severity of pedestrian and bicycle crashes as well as predict the probability of different crash severity levels for bicycle and vehicle crashes

2.3.3 Combination Approach

The combination approach uses information from both previous approaches, traditional and proactive. An example of the combination approach is having a score for the area of interest that includes crash frequency along with predictions from a safety performance function.

Combination Approach: Assumptions

The combination approach assumes that by combining information from the traditional approach, crash densities, and the proactive approach, using predictive models, then the system will be first narrowed down to the high crash locations and then the data used for finding similar factors throughout the system.

Combination Approach: Limitations

The limitations to the combination approach are that it might inherit any error of the previous two approaches if done wrong which may affect the results. Also, the process of identifying the countermeasures for a high crash location requires more steps, as it is a combination of two processes.

Combination Approach: Data Analysis

The data used for the combination approach uses both the historical crash data from the traditional approach and the risk and safety performance data from the proactive approach.

VDOT in their recent Pedestrian Safety Action Plan (2018) used the traditional approach to identify high-crash neighborhood-size clusters based on historic data. These crash clusters considered the geographic density of crashes only and the highest density of pedestrian crash clusters were used to suggest common factors. VDOT was able to map these crash clusters as heat maps to better depict the areas with high crash densities. VDOT was able to identify 12 key measures that may indicate high exposure for pedestrians. These data inputs were used to screen the road system using a GIS system. The roadways were scored out of 100, with 100 being the highest possible score, selecting only the highest 0.1% to be designated as priority corridors.

In another study, the Seattle Department of Transportation (Seattle DOT, 2016) developed an approach using risk-based analysis to identify safety deficiencies throughout the city. This Bicycle and Pedestrian Safety Analysis (Seattle DOT, 2016) examined crashes to isolate risk factors that lead to crashes with road users. A traditional approach was used in first step in the crash analysis, followed by a proactive approach. SDOT included other factors like land use, pedestrian and bicycle volume data, roadway characteristics and other information to calculate risk factors.

Ultimately, the identified risk factors were proactively addressed through various countermeasures.

2.3.4 Summary

A review of notable practices indicates that pedestrian and bicycle crashes can be analyzed using a traditional, proactive, or combination approach. The combination approach seems to be appropriate for larger geographic scales, where detailed roadway inventory data and exposure factor may not be readily available. In those cases, the traditional analysis of historical crash data can indicate the focus areas that are further analyzed using the proactive approach.

2.4 Tools for Pedestrian and Bicycle Crash Analysis

The objective of this Chapter is to summarize notable practices in crash analysis tools. It was found that there are only a few tools oriented exclusively on pedestrian and bicyclist crashes, as it is common for pedestrian and bicycle crashes to be analyzed as one of many crash categories in a general crash analysis. Crash analysis tools, including databases, GIS analysis tools, software packages, and interactive maps, are discussed in this Chapter.

2.4.1 Notable Practices in Crash Analysis Tools

Table 2.8 provides a summary of the notable practices in crash analysis tools described in this Chapter. It shows tools from Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation (USDOT), and the American Association of State Highway and Transportation Officials (AASHTO), followed by notable peer practices of six state departments of transportation.

Table 2.8 Overview of Notable Practices in Crash Analysis Tools.

Crash Analysis Tools	Notable Uses	Users	References
Pedestrian and Bicycle Crash Analysis Tool (PBCAT)	Methodology assigns 56 pedestrian crash types and 79 cyclist crash types based on a crash location, bicyclist position, direction, and approach path	Nationwide	FHWA (2006)
Fatality Analysis Reporting System (FARS)	PBCAT crash types assigned to fatal pedestrian and bicycle crash	Nationwide	NHTSA (2017b)
USDOT Pedestrian Fatality Risk Map	Estimates of pedestrian fatality risk for all census tracts nationwide	Nationwide	USDOT (2018b)
Areawide Nonmotorized Exposure Tool	State- and MPO-level estimates for pedestrian and bicycle risk exposure	Nationwide	Turner et al. (2017)
FHWA Pedestrian and Bicycle GIS Safety Analysis Tools	GIS add-in for determination of high pedestrian crash zones	Nationwide	FHWA (n.d.-a)
Highway Safety Manual and AASHTOWare Safety Analyst	Predictive methods, crash modification factors. Pedestrian and bicycle safety performance functions (SPFs) under development.	Nationwide	AASHTO (n.d., 2014); TRB (2017)
Planning Analysis Software for Safety (PASS)	Automatic extraction of data from the crash database	Indiana State Police	Tarko, Inerowicz, & Liang (2007, 2008)

Crash Analysis Tools	Notable Uses	Users	References
Indiana Crash Risk Map	Online map with daily crash risk prediction	Indiana State Police	State of Indiana (n.d.)
Roadsoft	Cross-asset inventory integrated with crash data	Michigan DOT	Michigan Technological University (n.d.)
Critical Analysis Reporting Environment (CARE)	Real-time statistics on traffic citations and crashes with automated narrative data searching	Alabama DOT	University of Alabama (n.d.)
Level of Service of Safety (LOSS)	Locations with highest crash reduction potential determined via Safety Performance Functions (SPFs)	Colorado DOT	CDOT (2017); FHWA (2016d)
Multimodal Transportation Planning Tool (MTPT)	Suitability for bicycle and pedestrian traffic	Georgia DOT	GDOT (2007)

The **Pedestrian and Bicycle Crash Analysis Tool (PBCAT)** is a crash coding methodology developed by the University of North Carolina for the Federal Highway Administration (FHWA, 2006). Its crash typing logic focuses on the sequence of events that led to crashes between motor vehicles and bicyclists or pedestrians. It assigns one of the 79 cyclist crash types and 56 pedestrian crash types based on a crash location, bicyclist position, direction, and approach path. Chapter 3 is dedicated to a detailed description of this tool.

The **Fatality Analysis Reporting System (FARS)** is a nationwide database that contains data on all fatal traffic crashes. All pedestrian and bicyclist fatalities since 2014 are assigned a PBCAT crash type and other pre-crash characteristics (pedestrian/bicyclist position, pedestrian/bicyclist direction of travel, motorist direction of travel, motorist maneuver, intersection leg, and pedestrian scenario (NHTSA, 2017b). The NHTSA is currently developing a visualization software to create interactive visualizations of their Traffic Safety Fact Sheets (USDOT, 2019) such as the pedestrian traffic fatality dashboard (USDOT, n.d.) One of the latest safety data initiatives from the Department of Transportation is the **Pedestrian Fatality Risk Map** (USDOT, 2018b), which estimates pedestrian fatality risk for all census tracts nationwide. Its model is built upon data from FARS, FHWA, the Environmental Protection Agency, and the U.S. Census Bureau (Mansfield, Peck, Morgan, McCann, & Teicher, 2018). Figure 2.10 shows the map for the NCTCOG MPO region with predicted yearly fatalities per 100,000 persons. Census tracts in dark and light red indicate that the risk is higher than in 90% and 80% of census tracts nationwide, respectively.

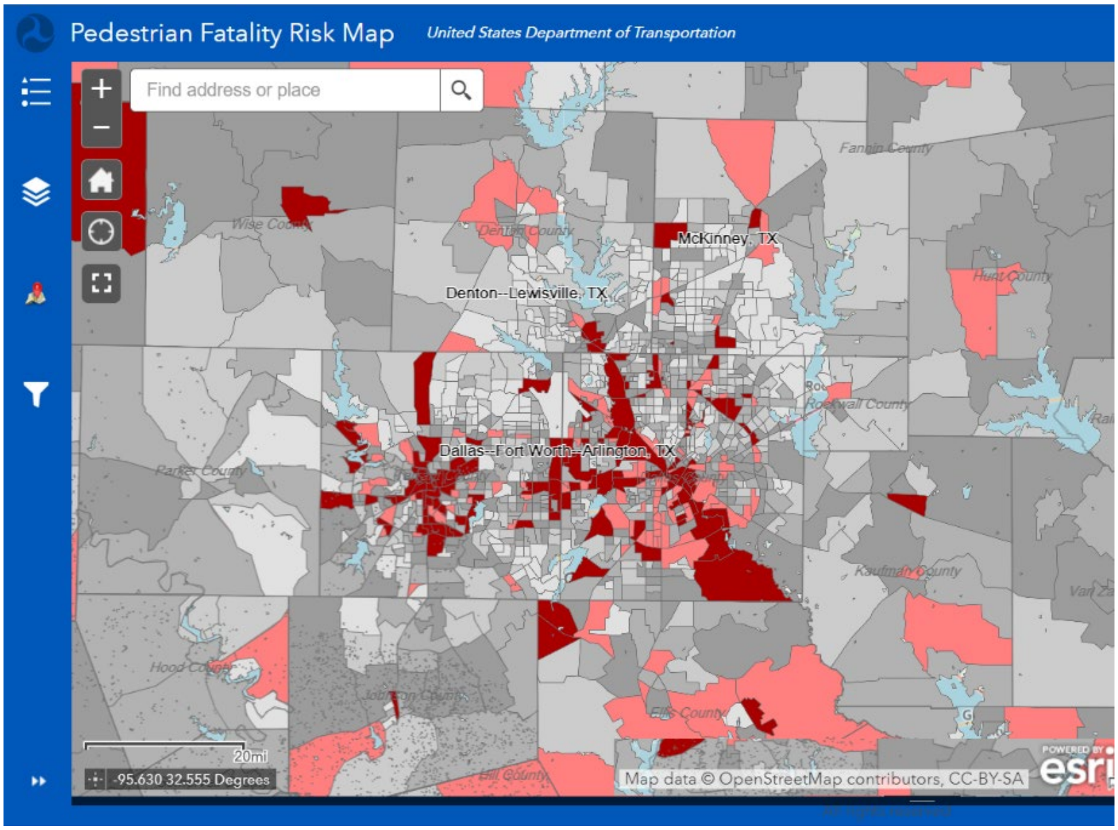


Figure 2.10 Estimated Pedestrian Fatality Risk in North Texas.
Source: USDOT (2018b)

Another source of pedestrian and bicyclist exposure to risk is the **Areawide Non-Motorized Exposure Tool** (Turner, et al., 2017, 2018) which provides statewide and MPO-level estimates based on pedestrian and bicyclist fatalities reported in FARS, U.S. Census Bureau's American Community Survey and FHWA's 2009 National Household Travel Survey.

FHWA offers a set of tools aimed specifically at pedestrian and bicycle safety. The **Pedestrian and Bicycle GIS Safety Analysis Tools** offer the ability to calculate high pedestrian crash zones and draw safe routes for walking to school or for bicycling (FHWA, n.d.-a).

The ***Highway Safety Manual*** **(HSM)** includes a collection of methods and tools for quantitative safety analysis developed by AASHTO in cooperation with FHWA and the Transportation Research Board (TRB). It covers a variety of topics, including roadway safety management process, human factors, predictive methods, as well as crash modification factors (AASHTO, 2014) Pedestrian and bicycle safety performance functions (SPFs) are currently missing in the HSM and will be developed in NCHRP project 17-84, which is estimated to be completed in 2020 (TRB, 2017). The **AASHTOWare Safety Analysis** is a software tool developed by AASHTO. It aims to identify and program highway safety improvements and builds upon the HSM roadway safety management process defined in the HSM, which consists of four steps: network screening, diagnosis and countermeasure selection, economic appraisal and priority ranking, and countermeasure evaluation (AASHTO, n.d.).

Planning Analysis Software for Safety (PASS) is an add-in tool for TransCAD developed by Purdue University (Tarko, Inerowicz, & Liang, 2007). The PASS uses crash prediction models to predict annual crash frequencies in roadway networks. The predictive equations are calibrated based on various factors, including recent crash data, and roadway characteristics (Tarko, Inerowicz, & Liang, 2008). A state-specific version of PASS, titled INPASS, was developed for the Indiana State Police in 2007. It automatically extracts crash data from the Indiana State Police database for analysis in INPASS. The extracted crash data includes collision location and severity, property damage, unit, damage, factors, trailer, commercial unit, injured individual, restriction, citation, non-motorist, test type, apparent physical condition, and citation type (Tarko, Inerowicz, & Liang, 2007).

The crash data extracted by INPASS feed into the **Indiana Crash Risk Map**. This application predicts the likelihood of crashes across the state on a 1-kilometer-by-1-kilometer grid, as Figure 2.11 shows. Daily predictions based on weather, traffic, road conditions, historical crash data, and Census data, are available in eight three-hour time windows (12am-3am, 3am-6am, etc.). The map shows areas with high/medium/low/very low crash risk, as well as locations of prior crashes. This interactive tool aims to reduce and prevent crashes by assisting law enforcement agencies to allocate resources in anticipated areas and reduce response time (State of Indiana, 2019).

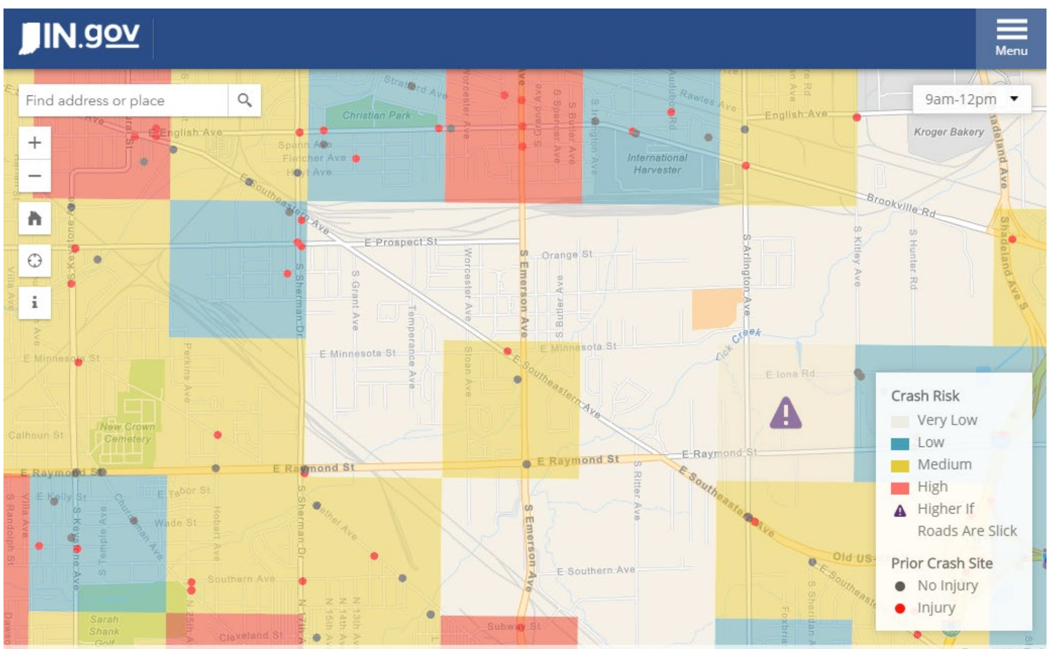


Figure 2.11 Indiana Crash Risk Map.
Source: State of Indiana (2019)

Roadsoft is a comprehensive roadway asset management system, developed by the Michigan Technological University, that collects, stores, and analyzes data associated with crashes, traffic counts, and asset inventories (MTU, n.d.). This database includes information about roadways, sidewalks, signs, driveways, intersections, pavement markings, guardrails, bridges, and culverts. Apart from asset maintenance management, Roadsoft also analyzes crash trends and identifies segments and intersections with a high frequency of crashes. Roadsoft is available at no cost to Michigan government agencies through a license funded by the Michigan Department of Transportation.

Critical Analysis Reporting Environment (CARE) is a crash data analysis software package developed by the University of Alabama. It automatically retrieves real-time data from crash and citation databases and creates dashboard summaries. It's advanced analytical and statistical techniques include data mining, narrative data searching, and automatic collision diagram generation (University of Alabama, n.d.) Alabama DOT uses CARE to describe safety trends and inform its Strategic Highway Safety Plan (Alabama DOT, 2017)

The **Level of Service of Safety (LOSS)** calculation procedure, developed by the Colorado Department of Transportation (CDOT), takes into account exposure when analyzing crash patterns. LOSS includes safety performance functions that are based on crash frequency, crash severity, traffic volume, functional classification, number of lanes, speed, traffic control, terrain, and environment. Figure 2.12 illustrates the concept of "using an SPF calibrated for total crashes expected on the 6-lane urban freeways. The delineated boundary line is located 1.5 standard deviations from the mean, reflecting a Negative Binomial error structure." (FHWA, 2011a) The LOSS "reflects how the roadway segment is performing in regard to its expected crash frequency and severity at a specific level of AADT." (FHWA, 2011a) The figure shows four LOSS categories: "LOSS-I - Indicates low potential for crash reduction; LOSS-II - Indicates low to moderate potential for crash reduction; LOSS-III - Indicates moderate to high potential for crash reduction; and LOSS-IV - Indicates high potential for crash reduction" (FHWA, 2011a). Colorado DOT uses LOSS to identify highway segments and intersections with over-represented crash patterns and a sub-standard level of service of safety within the Highway Safety Improvement Program (CDOT, 2017). The LOSS method helped Colorado DOT to reduce fatal crashes by 36% between 2002 and 2011 by identifying locations with the highest crash reduction potential (FHWA, 2016e).

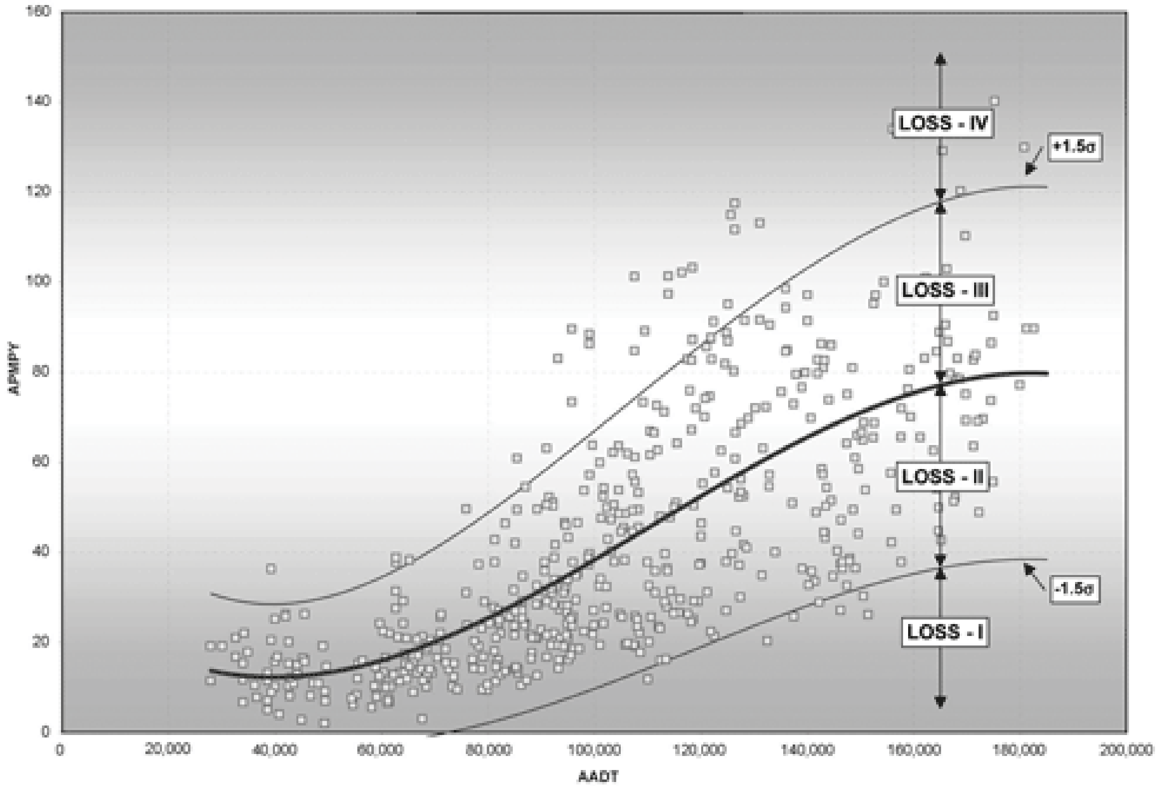


Figure 2.12 CDOT Level of Service of Safety.
Source: FHWA (2011a)

The **Multimodal Transportation Planning Tool (MTPT)**, developed by the Georgia Department of Transportation, calculates suitability for bicycle and pedestrian traffic on Georgia roadways based on a variety of factors, including historical crashes, Census commuting patterns, functional classification, speed limit, traffic volume, and travel lane width (GDOT, 2007). It assists GDOT in planning activities, as it recommends minor or major roadway upgrades for segments or intersections that are identified as sub-standard.

2.4.2 Pedestrian and Bicycle Crash Analysis Tool

The Pedestrian and Bicycle Crash Analysis Tool (PBCAT) was developed by the University of North Carolina for the Federal Highway Administration (FHWA, 2006). This crash coding methodology builds upon more than 40 years of research investigating causes of crashes that involved pedestrians and cyclists (Snyder & Knoblauch, 1971; Cross & Fisher, 1977; Hunter et al. 1996, 1997a, 1997b). These studies, based on interviews with participants and witnesses, police reports, and on-scene observations, were aimed to identify the causes of crashes and their potential countermeasures.

2.5 Safety Countermeasure Practices

This section describes information resources for safety management practices with prioritization methods to identify locations with higher risk of crashes. Emphasis is also given to provide additional information about enforcement and policy, and educational countermeasure best practices.

2.5.1 Notable Safety Management and Countermeasures

The following sections provides a summary of major resources related to countermeasures, and methods of approaching a safety analysis, that helped with the improvement of pedestrian and bicyclist safety.

Information Resources for safety management

- **Federal Highway Administration**: *Guidebook on Identification of High Pedestrian Crash Locations*. (FHWA, 2018b)
- **Federal Highway Administration**: *Reliability of Safety Management Methods*. (FHWA, 2016d)
- **Texas A&M Transportation Institute**: Developing Methodology for Identifying, Evaluating, and Prioritizing Systemic Improvements. (TTI, 2015)

Information Resources for safety countermeasures

- **Federal Highway Administration**: *Making Our Roads Safer: One Countermeasure at a Time.* (FHWA, 2018c)
- **Federal Highway Administration**: *Proven Safety Countermeasures*. (FHWA, 2018d)
- **National Cooperative Highway Research Program**: *Report 893: Systemic Pedestrian Safety Analysis*. (NCHRP, 2018)
- **Virginia Department of Transportation*: Pedestrian Safety Action Plan*** (VDOT, 2018)
- **National Association of City Transportation Officials:** *Urban Bikeway Design Guide* (NACTO, 2017)
- **National Highway Traffic Safety Administration:** Countermeasures that Work: Highway Safety Countermeasure Guide for State Highway Safety Offices. (NHTSA, 2017a)
- **National Cooperative Highway Research Program:** *Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways*. (NCHRP, 2016)

- **Federal Highway Administration**: Bicycle Safety Guide and Countermeasure Selection System (BIKESAFE). (FHWA, 2014).

- **Federal Highway Administration**: *Pedestrian Safety Guide and Countermeasure Selection System (PEDSAFE).* (FHWA, 2013a)

- **Federal Highway Administration:** *Roadway Departure (RWD) Strategic Plan.* (FHWA, 2013b)

- **Federal Highway Administration:** *Manual on Uniform Traffic Control Devices 2009 Edition*. (FHWA, 2012b)

- **Federal Highway Administration**: *Intersection Safety: A Manual for Local Rural Road Owners.* (FHWA, 2011b).

- **National Cooperative Highway Research Program**: *Report 500 Volume 18: A Guide for Reducing Collisions Involving Bicycles.* (NCHRP, 2008).

- **National Cooperative Highway Research Program:** *Report 500 Volume 10: Guide for Reducing Collisions Involving Pedestrians.* (NCHRP, 2004).

Safety Management

<u>*FHWA (2018a) Guidebook on Identification of High Pedestrian Crash Location*</u>

This report focuses on assisting communities in identifying high pedestrian crash locations, in order to get closer to the approach of reducing the frequency of pedestrian crashes. The report concluded after a long time of research that the best process to identify high pedestrian crash locations are: select the approach, gather the data, plan an assessment, conduct the assessment, and prioritize locations.

- **Select Approach**: Traditional Approach (Based on the historical crash pattern “Hot Spots”)**;** Proactive Approach (Use SPFs to determine the expected number of crashes for locations within a set region.)**;** Combination Approach **(**uses characteristics of both a traditional approach and a proactive approach).

- **Gather Data:** Crash Data (Crash Specifications, Vehicle/Unit, Person, Citation and Adjudication, Reporting Requirements), Roadway Characteristics; Exposure Data.
    - **Supplemental Data Sources:** Citizen’s Observation of Locations Needing Attention; Law Enforcement Observations; Law Enforcement Observations; Trauma Center Data; Land Use/Development Plans

- **Select Scale:** Intersections (points); Segments; Facilities; Area.

- **Select Performance Measures:** Crash Frequency; Crash Rate; Crash Type; Crash Severity; Safety Index; Others.

- **Select Screening Method:** Simple Ranking, Sliding Window; Peak Searching; Grid; Polygons; Visual.

FHWA (2016) Reliability of Safety Management Methods

This report focuses on four main objectives, which are: raise awareness of the systemic approach to safety management, characterize projects implemented through a comprehensive safety management program, demonstrate the value of integrating systemic approaches as part of a comprehensive safety management program, and present information on allocating funding to systemic projects within a comprehensive safety management program. Figure 2.13 is a visual representation of the three main stages in which the approach is separated.

- **Introduction to Roadway Safety Management**: Planning, Implementation; Evaluation.

- **Overview of Safety Management Approaches:**

    - Crash Based Approach: Network Screening; Diagnosis; Countermeasure Selection; Site-Specific data; Highly Dispersed Crashes Potential for High-Cost Improvements.

    - Systemic Approach: Identify Focus Crash Types; Facility Types and Risk Factor; Screen and Prioritize Candidate Locations; Select Countermeasures.

    - Policy-Based Method: Install Retroreflective Back Plates on all New Signal Installations and Signal Upgrades; Improve the Retro Reflectivity of Curve Warning Signs to Enhance Delineation on Horizontal Curves; Install Longitudinal Rumble Strips and Stripes on Two-Lane Roads; Install Safety Edge for all Asphalt Paving Projects without Curbs.

- **Demonstrating the Value of Integrating Systematic Approaches in a Comprehensive Safety Program:**

    - Value of Crash-Based Projects, Countermeasure: States(s); Service Life; Average Crash Frequency Before Treatment; CMF; Study Method; Similar CMFs from the CMF Clearinghouse; Average Cost per Mile.

- **Data Requirements for Crash-Based and Systemic Approaches:** Identify Focus Crash Types and Facility Types; Determine Risk Factors; Select Countermeasures; Screen Network for Suitable Locations; Evaluate Safety Effects.

- **Tools and Resources for Systemic Approaches:** National Cooperative Highway Research Program Report 500; CMF Clearinghouse; Roadway Safety Data and Analysis Toolbox.

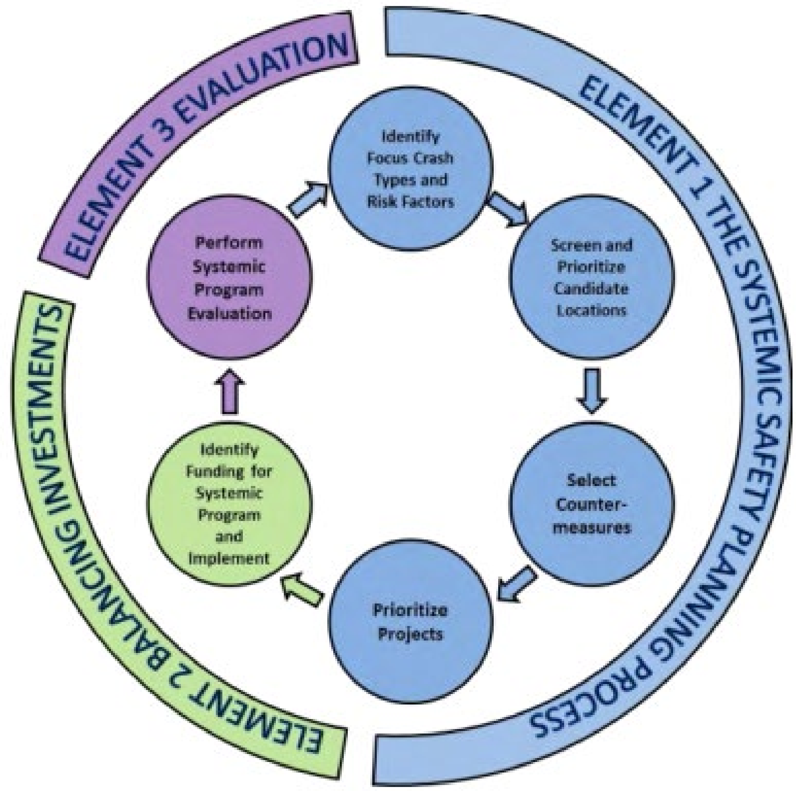


Figure 2.13 FHWA Systematic Tool.
Source: FHWA (2016d)

TTI (2015) Developing Methodology for Identifying, Evaluating, and Prioritizing Systemic Improvements

This report presents two systematic approaches: one with the intention of project selection and the second one to roadway characteristic evaluation. The approach to project selection emphasizes on reducing the number and severity of crashes happening on the TxDOT roadway network and the approach to roadway characteristics classification focuses on developing systematic improvements that deals with a particular countermeasure to create a positive impact.

- **Systemic Safety Planning Process:** Identify target crash types and risk factors, screen and prioritize candidate locations, select countermeasures, and prioritize projects.
- **Framework for Balancing Systematic and Traditional Safety Investments*:*** Review the historical funding investments; apply the funding determination framework to balance the two methods; and assess the possible benefits from the systemic improvement based on the determined funding

- **Evaluation of a Systemic Safety Program**: (1) short-term output, which consists of checking the implementation of the planned systemic program, including the general outputs, the finishing time, and the countermeasures; (2) long-term performance, which focuses on finding out if the focused crash types have been effectively reduced; and (3) specific countermeasure evaluation, which assesses the performance of the deployed countermeasures.

Safety Countermeasures

FHWA (2018c) Making Our Roads Safer: One Countermeasure at a Time

This report describes twenty proven safety countermeasures that offer significant and measurable impacts to improving safety. Additionally, FHWA maintains a list of Proven Safety Countermeasures that during the last update in 2017 reached a total of 20 treatments (FHWA, 2018c)

- **Countermeasures for preventing roadway departure**: Enhanced Delineation and Friction for Horizontal Curves; Longitudinal Rumble Strips and Stripes; Safety Edge; Roadside Design Improvements at Curves; Median Barriers.

- **Intersection countermeasures:** Back plates with Retroreflective Borders**;** Corridor Access Management; Left-and Right-Turn Lanes at Two Way Stop-Controlled Intersections; Reduced Left-Turn Conflict Intersections; Roundabouts; Systematic Application of Multiple Low-Cost Countermeasures at Stop-Controlled Intersections; Yellow Chang Intervals.

- **Pedestrian/Bicycles countermeasures:** Leading Pedestrian Intervals; Medians and Pedestrian Crossing Islands in Urban and Suburban Areas; Pedestrian Hybrid Beacons; Road Diets/ Reconfigurations; Walkways.

These countermeasures offer a significant impact. Leading pedestrian intervals reduce pedestrian-vehicle crashes at intersection by 60%. Pedestrian crossing islands reduce pedestrian crashes by 56%, while pedestrian hybrid beacons lead to a 69% reduction in pedestrian crashes. Then 65-89% of crashes involving pedestrians walking along roadways can be prevented by implementing adequate walkways and sidewalks (FHWA, 2018c, 2018d). Additionally, FHWA maintains a list of Proven Safety Countermeasures that during the last update in 2017 reached a total of 20 treatments (FHWA, 2018d). As Figure 2.14 shows, five countermeasures are specifically targeted to improve pedestrian and bicycle safety: leading pedestrian intervals (#13), medians and pedestrian crossing islands (#14), pedestrian hybrid beacons (#15), road diets and reconfiguration (#16), and walkways (#17).

Figure 2.14 Proven Safety Countermeasures.
Source: FHWA (2018d)

These countermeasures offer a significant impact. Leading pedestrian intervals reduce pedestrian-vehicle crashes at intersection by 60 percent. Pedestrian crossing islands reduce pedestrian crashes by 56%, while pedestrian hybrid beacons lead to a 69% reduction in pedestrian crashes. Then 65-89% of crashes involving pedestrians walking along roadways can be prevented by implementing adequate walkways and sidewalks (FHWA, 2018d).

NCHRP (2018) Report 893: Systemic Pedestrian Safety Analysis

In this report, Thomas et al. (2018) identified a dozen of countermeasures that are suitable for systemic pedestrian safety improvements, including (1) leading pedestrian intervals, (2) longer pedestrian phases, (3) restricted left turns during protected crossing phase, (4) in-roadway 'yield to pedestrian' signs, (5) advance stop/yield bars, (6) pedestrian hybrid beacons (PHB), (7) high visibility crosswalks, (8) traffic calming (raised devices), (9) median crossing island, (10) reduce number of lanes road diet, (11) curb extensions and parking restrictions, and (12) location-specific lighting improvements. Figure 2.14b identifies related risk factor, crash types, and location types for each countermeasure. This report also summarizes the general traffic context, such speed, volume, and the number of lanes, in which the countermeasures come into consideration.

Countermeasure	Related Risk Factor	Related Crash Type	Location Type
High visibility crosswalk	Conspicuity (driver failure to notice); compliance with crosswalks (motorist and pedestrian)	Any occurring at crossing locations	Signalized or Unsignalized*
Traffic calming (raised crosswalk/ speed table)	Traffic speed; conspicuity/pedestrian visibility (possibly); non-compliance with crosswalks	Through vehicle, pedestrian crossing at signalized/unsignalized location; turning vehicle, pedestrian crossing; pedestrian dart-outs and dashes; unique midblock crossing/pedestrian in roadway types; speeding related	Signalized or Unsignalized*
Median crossing island	Number of traffic lanes; number of lanes crossed in one maneuver; traffic speed (possibly, if roadway narrowed); turning speed at intersections (possibly, if restricts turning radius/corner cutting)	Through vehicle, pedestrian crossing at signalized/unsignalized location; turning vehicle, pedestrian crossing roadway; pedestrian dart-outs and dashes; possibly nighttime crashes if replaces two-way, center-turn lane	Signalized or Unsignalized*
Road diet	Number of lanes; number of conflict points associated with driveways/ junctions; traffic speed	Through vehicle, pedestrian crossing at unsignalized location; pedestrian dart-outs and dashes; potentially pedestrian walking along the roadway or other pedestrian in roadway types if sidewalks provided; speeding-related/ potentially all types; motorist types, including rear-end and sideswipe/angle	Unsignalized*
Curb extension with parking restriction	Parking presence; conspicuity/visibility; width of crossing	Through vehicle, pedestrian crossing at unsignalized location; pedestrian dart-outs and dashes; multiple threats; turning vehicle at intersection; waiting to cross	Unsignalized*
Improve lighting	Conspicuity (driver failure to notice); darkness	Nighttime pedestrian crashes	Signalized or Unsignalized*
In-roadway yield to pedestrian sign (R1-6)	Conspicuity; traffic speed; traffic volume/gap availability	Pedestrian crossing, through vehicle at unsignalized location; multiple threats; motorist failure to yield	Unsignalized*
Advance stop/yield marking and R1-5/R1-5a sign	Number of traffic lanes (> 1 by direction); conspicuity/sight lines	Pedestrian crossing, through vehicle at unsignalized location; multiple threats; motorist failure to yield	Unsignalized*
PHB	Traffic volume; no traffic signal/stop sign; multiple traffic lanes (possibly)	Through vehicle at unsignalized location; motorist failure to yield; multiple threats; bus related	Unsignalized*
LPI	Conflicts at signalized locations; motorist failure to yield when turning	Pedestrian crossing, vehicle turning left or right	Signalized
Longer pedestrian phase	Conflicts at signalized locations; insufficient crossing time	Pedestrian crossing, through vehicle; pedestrian crossing, vehicle turning left or right; pedestrian failure to yield types and pedestrian dashes	Signalized
Protected crossing phase	Conflicts with turning traffic; pedestrian delay (due to turning traffic)	Pedestrian crossing, vehicle turning left; motorist failure to yield when turning	Signalized

*Unsignalized locations include midblock crossings lacking signal controls.

Figure 2.15 Pedestrian Countermeasures and Related Risk Factors, Crash Types, and Locations.
Source: NCHRP (2018)

VDOT (2018) Pedestrian Safety Action Plan

This report focuses on pedestrian safety action plan in the state of Virginia. The report priority is to reduce the pedestrian crashes by creating performance metrics and ultimately reduce pedestrian fatalities throughout the Commonwealth.

- **Countermeasures for signage and pavement markings:** Advance stop or yield lines; Advance warning for motorists (ped-activated, flashing yellow beacons); High-visibility crosswalk; High-vis crosswalk in conjunction with illuminated overhead crosswalk sigh; improved conspicuity of signs; in-roadway/curbside yield signs; “look” pavement stencils; Marked crosswalks; No left turns; No turn on red; Pedestrian hybrid beacon (PHB); Pedestrian warning signs; Rectangular rapid beacon (RRFB); Restrict parking near intersections; Restrict right-turn-on-red (RTOR) by time-of-day; Turning vehicles yield to pedestrians; Yield here to pedestrians signs.

- **Countermeasures for speed management and traffic calming:** Lower speed limits; Radar speed display/dynamic speed feedback signs; Speed humps/cushions/table; Road diet (lane reduction)/Lane re-utilization; Street trees; Transverse rumble strips.

- **Countermeasures for pedestrian signals:** Accessible pedestrian signals (APS); Automatic pedestrian devices; Convert permissive or permissive/protected to protected left-turn phasing; Flashing yellow arrow (FYA) for left turns; Increase pedestrian crossing time; Leading pedestrian interval; Pedestrian countdown signal; Pedestrian detection to extend crossing time when pedestrian is detected within the intersection; Pedestrian scrambles (Barnes dance)/exclusive ped phasing.

- **Countermeasures for lighting:** Intersection lighting/crosswalk lighting; Segment lighting; Smart/dynamic lighting.

- **Countermeasures for transit:** Access to transit; Bus bulb outs; Right turn pockets; Transit stop improvements.

- **Countermeasures for design:** Choker; Corner bulb outs and chockers/curb extensions; Curb radius reduction; Danish offset (also known as angled median crosswalks and split pedestrian crossover (SPXO)); Install raised ped crossing/raised crosswalks/speed tables; Install refuge islands/raised median; install/modify design of channelized right turn lane; Neighborhood traffic circles; On-street bicycle facilities; On-street parking enhancements/ restrictions; Sidewalks/shared use paths.

NACTO (2017) Urban Bikeway Design Guide

The NACTO Urban Bikeway Design Guide, focuses in providing safe and effective streets for cyclist. This report is based on cities that have a high number of street cyclist.

- **Countermeasures for on-road bike facilities:** Conventional Bike Lanes; Buffered Bike Lanes; Contra-Flow Bike Lanes; Left-Side Bike Lanes**.**

- **Intersection treatment countermeasures:** Bike Boxes; Intersection Crossing Markings; Two-Stage Turn Queue Boxes; Median Refuge Island; Through Bike Lanes; Combined Bine/Turn Lane; Cycle Track Intersection Approach**.**

- **Markings, signals, and signs countermeasures:** Colored Bike Facilities; Colored Pavement Material Guidance; Shared Lane Markings; Bike Route Wayfinding Signage and Marking System.

- **Countermeasures for cycle tracks:** One-Way Protected Cycle Tracks; Raised Cycle Tracks; Two-way Cycle Tracks.

- **Bicycle signal countermeasures:** Active Warning Beacon for Bike Route at Un-signalized Intersection; Bicycle Signal Heads; Hybrid Beacon for Bike Route Crossing of Major Street; Signal Detection and Actuation.

- **Bicycle boulevards countermeasures:** Route Planning; Signs and Pavement Markings; Speed Management; Volume Management; Minor Street Crossings; Major Street Crossings; Offset Crossings; Green Infrastructure.

NHTSA (2017) Countermeasures that Work: Highway Safety Countermeasure Guide for State Highway Safety Office

NHTSA considers the following pedestrian safety countermeasures to be effective or likely effective: elementary-age child pedestrian training, safe routes to school, pedestrian safety zones, speed limit reduction and enforcement, conspicuity enhancements, and enforcement strategies (Richard et al., 2017).

Countermeasures to improve bicycle safety considered by the NHTSA to be effective or likely effective include bicycle helmet laws for children and adults, safe routes to school, as well as active lighting and rider conspicuity (Richard et al., 2017).

NCHRP (2016) Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways

The NCHRP Synthesis 498 recommends the following countermeasures to improve pedestrian safety (Thomas et al., 2016):

- **Roadway design countermeasures** include narrow lane width, road diets, raised median and pedestrian median islands, raised crosswalks and speed tables, curb extensions and bulb-outs, reduced corner radius, corridor-wide speed calming, pedestrian overpasses and underpasses, and enhanced illumination at crossings.

- **Traffic control countermeasures** include active devices, passive devices, stop laws, yield laws, high-visibility crosswalks, advance stop/yield bars and signs, in-roadway 'yield to pedestrians' signs, pedestrian warning signs, in-pavement flashing lights, overhead or roadside mounted flashing beacons, rectangular rapid flash beacons, pedestrian hybrid beacon, traffic signals with/without pedestrian countdown signal, leading pedestrian signal, right turn on red restrictions, and parking restrictions.

<u>FHWA (2014) Bicycle Safety Guide and Countermeasure Selection System (BIKESAFE)</u>

Similar to the FHWA PEDSAFE, the Bicycle Safety Guide and Countermeasure Selection System (BIKESAFE) includes a wide variety of proven countermeasures. As Figure 2.16 shows, BIKESAFE countermeasure groups targeting 13 common bicycle crash types that are aligned with the Pedestrian and Bicycle Crash Analysis Tool (PBCAT): motorist failed to yield – signalized intersection, motorist failed to yield – non-signalized intersection, bicyclist failed to yield – signalized intersection, bicyclist failed to yield – non-signalized intersection, motorist drove out – midblock, bicyclist rode out – midblock, motorist turned or merged left into path of bicyclist, motorist turned or merged right into path of bicyclist, bicyclist turned or merged left into path of motorist, bicyclist turned or merged right into path of motorist, motorist overtaking bicyclist, bicyclist overtaking motorist, non-motor vehicle crashes (FHWA, 2014).

Crash Type	Shared Roadway	On-Road Bike Facilities	Intersection Treatments	Maintenance	Traffic Calming	Trails/ Shared-Use Paths	Markings, Signs & Signals	Other Measures
Motorist failed to yield - signalized intersection	X		X		X	X	X	X
Motorist failed to yield - non-signalized intersection	X		X		X	X	X	X
Bicyclist failed to yield - signalized intersection	X		X		X	X	X	X
Bicyclist failed to yield - non-signalized intersection	X		X		X	X	X	X
Motorist drove out - midblock	X					X	X	X

Figure 2.16 BIKESAFE Countermeasure Groups Related to Bicycle Crash Types.

Source: FHWA (2014)

Crash Type	Shared Roadway	On-Road Bike Facilities	Intersection Treatments	Maintenance	Traffic Calming	Trails/ Shared-Use Paths	Markings, Signs & Signals	Other Measures
Bicyclist rode out - midblock	X	X			X	X	X	X
Motorist turned or merged left into path of bicyclist	X	X	X		X	X	X	X
Motorist turned or merged right into path of bicyclist	X	X	X		X	X	X	X
Bicyclist turned or merged left into path of motorist	X	X	X	X	X	X	X	X
Bicyclist turned or merged right into path of motorist	X	X	X	X	X	X	X	X
Motorist overtaking bicyclist	X	X		X	X	X	X	X
Bicyclist overtaking motorist	X	X		X		X	X	X
Non-motor vehicle crashes	X			X		X	X	X

Figure 2.16 Cont'd. (FHWA, 2014)

Each BIKESAFE countermeasure group is associated with specific countermeasures (FHWA, 2014):

- **Countermeasures for shared roadways** include roadway surface improvements, bridge and overpass access, tunnel and underpass access, lighting improvements, parking treatments, median, crossing island, driveway improvements, lane reductions (road diet), lane narrowing, streetcar track treatments.
- **Countermeasures for on-road bike facilities** include bike lanes, wide curb lanes, paved shoulders, shared bus-bike lanes, contraflow bike lanes, separated bike lanes.
- **Intersection treatment countermeasures** include curb radius reduction, roundabouts, intersection markings, sight distance improvements, turning restrictions, merge, and weave area redesign.

- **Countermeasures related to maintenance** include repetitive and short-term maintenance, major maintenance, and hazard identification program.

- **Traffic calming countermeasures** include mini-circles, chicanes, speed tables, humps, cushions, traffic diversion, and visual narrowing.

- **Countermeasures for trails and shared-use paths** include separate shared-use paths, path intersection treatments, share the path treatments.

- **Markings, signals, and signs countermeasures** include optimizing signal timing for bicyclists, bike-activated signal detection, sign improvements for bicyclists, pavement marking improvements, school-zone improvements, rectangular rapid flashing beacons, pedestrian hybrid beacon, bicycle signal heads.

- **Other countermeasures** include law enforcement, bicyclist and motorist education, transit access, wayfinding, landscaping, and aesthetics.

FHWA (2013a) Pedestrian Safety Guide and Countermeasure Selection System (PEDSAFE)

The Pedestrian Safety Guide and Countermeasure Selection System (PEDSAFE) includes a wide variety of proven countermeasures that have been implemented in various case studies to measure their effectiveness. As Figure 2.17 shows, FHWA PEDSAFE countermeasure groups targeting 12 common pedestrian crash types that are aligned with the Pedestrian and Bicycle Crash Analysis Tool (PBCAT): dart/dash, multiple threat/trapped, unique midblock, through vehicle at un-signalized intersection, bus-related, turning vehicle, through vehicle at signalized location, walking along roadway, working or playing in roadway, non-roadway, backing vehicle, and crossing expressway (FHWA, 2013a).

- **Countermeasures along the roadway** include sidewalks, walkways, paved shoulders, street furniture, walking environment.

- **Countermeasures at crossing locations** include curb ramps, marked crosswalks and enhancements, curb extensions, crossing islands, raised pedestrian crossings, lighting and illumination, parking restrictions (at crossing locations), pedestrian overpasses/underpasses, automated pedestrian detection, leading pedestrian interval, advance yield/stop lines.

- **Transit-related countermeasures** include transit stop improvements, access to transit, bus bulb outs.

- **Roadway design countermeasures** include bicycle lanes, lane narrowing, lane reduction (road diet), driveway improvements, raised medians, one-way/two-way street conversions, and improved right-turn slip-lane design.

- **Intersection design countermeasures** include roundabouts, modified T-intersections, intersection median barriers, curb radius reduction, modified skewed intersections, pedestrian accommodations at complex interchanges.

- **Traffic calming countermeasures** include temporary installations for traffic calming, chokers, chicanes, mini-circles, speed humps, speed tables, gateways, landscaping, specific paving treatments, serpentine design.

Crash Type	Along Roadway	Crossing Locations	Transit	Roadway Design	Intersection Design	Traffic Calming	Traffic Mgmt.	Signals/ Signs	Other
Dart/Dash	X	X	X	X		X	X	X	
Multiple Threat/Trapped		X	X	X	X	X		X	X
Unique Midblock		X		X		X		X	X
Through Vehicle at Unsignalized Location		X	X	X	X	X		X	X
Bus-Related	X	X	X	X				X	X
Turning Vehicle		X	X	X	X	X	X	X	X
Through Vehicle at Signalized Location		X	X	X	X	X	X	X	X
Walking Along Roadway	X	X	X	X				X	X
Working or Playing in Roadway	X	X		X		X	X	X	X
Non-Roadway	X	X		X	X	X		X	X
Backing Vehicle	X	X		X		X			X
Crossing an Expressway		X						X	X

Figure 2.17 FHWA PEDSAFE Countermeasure Groups Related to Pedestrian Crash Types.
Source: FHWA (2013a)

- **Traffic management countermeasures** include diverters, full street closure, partial street closure, left turn prohibitions.

- **Signals and signs countermeasures** include traffic signals, pedestrian signals, pedestrian signal timing, traffic signal enhancements, right-turn-on-red restrictions, advanced stop lines at traffic signals, left turn phasing, push buttons and signal timing, pedestrian hybrid beacon, rectangular rapid flash beacon, puffin crossing, signing.

- **Other countermeasures** include school zone improvement, neighborhood identity, speed-monitoring, on-street parking enhancements, pedestrian/driver education, police enforcement, automated enforcement systems, pedestrian streets/malls, work zones and pedestrian detours, pedestrian safety at railroad crossings, shared streets, streetcar planning and design.

FHWA (2013b) Roadway Departure (RWD) Strategic Plan

The roadway departure strategic plan focuses on reducing national roadway departure fatalities.

- **Countermeasures that keep vehicles on the roadway, in their appropriate directional lane:** Improved curve delineation, Friction treatments in curves and other spot locations; and edge line and shoulder rumble strips.
- **Countermeasures that reduce the potential for crashes when vehicles do leave the roadway or cross into opposing traffic lanes**: The Safety Edge for all paving projects; Maintained clear zones; Traversable roadside slopes.
- **Countermeasures that minimize the severity of those crashes that do occur:** Design and placement of barriers in medians.

FHWA (2012) Manual on Uniform Traffic Control Devices (MUTCD) 2009 Edition

When selecting engineering countermeasures, it is important to keep in mind that any traffic control devices on roads open to public must comply with the MUTC. The MUTCD is "recognized as the national standard for all traffic control devices installed on any street, highway, bikeway, or private road open to public travel" (FHWA, 2012b). Pedestrian and bicycle safety countermeasures currently available in the MUTCD include, for example:

- Pedestrian islands and medians, pedestrian hybrid beacons, pedestrian signal heads, pedestrian intervals and signal phases, countdown pedestrian signals, pedestrian detectors, in-roadway warning lights at crosswalks, 'yield here to pedestrians' signs, 'stop here for pedestrians' sign, in-street and overhead pedestrian crossing signs, traffic signal pedestrian actuation signs, and pedestrian considerations for temporary traffic control.
- Markings for bicycle lanes, bicycle detectors, shared lane markings, signal operations for bicycles, bike lane signs, 'yield here to bikes' sign, shared-use path, bicycle surface condition warning, bicycle guide and route signs, bicycles may use full lane, and traffic signal bicycle actuation signs.

The MUTCD also defines factors for justifying traffic control signals, including pedestrian volume, school crossing and crash experience.

Since the transportation needs are constantly changing, FHWA considers interim approvals "based on the results of successful experimentation, studies, or research, and an intention to place the new or revised device into a future rulemaking process for MUTCD revisions" (FHWA, 2018a). As of December 2018, interim approvals valid under the 2009 MUTCD related to pedestrian and bicycle treatments include:

- Optional Use of Pedestrian-Actuated Rectangular Rapid-Flashing Beacons at Uncontrolled Marked Crosswalks
- Optional Use of Two-Stage Bicycle Turn Boxes
- Optional Use of an Intersection Bicycle Box
- Optional Use of a Bicycle Signal Face
- Optional Use of Green Colored Pavement for Bike Lanes

FHWA (2011) Intersection Safety: A Manual for Local Rural Road Owners

This report describes intersection-related countermeasures based on the type of crash related.

- **Enhanced Sign and Pavement Marking Improvements:** Installation recommended for intersection locations experienced a high or moderate level of crashes. Two stop signs (mounted left and right); Painted Stop Bar; Double Arrow Bar at a three-leg T-intersection; Intersection Ahead warning signs (mounted left and right); Street name plaques underneath each intersection warning sign; installation of edge line and centerline pavement markings; word STOP painted on the roadway before the stop bar.

NCHRP (2008) Report 500 Series: A Guide for Reducing Collisions Involving Bicycles

This NCHRP report lists the following categories of bicycle safety countermeasures (Raborn et al., 2008):

- **Countermeasures that reduce bicycle crashes at intersections:** visibility improvements at intersections; bicycle signal timing; bicycle presence detectors; regulatory and warning signs; pavement markings at intersections; intersection geometry; right-turn-on-red restrictions; roundabouts; bicycle overpasses and underpasses.
- **Countermeasures that reduce bicycle crashes along roadways:** bicycle lane striping; shared lane marking; paved shoulder; colored pavement marking; contraflow bicycle lanes;

lighting; shared roadway signage; special bicycle-related signage; bicycle route signage; bicycle-tolerable rumble strips.

- **Countermeasures that reduce motor vehicle speeds**: traffic calming; speed enforcement.
- **Countermeasures that reduce bicycle crashes at midblock crossings:** establishing minimum spacing between driveways; providing for right-in, right-out only driveway movements; locating signals to favor through movements; restricting turns at certain intersections; using non-traversable medians to manage left- and U-turn movements.
- **Countermeasures that improve safety awareness and behavior:** bicyclist skill education; enforcement of bicycle-related laws.
- **Countermeasures that increase use of bicycle safety equipment:** increase use of bicycle helmets; reflective and retroreflective clothing; lights on bicycle.
- **Countermeasures that reduce effect of hazards:** treatments of surface irregularities; routine maintenance.

NCHRP (2004) Report 500 Series: Guide for Reducing Collisions Involving Pedestrians.

This report is a part of the *NCHRP Report 500 Series: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan* and groups pedestrian safety countermeasures in four categories (Zegeer et al., 2004):

- **Countermeasures that reduce exposure to vehicular traffic:** sidewalks; walkways, curb ramps; bollards and protective barriers; traffic signal; pedestrian signals; pedestrian signal timing; accessible pedestrian signals; signal enhancements; right-turn-on-red restrictions; raised medians; crossing islands; diverters; partial street closure; full street closure; pedestrian street; pedestrian overpasses and underpasses.
- **Countermeasures that improve sight distance and/or visibility between motor vehicles and pedestrians:** crosswalk enhancements; lighting and crosswalk illumination; sight distance; parking; utility poles, signs, and street furniture; advance yield markings and signs for crosswalks; pedestrian-activated yellow beacons; electronic signs that indicate the direction pedestrians are crossing; in-pavement lighted markings at uncontrolled crossings
- **Countermeasures that reduce vehicle speed:** road narrowing measures; serpentine street; chicane; choker; speed humps and speed tables; woonerf; curb radius reduction; mini-circle; curb-extension; raised intersection; modern roundabout; school route improvements.

- **Countermeasures that improve pedestrian and motorist safety awareness and behavior:** educational campaigns and programs; public awareness campaigns; campaigns to targeted groups and settings; individual campaigns.

2.5.2 Summary of Enforcement and Policy Countermeasure Practices

Enforcement laws and policy countermeasures are implemented in combination with engineering countermeasures to be more effective. Some of the best practices are summarized in this section.

Automated enforcement systems for red lights offenses and speed monitoring

The City of Chicago currently uses red-light cameras in several intersections throughout the city, with the purpose of increasing safety by reducing crashes from re-light runs at intersections. The city has been using the cameras since 2003 and new cameras are installed at intersections with high crash frequency or severity. A public community meeting is held before any camera is installed, removed, or relocated (City of Chicago, 2020a) Although, Texas legislature approved in 2019 a law that prohibits the use of red-light cameras or photographic enforcement systems. However, it does allow the municipalities that had already a contract to continue using cameras until the end of their contract (TxDOT, 2020a).

Another automated enforcement system is the “Children’s Safety Program & Automated Speed Enforcement” adopted in Chicago. The goal is to reduce crashes between motor vehicles and pedestrians, especially in school and park zones. The program uses cameras to ticket drivers who exceed the speed limits (City of Chicago, 2020b).

Police enforcement

Indiana law enforcement allocates resources in areas with higher anticipated risk of crashes and therefore reduces response time. The Indiana Crash Risk Map is an application that predicts the likelihood of crashes across the state on a 1-kilometer-by-1-kilometer grid, as Figure 2.18 shows. Daily predictions based on weather, traffic, road conditions, historical crash data, and Census data, are available for three-hour time windows (e.g., 12am-3am, 3am-6am). The map shows areas with high/medium/low/very low crash risk, and prior crash locations.

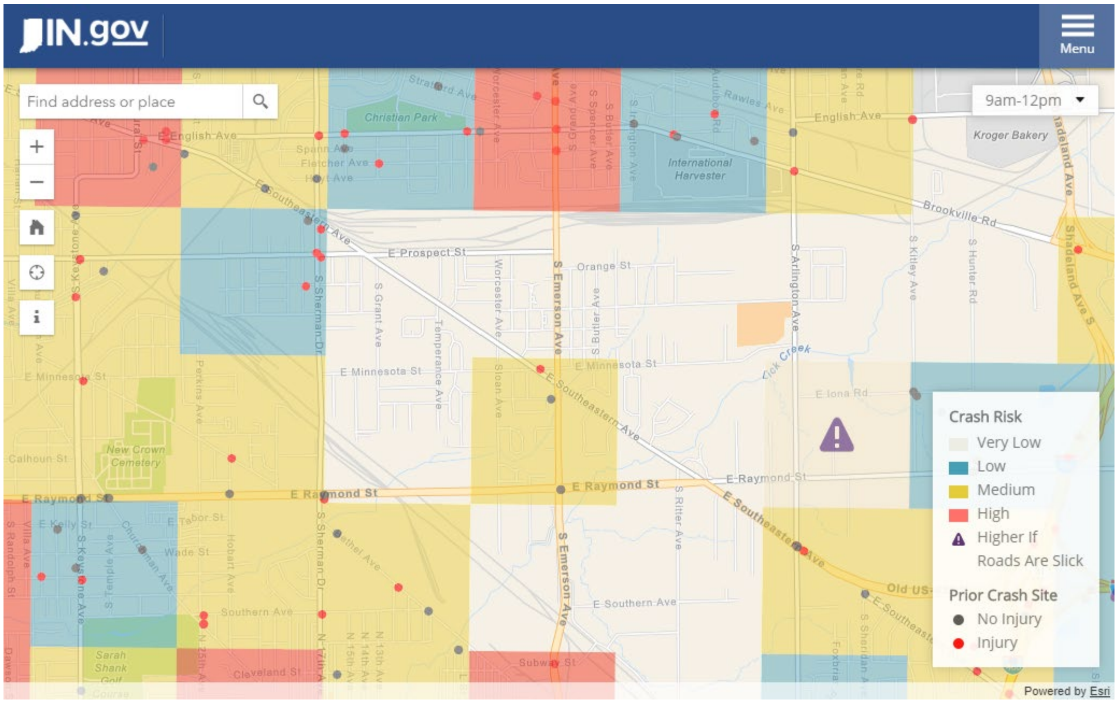


Figure 2.18 Indiana Crash Risk Map.
Source: State of Indiana (2019)

In Texas, there are various laws and policies to reduce crashes and improve safety. For example, in 2017 Texas lawmakers approved a law to prohibit the use of cell phone while operating a motor vehicle (TxDOT, 2020b). In 2002, Texas launched a campaign called “Click It or Ticket” to encourage people use the seat belt and increase the chances of surviving when involved in a crash accident (TxDOT, 2020c).

USLIMITS2

USLIMITS2 is a web tool designed by the FHWA to guide agencies in setting of speed limits. It can be used in all types of roads (rural/urban, from residential to freeways) except for school and construction zones. The objective of this tool is to assist communities establishing safe and appropriate speed limits for their roads. (FHWA, n.d.-b) Arizona DOT mentions USLIMITS2 on its 2017 Pedestrian Safety Action Plan (Arizona DOT, 2017) as a good tool to help reduce crashes between motorized vehicles and pedestrians and suggests train agency staff to use the tool.

Safe passing laws

Florida’s Driver License Handbook specifies that while driving in a shared lane an individual must drive three feet away from a bicycle (FDOT, 2018). However, in Texas, there have been several attempts to establish that "'safe distance' for passing bicyclists is at least 3 feet, but it always failed (2009, 2011, 2013)” (Bike Texas, 2020a).

Local road safety plan

Local road safety plans provide a framework to prioritize safety improvements on local and rural roads, to help reduce fatalities and serious injuries rates. For example, in Nevada county in California, in the past 3 years 1% of the crashes on local roadways resulted in fatalities, therefore the 2019 Nevada County Local Road Safety Plan was adopted aiming to reduce fatality rates and achieve zero fatalities (Nevada County, 2019).

Neighborhood identity

Fostering identity development in a neighborhood can create a safe and attractive environment for pedestrians and bicyclist (FHWA, 2013a). Features such as gateways, welcome signs, decorative street lighting, flower planters, banners among others are useful for this purpose. In Tempe, Arizona, neighborhood identity was used to reduce traffic volume passing through 5th Street (FHWA, 2013b). With help from the federal government, the city was able to implement narrowed lanes and traffic chokers besides wider sidewalks and new bicycle lanes. After the implementation of these countermeasures, the city achieved a daily traffic volume reduction from 10,000 vehicles to 6,000 vehicles.

2.5.3 Summary of Educational Countermeasure Practices

Examples of educational countermeasures adopted in Texas include the "Drive Kind Ride Kind" campaign (Drive Kind Ride Kind, n.d.) targeting drivers to increase awareness about pedestrians and bicyclists. An interactive education program "Texas in Motion" is a game for children to learn about basic bicycle safety (Bike Texas, 2020b). "Look Out Texans" is a regional safety and education campaign in North Central Texas (NCTCOG, n.d.-a). On the federal level, the educational materials include "Pedestrian Safer Journey" and "Bicycle Safer Journey" (FHWA, n.d.-c) programs to educate the people using videos and quizzes.

Educational materials

Measures adopted in New York City include the distribution of "Bike Smart: The Official Guide to Cycling in NYC" which is available in multiple languages and includes general bicycle safety rules, see Figure 2.19. For example, correct use of helmet, rear/front bike lights use of reflective clothing. The city also organizes events where besides teaching how to properly fit and wear a helmet, distribute free helmets to the assistants of the event (NYC, 2020).

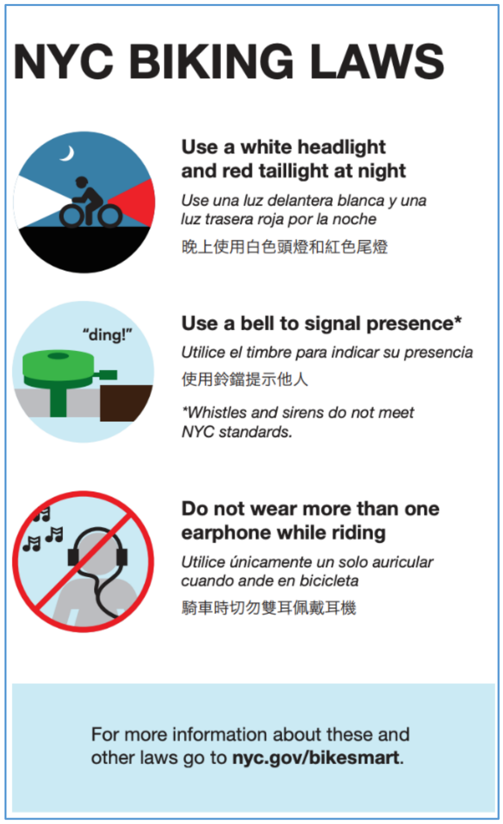


Figure 2.19 Example of NYC Bike Laws.
Source: NYC (2020)

Driver Handbook education

A number of states including Oregon, New York, California, and Florida among others have in their driver's handbook how to deal with pedestrians and bicycles in a safe way. It is very important that the educational information provided is updated with the evolution of new countermeasures and safety procedures. For example, Oregon DOT explains specific situations that drivers may encounter with pedestrians and bicyclists (ODOT, 2018). An example of this countermeasure is to watch for pedestrians in the crosswalks when making turns, double-check the "blind spots" before turning or open a door, share the road correctly, and leave space between cyclists and vehicles. Figure 2.20 shows the types of crosswalks where a motorist is expected to yield the right of way to non-motorized users, including an unmarked crosswalk at every intersection.

Figure 2.20 Types of Crosswalks in Oregon's Driver Handbook.
Source: Oregon DMV (2018)

Florida DOT provides in their handbook instructions on how to share the road correctly with bicyclists. For example, bicycles are legally defined as vehicles, and a bicyclist may leave the bike lane and use the normal lane to avoid any hazards that may appear in the bike lane (FDOT, 2018).

New York DOT considers pedestrians and skateboarders as high-risk traffic and encourage the drivers to have special care when making a turn and look for any person crossing the street. It also encourages drivers to learn how to share the road with bicyclists and in-line skaters, check blind spots, reduce speed when passing them, and provide enough space to avoid crashes (NYDMV, 2018).

As technology evolves, it is important to properly educate pedestrians and pedalcyclist to deal with any new challenges that may arise. For example, hybrid cars do not emit any sound which is how pedestrians sometimes notice the presence of vehicles, and this is even a critical issue for visually impaired individuals. California's Driver Handbook addresses this new challenge through educational information, especially for pedestrians, including blind and visually impaired pedestrians when crossing a street. It suggests drivers of hybrid or electric vehicles pay special attention to pedestrians with canes since "the lack of engine or electric motor noise may cause a blind pedestrian to assume there is not a vehicle nearby" (CaDMV, 2018).

School zone education

California's Driver Handbook (CaDMV, 2018) and Oregon's Driver Handbook (Oregon DMV 2018) explains how to determine school zone boundaries, how to behave on it with recommendations for school signs, speed limits, and other safety tips on how to drive near schools.

2.5.4 TxDOT's Safety Countermeasures and Strategies

The ***Texas Strategic Highway Safety Plan 2017-2022 (SHSP)*** represents an effort to reduce crashes, fatalities, and injuries. The SHSP is structured around seven emphasis areas: distracted driving, impaired driving, intersection safety, older road users, pedestrian safety, roadway and lane departures, and speeding. Appendix C of the SHSP includes a list of strategies and countermeasures for each of the emphasis areas. Federal Highway Administration offers a webpage including countermeasures for pedalcyclist and pedestrian see (FHWA, 2013a) and (FHWA, 2014). The following SHSP strategies are related to pedestrian and bicyclist safety improvements (TxDOT, 2017):

- Improve pedestrian safety at intersections with high probability of crashes
- Design and operate roadways to meet the needs of older road users
- Implement methods to reduce injury severity among older road users
- Improve driver and pedestrian safety awareness and behavior

- Reduce pedestrian crashes on urban arterials and local roadways
- Improve pedestrians' visibility at crossing locations
- Improve pedestrian networks
- Improve pedestrian involved crash reporting
- Establish vehicle operating speeds to decrease crash severity
- Develop strategic pedestrian safety plans tailored to local conditions
- Use the concept of establishing target speed limit and road characteristics to reduce speeding
- Leverage data to improve engineering, education, and enforcement

TxDOT Highway Safety Improvement Program Manual (TxDOT, 2015) distinguishes between preventable and non-preventable crashes. If roadway countermeasures reduce the crash risk of a contributing factor, then these crashes are classified as preventable. The ***2018 Highway Safety Improvement Program Call*** lists the following countermeasures aimed for preventing pedestrian and bicycle crashes that are eligible for Federal Highway Safety Improvement Program funds (TxDOT, 2018):

- Install sidewalks
- Improve school zone
- Safety lighting
- Install pedestrian crosswalk
- Pedestrian hybrid beacon
- Replace flashing beacon with a traffic signal
- Install traffic signal
- Improve traffic signals
- Install pedestrian signal
- Improve pedestrian signals
- Safety lighting at intersection
- Construct pedestrian over/under pass

The HSIP Work Codes Table defines a crash reduction factor, service life, maintenance cost each countermeasure, as well as the type of crash that it aims to prevent. Table 2.9 shows an example of the HSIP Work Codes Table for one of the HSIP countermeasures, pedestrian hybrid beacon.

Table 2.9 Example of a HSIP Work Codes Table for a Pedestrian Hybrid Beacon.

143	Pedestrian Hybrid Beacon	
	Definition:	Provide pedestrian hybrid beacon at established crosswalk
	Reduction Factor (%):	15
	Service Life (Years):	10
	Maintenance Cost:	$2,100
	Preventable Crash:	First Harmful Event = 1

Note: From TxDOT (2018).

A previous TxDOT research study investigated the effectiveness of pedestrian treatments. Fitzpatrick, Avelar, & Turner (2018) found that 98% of drivers yielded to pedestrians at intersections controlled by traffic signals, while the yielding rate for pedestrian hybrid beacons and rectangular rapid-flashing beacons was 89% and 86%, respectively.

CHAPTER 3. PEDESTRIAN AND BICYCLE CRASH DATABASE

3.1 Description of Bicycle and Pedestrian Crash Database

This section describes how the pedestrian and bicycle crash database created in this project was populated for statistical analysis.

The database includes data fields from the Pedestrian and Bicycle Crash Analysis Tool (PBCAT) Version 2.0 (FHWA, 2006), as well as notable peer practices identified during this project. As Figure 3.1 shows, the database was created based on data from three major sources:

- CR-3 crash report form PDF files summarizing crash investigation by a police officer, including a diagram of the crash and narrative how crash occurred,
- CRIS Automated Crash Data Public Extract (TxDOT, 2017) which is a CSV file containing data from the CR-3 crash report forms, and
- Secondary GIS data sources including roadways, bikeways, Strava Metro, U.S. Census, location of transit stops, parks, and schools, as well as land use.

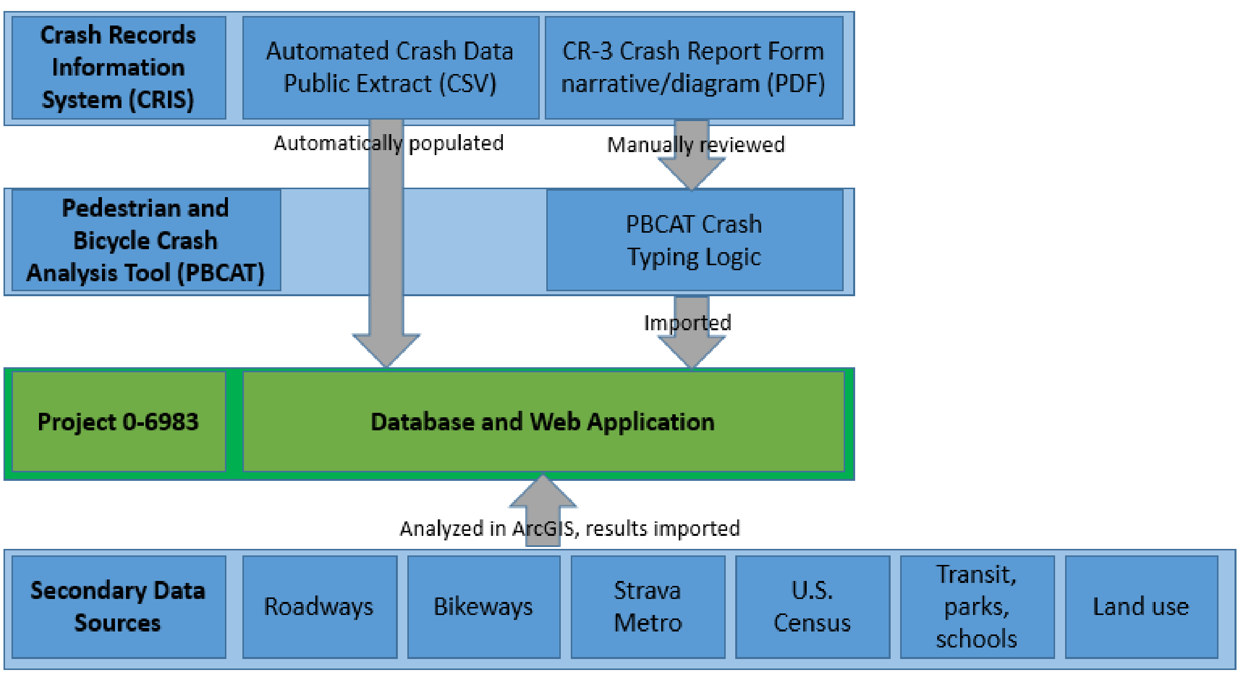


Figure 3.1 Data Sources for 0-6983 Pedestrian and Bicycle Crash Database.

The CRIS Automated Crash Data Public Extract CSV files and secondary GIS data sources were used to populate the pedestrian and bicycle crash database. It is organized into 13 topics, following the PBCAT manual: principal information, location, area characteristics, environmental conditions, roadway features, bicycle facility, driver information, vehicle information, pedestrian information, pedalcyclist information, contributing factors and citations, PBCAT crash typing, and secondary GIS data.

A majority of the database fields were populated from the CRIS Automated Crash Data Public Extract, however for some fields (such as the development type, bicycle facility presence, curb lane width, paved shoulder width), researchers performed geospatial queries in ArcGIS with the secondary GIS data sources and then added the results to the database. The research team then manually reviewed narrative and diagram in CR-3 crash report forms in order to identify information for fields related to pedestrian (position, direction, unique characteristic), pedalcyclist (position, direction), and motorist (direction, maneuver) which were the inputs for PBCAT crash types. Chapter 3 includes a description how the CR-3 crash report forms were reviewed.

The research team aimed to find the closest match between the PBCAT data elements and data in the CRIS Automated Crash Data Public Extract. For example, PBCAT uses the following five values for data field *"Surface conditions"*: dry, wet, snow/ice, other, unknown. This field was matched with column *"Surf_Cond_ID"* from the CRIS Automated Crash Data Public Extract, where possible values are: dry, wet, standing water, slush, ice, other, snow, sand/mud/dirt, reported invalid, not reported.

Voluntary guidelines for crash data collection, the ***Model Minimum Uniform Crash Criteria (MMUCC)*** by the National Highway Traffic Safety Administration (NHTSA, 2017a) were compared with the data elements that are currently collected in Texas in order to identify any potential improvements that could make PBCAT crash typing easier. The recommendations are summarized in Section 3.1.13.

An overview of the web application and the geodatabase that includes data gathered during this project can be found in *Technical Memorandum 4 Appendix A*. The following section focuses on the process of populating PBCAT fields from existing data sources that were identified during this project.

3.1.1 Principal Information

Principal information about a crash includes report number, date and time when the crash occurred, number of pedestrians or bicyclists involved in a crash, and a hit and run flag. As shown in Table 3.1, all data is available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019).

Table 3.1 Principal Information.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Report number	Crash ID (crash_id)	CRIS Data Extract	Crash_ID
Date of crash	Crash date (crash_date)	CRIS Data Extract	Crash_Date, Crash_Time
Time of day			
Number of pedestrians	Number of pedestrians	CRIS Data Extract	counting Prsn_Type_ID=4
Number of bicyclists	Number of bicyclists	CRIS Data Extract	counting Prsn_Type_ID=3
Hit and run	Hit and run (hit_run)	CRIS Data Extract	Veh_HNR_FI

3.1.2 Location

Location information includes city, county, street or route number, reference street number, and latitude and longitude. As shown in Table 3.2, all data is available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019) except direction and distance from reference street. Since this information is not included in the MMUCC recommendations, it is not included in the database for 0-6983. The research team observed differences between the crash location determined by the latitude and longitude and the locations showed in the crash report diagram, as discussed in *Technical Memorandum 4 Appendix B*.

Table 3.2 Location.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Jurisdiction	City (city_cityId)	CRIS Data Extract	City_ID
	County (county_countyId)	CRIS Data Extract	Cnty_ID
Route/Street name	Route/Street name (street_name_1)	CRIS Data Extract	Street_Name
Route/Street number	Route/Street number (street_num_1)	CRIS Data Extract	Street_Nbr
Reference street	Reference street name (street_name_2)	CRIS Data Extract	Street_Name_2
	Reference street number (street_num_2)	CRIS Data Extract	Street_Nbr_2
Direction from reference street	-	Not available	-
Distance from reference street	-	Not available	-
GPS longitude	Latitude (latitude)	CRIS Data Extract	Latitude
GPS latitude	Longitude (longitude)	CRIS Data Extract	Longitude

3.1.3 Area Characteristics

Area characteristics include the area type (rural, small urban, etc.), development type, and a presence of a school zone. As Table 3.3 indicates, the data is sourced from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019) as well as from GIS files provided by the North Central Texas Council of Governments (NCTCOG). MMUCC recommends collecting information about traffic control devices, including: school zone sign, flashing school zone signal, school zone pavement marking (NHTSA, 2017a).

Table 3.3 Area Characteristics.

PBCAT Field	**0-6983 Web Application (geodatabase field)**	**Populated from Data Source**	**Column in Data Source**
Type of area	Type of area (rural_urban_type_id)	CRIS Data Extract	Rural_Urban_Type_ID
Development type	Development type (development_type)	NCTCOG 2015_Land_Use	column CATEGORY
School zone	School zone (school_zone)	CRIS Data Extract	Active_School_Zone_FI

3.1.4 Environmental Conditions

Environmental conditions include weather, surface condition, and light condition. As shown in Table 3.4, all data is available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019).

Table 3.4 Environmental Conditions.

PBCAT Field	**0-6983 Web Application (geodatabase field)**	**Populated from Data Source**	**Column in Data Source**
Weather conditions	Weather conditions (weather_WeatherID)	CRIS Data Extract	Wthr_Cond_ID
Surface conditions	Surface condition (surfCond_SurfCondID)	CRIS Data Extract	Surf_Cond_ID
Light conditions	Light conditions (lightCond_conditionId)	CRIS Data Extract	Light_Cond_ID

3.1.5 Roadway Features

Roadway features include the number of through lanes, roadway classification, roadway type, roadway alignment, roadway surface, traffic control, speed limit, and presence of marked crosswalks or sidewalks. As Table 3.5 indicates, the data is sourced from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019) as well as from GIS files provided by the NCTCOG. MMUCC recommends collecting information about roadway defects, such as debris, ruts, holes, bumps, or worn surface under ‘Contributing Circumstances – Roadway Environment’ (NHTSA, 2017a). MMUCC recommends also to include a mandatory field in the crash report for collecting information about ‘Non-motorist Location at the Time of Crash’: intersection – marked crosswalk, intersection – unmarked crosswalk, midblock – marked crosswalk, sidewalk (NHTSA, 2017a).

Table 3.5 Roadway Features.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
No of through lanes	No of through lanes (lane_num)	CRIS Data Extract	Nbr_Of_Lane
Roadway type	Road Classification (rdwy Class_classificationId)	CRIS Data Extract	Road_Cls_ID
Roadway configuration	Roadway type (rdwyType_RdwyTypeId)	CRIS Data Extract	Road_Type_ID
Roadway terrain Roadway alignment	Roadway alignment (rdwyAlgn_alignmentId)	CRIS Data Extract	Road_Algn_ID
Roadway surface	Roadway surface type (surfType_SurfaceTypeID)	CRIS Data Extract	Surf_Type_ID
Roadway defects	Roadway defects	Not available	
Traffic control	Traffic control (traffCntrl_controlId)	CRIS Data Extract	Traffic_Cntl_ID
Speed limit	Speed limit (crash_speed)	CRIS Data Extract	Crash_Speed_Limit

3.1.6 Bicycle Facility

Bicycle facility information includes bicycle facility presence, curb lane width, and paved shoulder width. As Table 3.6 shows, the data is sourced from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019) and the Annual Roadway Inventory (TxDOT, 2017). PBCAT offers the opportunity to include information about the type of bicycle (adult/child two-wheel/tricycle/other/recumbent/motorized) and bicycle defects (brakes, lights, tires), however no such recommendation was found in MMUCC. For bicycle facility presence, MMUCC recommends distinguishing between the following bicycle facilities: marked bicycle lane, separate bicycle path/trail, unmarked paved shoulder, wide curb lane, unknown, signed bicycle route yes/no, none (NHTSA, 2017a).

Table 3.6 Bicycle Facility.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Bicycle type	-	Not available	-
Bicycle defects	-	Not available	-
Bicycle facility presence	Bicycle facility presence and distance to (bike_facil_pres, bike_facil_dist)	NCTCOG GIS file	column COG_Facili
Curb lane width	Lane width (lane_width)	TxDOT_Roadway_Line work 2017	column LANE_WIDTH
Bike lane / paved shoulder width (paved_shldr_width)	Paved shoulder width	TxDOT_Roadway_Line work 2017	S_WID_O

3.1.7 Driver Information

Driver information includes driver age, gender, race, alcohol or drug use, injury severity, and in case of a motorcyclist, whether the driver wore a helmet. As shown in Table 3.7, all data is available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019), except the date of birth which is substituted by age.

Table 3.7 Driver Information.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Driver date of birth	-	Substituted by age	-
Driver age	Driver Age (age)	CRIS Data Extract	Prsn_Age
Driver gender	Driver Gender (gender_PersonGenderID)	CRIS Data Extract	Prsn_Gndr_ID
Driver race	Driver Ethnicity (ethn_PersonEthnID)	CRIS Data Extract	Prsn_Ethnicity_ID
Driver alcohol/drug use	Driver Alcohol (alch_PersonAlcoholID)	CRIS Data Extract	Prsn_Alc_Rslt_ID
	Driver Drug (drug_PersonDrugID)	CRIS Data Extract	Prsn_Drg_Rslt_ID
Driver injury severity	Driver Injury (injuryPersonInjuryID)	CRIS Data Extract	Prsn_Injry_Sev_ID
	Driver Helmet (hlmt_PersonHelmetID)	CRIS Data Extract	Prsn_Helmet_ID

3.1.8 Vehicle Information

Vehicle information includes the vehicle body type, vehicle description, as well as any defects noted in the police crash report. As shown in Table 3.8, all data is available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019), except for the estimated original vehicle speed and estimated speed at impact. MMUCC recommends collecting information about the 'Motor Vehicle Posted/Statutory Speed Limit' (NHTSA, 2017a)*,* which is included under Roadway Features earlier in this Chapter.

Table 3.8 Vehicle Information.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Motor vehicle type	Vehicle Body (vehBody_vehBodyId)	CRIS Data Extract	VEH_BODY_STYL_ID
	Vehicle Description (desc_descriptionId)	CRIS Data Extract	Unit_Desc_ID
Motor vehicle defects	Defects (vehicleDefectsDefectId)	CRIS Data Extract	VEH_DFCT_ID
Estimated original vehicle speed	-	Not available	-
Estimated speed at impact	-	Not available	-

3.1.9 Pedestrian Information

Pedestrian information includes pedestrian age, gender, race, alcohol or drug use, and injury severity. As shown in Table 3.9, all data is available from the CRIS Automated Crash Data Public

Extract files (TxDOT, 2019), except the date of birth which is substituted by age. MMUCC recommends collecting information about the 'Person Type' (driver, passenger, occupant of MV not in transport, bicyclist, other cyclist, pedestrian, other pedestrian – wheelchair/skater/personal conveyance, occupant of a non-motor vehicle transportation device, unknown type of non-motorist, unknown) which is similar to 'Unique Ped Characteristic' in PBCAT.

Table 3.9 Pedestrian Information.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Pedestrian date of birth	-	Substituted by age	
Pedestrian age	Pedestrian Age (age)	CRIS Data Extract	Prsn_Age
Pedestrian gender	Pedestrian Gender (gender_PersonGenderID)	CRIS Data Extract	Prsn_Gndr_ID
Pedestrian race	Pedestrian Ethnicity (ethn_PersonEthnID)	CRIS Data Extract	Prsn_Ethnicity_ID
Pedestrian alcohol/drug use	Pedestrian Alcohol (alch_PersonAlcoholID)	CRIS Data Extract	Prsn_Alc_Rslt_ID
	Pedestrian Drug (drug_PersonDrugID)	CRIS Data Extract	Prsn_Drg_Rslt_ID
Pedestrian injury severity	Pedestrian Injury (injuryPersonInjuryID)	CRIS Data Extract	Prsn_Injry_Sev_ID
Unique ped characteristic	Unique ped characteristic (ped_charac)	Police Crash Report	Narrative

3.1.10 Pedalcyclist Information

Pedalcyclist information includes pedalcyclist age, gender, race, alcohol or drug use, and injury severity. As shown in Table 3.10, all data is available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019) except the date of birth which is substituted by age.

Table 3.10 Pedalcyclist Information.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Bicyclist date of birth	-	Substituted by age	
Bicyclist age	Pedacyclist Age (age)	CRIS Data Extract	Prsn_Age
Bicyclist gender	Pedacyclist Gender (gender_PersonGenderID)	CRIS Data Extract	Prsn_Gndr_ID
Bicyclist race	Pedacyclist Ethnicity (ethn_PersonEthnID)	CRIS Data Extract	Prsn_Ethnicity_ID
Bicyclist alcohol/drug use	Pedacyclist Alcohol (alch_PersonAlcoholID)	CRIS Data Extract	Prsn_Alc_Rslt_ID
	Pedacyclist Drug (drug_PersonDrugID)	CRIS Data Extract	Prsn_Drg_Rslt_ID
Bicyclist injury severity	Pedacyclist Injury (injuryPersonInjuryID)	CRIS Data Extract	Prsn_Injry_Sev_ID
Bicyclist helmet use	Pedacyclist Helmet (hlmt_PersonHelmetID)	CRIS Data Extract	Prsn_Helmet_ID

3.1.11 Contributing Factors and Citations

Contributing factors and citations are available from the CRIS Automated Crash Data Public Extract files (TxDOT, 2019) as Table 3.11 shows. Fault is not included in the database, due to inconsistent data availability; some police crash reports mention in the narrative who was at fault, however the majority of these reports do not include any information about who was at fault. Also, fault is not among the minimum recommended fields in the MMUCC (NHTSA, 2017a), however it is recommended to collect information about 'Driver Actions at Time of Crash' and—for all drivers and non-motorists—'Distracted By', which includes both the actions (not distracted, listening/talking, manually operating, other action, unknown) and the sources of distraction (hands-free mobile phone, hand-held mobile phone, other electronic device, vehicle-integrated device, passenger/other non-motorist, external, other distraction, not applicable, unknown).

Table 3.11 Contributing Factors and Citations.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Driver contributing factors	Contributing Factors (table contributing_factors)	CRIS Data Extract	CONTRIB_FACTR_ID (Prsn_Type_ID=1)
Pedestrian contributing factors	Contributing Factors (table contributing_factors)	CRIS Data Extract	CONTRIB_FACTR_ID (Prsn_Type_ID=4)
Bicyclist contributing factors	Contributing Factors (table contributing_factors)	CRIS Data Extract	CONTRIB_FACTR_ID (Prsn_Type_ID=3)
Driver/pedestrian/bicyclist citation	Unit Number Charged (units_num)	CRIS Data Extract	UNIT_NBR
	Person Number Charged (person_num)	CRIS Data Extract	PRSN_NBR
	Charge Desc (charge)	CRIS Data Extract	CHARGE
Fault	-	Not available	-

3.1.12 PBCAT Crash Typing

Narratives and diagrams in 10,040 crash reports were reviewed and one of the 56 pedestrian crash types or one of the 79 bicyclist crash types were assigned following the PBCAT methodology (FHWA, 2006). As Table 3.12 shows, additional attributes that were assessed based on the CR-3 form narratives and diagrams included: pedestrian position and direction, as well as bicyclist position and direction. For pedestrian crashes that occurred at intersections, also the leg intersection, motorist maneuver, and scenario were assessed. Chapter 3.2 describes how the narrative and diagram in CR-3 crash report forms was reviewed in order to identify this information.

Table 3.12 PBCAT Crash Typing.

PBCAT Field	0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Crash type number & description	Crash Type Number (crash_type_number)	PBCAT Crash Typing Logic	Crash Type Number
	Crash Type Desc (crash_type_description)	PBCAT Crash Typing Logic	Crash Type Description
Crash group number & description	PBCAT Group Number (crash_group_number)	PBCAT Crash Typing Logic	Crash Group Number
	PBCAT Group Desc (crash_group_description)	PBCAT Crash Typing Logic	Crash Group Description
Crash location	PBCAT Location Desc (crash_loc_desc)	PBCAT Crash Typing Logic, CR-3 form	Crash Location
Pedestrian position	Pedestrian position (pedestrian_position, pedestrian_pos_description)	PBCAT Crash Typing Logic, CR-3 form	Pedestrian Position Description
Pedestrian direction	Pedestrian direction (pedestrian_direction)	PBCAT Crash Typing Logic, CR-3 form	Pedestrian Direction
Bicyclist position	Bicyclist position (bicyclist _pos_description)	PBCAT Crash Typing Logic, CR-3 form	Bicyclist Position Description
Bicyclist direction	Bicyclist direction (bicyclist_dir_description)	PBCAT Crash Typing Logic, CR-3 form	Bicyclist Direction Description
Motorist direction	Motorist direction (motorist_direction)	PBCAT Crash Typing Logic, CR-3 form	Motorist Direction
Motorist maneuver	Motorist maneuver (motorist_maneuver)	PBCAT Crash Typing Logic, CR-3 form	Motorist Maneuver
Leg intersection	Leg intersection (leg_intersection)	PBCAT Crash Typing Logic, CR-3 form	Leg Intersection
Scenario	Scenario (scenario)	PBCAT Crash Typing Logic, CR-3 form	Scenario
Crash type expanded	PBCAT Type Expanded (crash_type_expanded)	PBCAT Crash Typing Logic	Crash Type Expanded
Crash group expanded	PBCAT Group Expanded (crash_group_expaned)	PBCAT Crash Typing Logic	Crash Group Expanded

3.1.13 MMUCC Recommendations

MMUCC voluntary guidelines (NHTSA, 2017a) recommend including various data elements in crash reports and those that could potentially benefit pedestrian and bicycle crash analysis efforts in Texas are summarized in the following tables.

Table 3.13 shows the data elements that MMUCC recommends completing for every crash that involved a non-motorist - a person who was not the driver or a motor vehicle occupant. Non-motorist person type includes bicyclists, other cyclists, pedestrians, other pedestrians (wheelchair, skater, personal conveyance), occupants of a non-motor vehicle transportation device, and unknown types of non-motorists (NHTSA, 2017a). Knowledge of the actions prior to crash and non-motorist's location is important for effective countermeasure selection.

Table 3.13 Non-Motorist Data Elements Recommended by MMUCC.

MMUCC Data Elements	Examples of Values Recommended in MMUCC
Non-motorist action/circumstance prior to crash	**Action/Circumstance**: none, adjacent to roadway, crossing roadway, in roadway-other, waiting to cross roadway, walking/cycling along roadway against/with traffic, walking/cycling on sidewalk, working in trafficway (incident response), other, unknown **Origin/Destination:** going to or from school (K-12), going to or from transit, not applicable, unknown
Non-motorist contributing action(s)/ circumstance(s)	None (no improper action), dart/dash, disabled vehicle-related (working on, pushing, leaving/approaching), entering/exiting parked/standing vehicle, failure to obey traffic signs/signals/officer, failure to yield right-of-way, improper passing, improper turn/merge, inattentive (talking, eating, etc.), in roadway improperly (standing, lying, working, playing), not visible (dark clothing, no lighting, etc.), wrong-way riding or walking, other, unknown.
Non-motorist location at time of crash	**Roadway facility:** intersection-marked crosswalk, intersection-unmarked crosswalk, intersection-other, median/crossing island, midblock-marked crosswalk, shoulder/roadside, travel lane-other location. **Bicycle facility:** signed route, shared lane markings, on-street bike lanes, on-street buffered bike lanes, separated bike lanes, off-street trails/side paths. **Other facility:** driveway access, non-trafficway area, shared-use path or trail, sidewalk, other, unknown.
Non-motorist safety equipment	None, helmet, protective pads used, reflective gear, lighting, reflectors, other, unknown.
Initial contact point on non-motorist	Front, right, rear, left, unknown.

Note: Table from NHTSA (2017a).

Table 3.14 shows data elements recommended by MMUCC related to roadways and vehicles that could be beneficial in pedestrian and bicycle crash analysis.

Table 3.14 Roadway and Vehicle Data Elements Recommended by MMUCC.

MMUCC Data Elements	Examples of Values Recommended in MMUCC
Traffic control device type	**Signs:** bicycle crossing sign, "curve ahead" warning sign, "intersection ahead" warning sign, other warning sign, pedestrian crossing sign, railroad crossing sing, "reduce speed ahead" warning sign, school zone sign, stop sign, yield sign **Signals:** flashing railroad crossing signal, flashing school zone signal, flashing traffic control signal, lane use control signal, other signal, ramp metering signal, traffic control signal) **Pavement markings:** bicycle crossing, other pavement parking (excluding edge lines, center lines, or lane lines), pedestrian crossing, railroad crossing, school zone, other, none)
Presence/type of bicycle facility	**Facility:** none, marked bicycle lane, separate bicycle path/trail, unmarked paved shoulder, wide curb lane, unknown **Signed bicycle route:** no, yes, not applicable, unknown

MMUCC Data Elements	Examples of Values Recommended in MMUCC
Contributing circumstances – roadway environment	None, animal(s), glare, non-highway work, obstructed crosswalks, obstruction in roadway, prior crash, prior non-recurring incident, regular congestion, related to a bus stop, road surface condition (wet, icy, snow, slush, etc.), ruts/holes/bumps, shoulders (none, low, soft, high), toll booth/plaza related, traffic control device, traffic incident, visual obstruction(s), weather conditions, work zone (construction/maintenance/ utility), worn/travel-polished surface, other, unknown
Direction of travel before crash	Not on roadway, northbound, eastbound, southbound, westbound, unknown
Motor vehicle maneuver/action	Backing, changing lanes, entering traffic lane, leaving traffic lane, making U-turn, movements essentially straight ahead, negotiating a curve, overtaking/passing, parked, slowing, stopped in traffic, turning left, turning right, other, unknown

Note: Table from NHTSA (2017a).

In future research projects it is recommended to investigate how pedestrian and bicyclist crash analysis could be automated based on information collected directly on the crash report form and whether PBCAT crash types could be determined based solely on the data elements without the need for manual review of the crash diagram and narrative.

3.1.14 Secondary GIS Data

Crash reports are the primary data source with information about the people and units involved in the crash and their actions prior to crash. Secondary GIS data provide additional context based on data from Roadway Inventory Annual Data, Strava Metro, U.S. Census Bureau, and other local datasets provided by NCTCOG. Table 3.15 shows the datasets and columns that served to populate the 0-6983 Web Application.

Table 3.15 Secondary GIS Data.

0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Speed limit (speed_limit)	Roadway Inventory Annual Data 2017	SPD_MAX
Roadway width (roadway_width)	Roadway Inventory Annual Data 2017	SUR_W
On-street parking presence (strParking_ID)	Roadway Inventory Annual Data 2017	S_USE_I: 1=Diagonal Parking, 2=Parallel Parking
Median type (median_typeID)	Roadway Inventory Annual Data 2017	MED_TYPE
Freight network (freight_net_ID)	Roadway Inventory Annual Data 2017	T FRGHT_NTWRK
Average daily traffic (avg_daily_traffic)	Roadway Inventory Annual Data 2017	ADT_CUR
Average daily truck traffic (avg_truck_traffic)	Roadway Inventory Annual Data 2017	TRK_AADT_PCT
Controlled access facility (access_control)	Roadway Inventory Annual Data 2017	ACES_CTRL

0-6983 Web Application (geodatabase field)	Populated from Data Source	Column in Data Source
Population density (population, population_density_persqmi)	U.S. Census Bureau	Total population, ALAND
Employment density (employment_density_persqmi)	U.S. Census Bureau	PRIM_Jobs_C000, ALAND
Vehicle ownership (vehicle_ownership)	U.S. Census Bureau	Tenure by vehicles available: calculated the percentage of households that do not own any vehicle within a census block group
Worker commute mode-share (commuter_modeshare)	U.S. Census Bureau	Means of transportation to work: calculated the percentage of workers what commute by walking, biking, or transit within a census block group
Signalized intersections (signalized_intersection_distance)	NCTCOG GIS inventory (partial)	Distance in meters to the nearest signalized intersection
Transit stops (transit_stops, transit_stop_dist)	NCTCOG GIS inventory	Captured the number of transit stops within 300 ft. from the crash location and the distance in meters to the nearest transit stop (up to 1 mile search area)
Parks (parks, parks_dist)	NCTCOG GIS inventory	Captured the number of parks within 300 ft. from the crash location and the distance in meters to the nearest park (up to 1 mile search area)
Schools (schools, school_dist)	NCTCOG GIS inventory	Captured the number of schools within 300 ft. from the crash location and the distance in meters to the nearest school (up to 1 mile search area)
Strava bicycle trips (strava_bike)	Strava Metro 2018	TACTCNT in ride_rollup_total (edges)
Strava walking trips (strava_ped)	Strava Metro 2017	TACTCNT in ped_rollup_total (edges)
Pedestrian fatality risk (ped_fatal_pred_yr, ped_fatal_rate)	USDOT 2018	PredYearly, Rate
Social Vulnerability Index (social_vul_index)	CDC 2016	F_total

Roadway characteristics, such as speed limit, roadway width, paved shoulder width, on-street parking presence, median type, freight network, average daily traffic, average daily truck traffic, and control access facility, were identified in the Roadway Inventory Annual Data (TxDOT, 2017).

Population and employment density, vehicle ownership, as well as worker commute mode-share estimates were extracted from U.S. Census Bureau datasets (U.S Census Bureau, 2015, 2017) for census block groups in North Central Texas.

NCTCOG provided local GIS inventories for signalized intersections, parks, schools, land use, and public transit stops including Dallas Area Rapid Transit (DART), Denton County Transportation Authority (DCTA), and Trinity Metro.

Bicycle trips collected by Strava Metro as the total number of trips on the piece of street regardless of direction of travel for a rolled-up date frame during 2018 will be adjusted to Average Annual Daily Bicyclist Traffic (AADB) following an adjustment process outlined in the Guide for

Seasonal Adjustment and Crowdsourced Data Scaling (Dadashova, Griffin, Das, Turner, & Graham, 2018).

Strava walking trips collected by Strava Metro as the total number of trips on the piece of street regardless of direction of travel for a rolled-up date frame during 2017 will be included in the analysis without any adjustments, because an adjustment process for Texas has not been developed yet. To supplement this potential gap in pedestrian exposure, the analysis will also consider indices such as the Pedestrian Fatality Risk (USDOT, 2018b) and the Social Vulnerability Index (CDC, 2016). Mansfield, Peck, Morgan, McCann, & Teicher (2018) analyzed the effects of roadway characteristics and built environment on pedestrian fatality risk in a study for USDOT and estimated the Pedestrian Fatality Risk for every census block group across the nation based on traffic density, public transit and walking commuting, population and employment density, land use diversity, density of auto-oriented intersections, density of multi-modal intersections, as well as sociodemographic data. The Social Vulnerability Index developed by the Centers for Disease Control and Prevention is estimated based on 15 U.S. Census variables, including socioeconomic status, household composition and disability, minority status and language, as well as housing and transportation (Flanagan, Hallisey, Heitgerd, & Lewis, 2011).

Local counts of pedestrians and bicyclists downloaded from the Texas Bicycle and Pedestrian Count Clearinghouse cannot be used to adjust the Strava Metro pedestrian and bicyclist trips for the purposes of this project, because the 52 out of the 53 count locations in the North Central Texas are on trails that are not associated with roadways.

3.2 Assignment of PBCAT Crash Types

This section describes how the crash narratives and diagrams in the Texas Peace Officer's Crash Report Form (CR-3 crash report form) were reviewed in order to answer PBCAT crash typing logic questions for all crashes that involved a pedestrian or a pedalcyclist in the North Central Texas region between 2014 and 2018.

The Pedestrian and Bicycle Crash Analysis Tool, version 2.0, classifies pedestrian and bicycle crashes based on the actions of a driver, pedestrian, or bicyclist prior to a crash. Crashes are classified into 16 pedestrian crash groups and 56 detailed pedestrian crash types, or 20 bicyclist crash groups and 79 detailed bicyclist crash types based on:

- **Crash location**: Intersection, Intersection-related, Non-intersection, Non-roadway, Unknown.
- **Pedestrian position**: Intersection, Crosswalk Area, Travel Lane, Paved Shoulder/Bike Lane/Parking Lane, Sidewalk / Shared-Use Path/Driveway Crossing, Unpaved Right-of-Way, Driveway/Alley, Nonroadway-Parking lot/Other, Other/Unknown.

- **Bicyclist position:** Travel Lane, Bike Lane / Paved Shoulder, Sidewalk / Crosswalk / Driveway Crossing, Driveway / Alley, Multi-use Path, Nonroadway, Other, Unknown.

- **Bicyclist direction:** With Traffic, Facing Traffic, Not Applicable, Unknown.

- **Initial bicycle approach path:** Crossing Paths, Parallel Paths, Unknown / Insufficient Information.

- **Circumstances prior to a pedestrian crash:** Backing Vehicle, Bus / Transit-Related, Unique Midblock, Working or Playing in Roadway, Unusual Circumstances, Off Roadway, Crossing / In the Roadway, Walking Along the Roadway, Crossing a Driveway or Alley, Waiting to Cross, Pedestrian Dash / Dart-Out, Pedestrian Crossing the Roadway, Multiple Threat / Trapped, Crossing an Expressway, Pedestrian in Roadway – Other / Unknown.

- **Circumstances prior to a bicyclist crash:** Motorist Failed to Yield – Signalized Intersection / Sign-Controlled Intersection / Midblock, Bicyclist Failed to Yield – Signalized Intersection / Sign-Controlled Intersection / Midblock, Motorist Left / Right Turn/Merge, Bicyclist Left / Right Turn / Merge, Motorist Overtaking Bicyclist, Bicyclist Overtaking Motorist, Head-On, Parking / Bus-Related, Backing Vehicle, Loss of Control/ Turning Errors, Non-Roadway, Other / Unusual Circumstances.

Information about any crash on a public roadway that involved a motorized vehicle and resulted in a death, personal injury, or property damage of at least $1,000 is recorded on a Texas Peace Officer Crash Report Form CR-3. The CR-3 crash report form includes seven major sections:

- Identification and location
- Vehicle, driver, and persons
- Charges
- Damage
- Commercial vehicle (CMV)
- Factors and conditions
- Narrative and diagram

As Table 3.16 shows, majority of PBCAT questions were answered based on the information included in the *"Narrative and Diagram"* section of the CR-3 crash report form, complemented by information captured in the *"Identification and location"* section and the *"Vehicle, driver, and persons"* section.

Table 3.16 PBCAT Crash Typing and CR-3 Form.

PBCAT Crash Typing Questions	CR-3 Form Section	CR-3 Form Fields
Crash location	Narrative and diagram	-
	Identification and location	• At intersection: Y/N • Distance from intersection or reference marker: _ ft.
Pedestrian/bicyclist position	Narrative and diagram	-
	Vehicle, driver, and persons	• Unit number, unit description, person type
Bicyclist direction	Narrative and diagram	-
Initial bicycle approach path	Narrative and diagram	-
Circumstances prior to a pedestrian crash	Narrative and diagram	-
Circumstances prior to a bicyclist crash	Narrative and diagram	-

3.2.1 Crash Location Question

PBCAT classifies pedestrian and pedalcyclist crashes based on the location into four categories:

- **Intersection:** "crash occurred within the intersection proper or within the crosswalk area" (FHWA, 2006).
- **Intersection-Related:** "crash occurred outside the crosswalk area but within 15 meters (50 feet) of the intersection" (FHWA, 2006).
- **Non-Intersection:** "crash occurred on or along the roadway and more than 15 meters (50 feet) away from an intersection" (FHWA, 2006).
- **Non-Roadway:** "crash occurred off the roadway, including parking lots, driveways, private roads, yards, alleys, and other open areas" (FHWA, 2006).

Figure 3.2 shows an example of the crash location question in PBCAT.

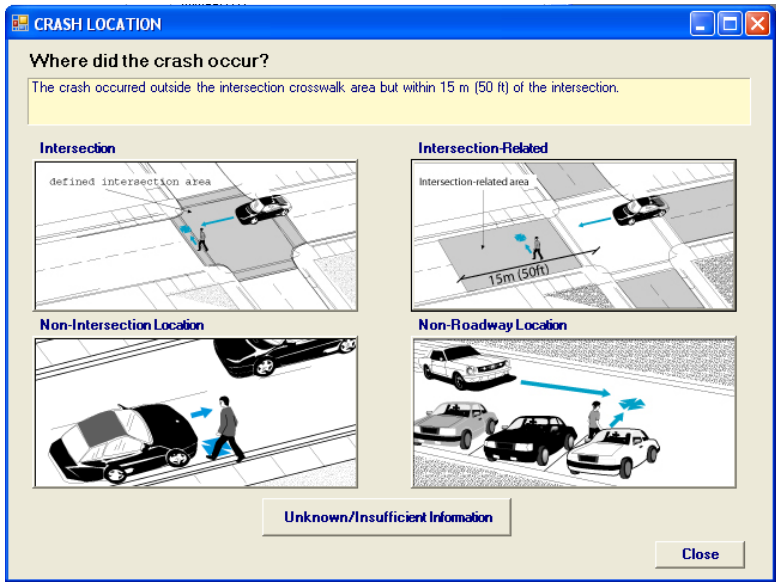
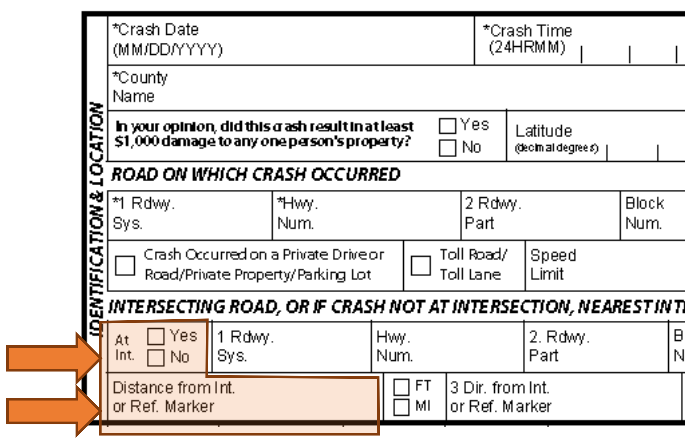


Figure 3.2 PBCAT Pedestrian Crash Location.
Source: Images from FHWA (2006)

Crash location was identified from the CR-3 crash report form based on the narrative and diagram, as well as the *"At intersection"* and *"Distance from intersection"* fields in the *"Identification and location"* section, as Figure 3.3 shows.


IDENTIFICATION & LOCATION

*Crash Date (MM/DD/YYYY)
*Crash Time (24HRMM)
*County Name
In your opinion, did this crash result in at least $1,000 damage to any one person's property? ☐ Yes ☐ No
Latitude (decimal degrees)
ROAD ON WHICH CRASH OCCURRED
*1 Rdwy. Sys. | *Hwy. Num. | 2 Rdwy. Part | Block Num.
☐ Crash Occurred on a Private Drive or Road/Private Property/Parking Lot | ☐ Toll Road/ Toll Lane | Speed Limit
INTERSECTING ROAD, OR IF CRASH NOT AT INTERSECTION, NEAREST INT
At Int. ☐ Yes ☐ No | 1 Rdwy. Sys. | Hwy. Num. | 2. Rdwy. Part | B N
Distance from Int. or Ref. Marker | ☐ FT ☐ MI | 3 Dir. from Int. or Ref. Marker

Figure 3.3 Part of the "Identification & Location" Section in a CR-3 Form.
Source: Based on TxDOT (2018)

Crash reports with the *"At intersection"* box checked were categorized as intersection in PBCAT. In cases where the "At intersection" box was unchecked, the report included the *"Distance from intersection or reference marker"* box indicating the distance in feet or meters. Any crash within 15 meters or 50 feet from the intersection was categorized as intersection-related in PBCAT.

Crashes that occurred even further from the intersection were categorized as non-intersection or non-roadway, depending on further details in the narrative and diagram.

Although this approach worked for majority of cases, there were several crashes where the CR-3 form indicated *"Not at intersection"* but the distance from the intersection was between 1 foot to 10 feet. These crashes appeared to be close to the intersection, therefore the research team would read the narrative and check the diagram again. In most of these cases the crash occurred within the crosswalk, so following the PBCAT terminology the location of these crashes was categorized as intersection. Some reports would indicate that the crash occurred at an intersection but when reading the narrative, it would state that the crash occurred right outside of the crosswalk area. These cases were then coded as intersection-related according to PBCAT terminology.

3.2.2 Pedestrian/Bicyclist Position Question

PBCAT position question identifies where the pedestrian or bicyclist was in reference to the roadway when the crash occurred, as Figure 3.4 shows.

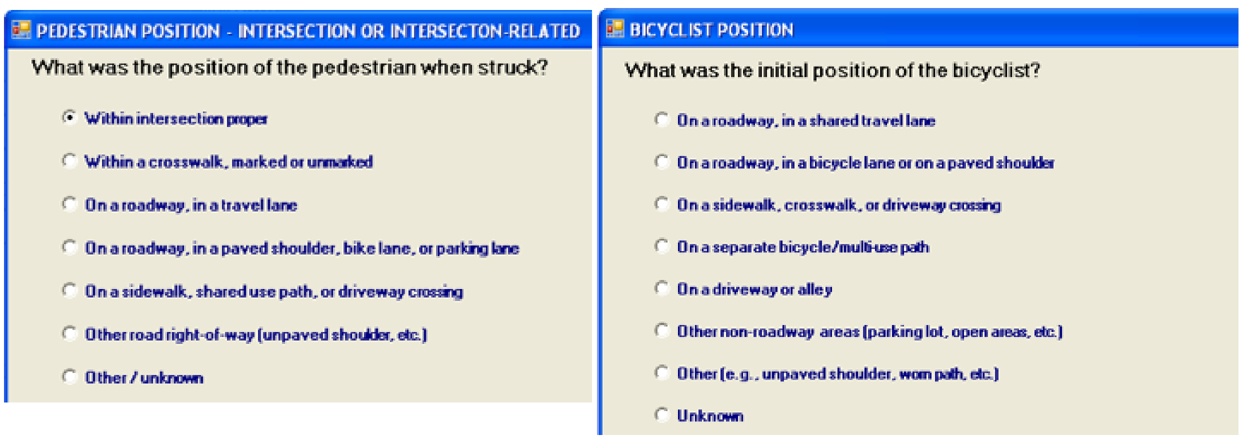


Figure 3.4 PBCAT Pedestrian Position and Bicyclist Position.
Source: Based on FHWA (2006)

The only section of the CR-3 crash report form that was found helpful in the identification of the position was the narrative and diagram, shown in Figure 3.5. There were no other fields in the report that were considered relevant to the position question in PBCAT. In cases there the narrative or diagram was vague about the location of the pedestrian or pedalcyclist (for example "on the side of the roadway"), the research team also referred to Google Earth™ to see if the roadway had a paved or unpaved shoulder, or if there were sidewalks or crosswalk, in order to be able to answer this question in PBCAT.

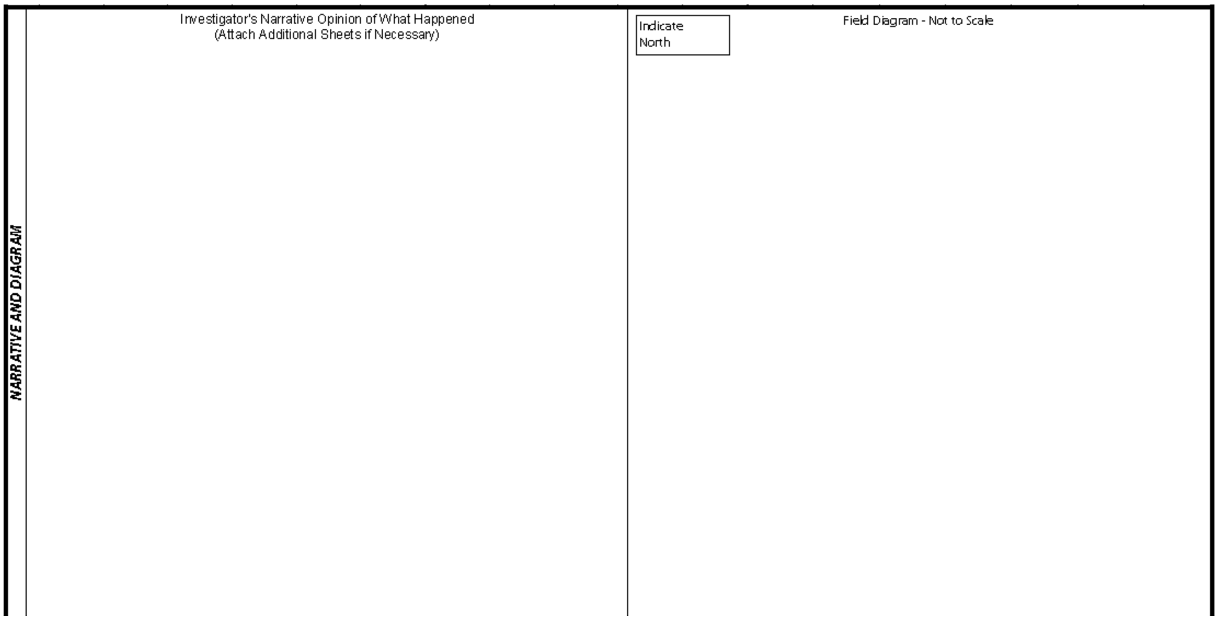


Figure 3.5 "Narrative and Diagram" Section in a CR-3 form.
Source: Based on TxDOT (2018)

In some cases, the narrative did not match with the diagram—for example in the units mentioned. In those cases, the research team would seek an explanation in the *"Vehicle, driver and persons"* section, as shown in Figure 3.6.

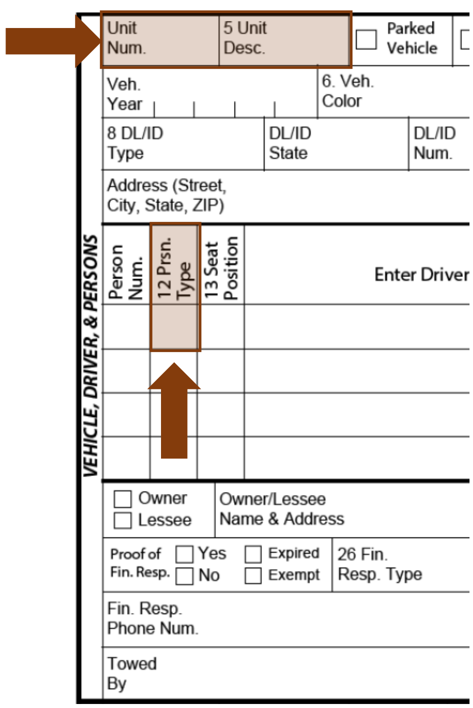


Figure 3.6 Part of the Vehicle, Driver and Persons section in a CR-3 form.
Source: FHWA (2006)

3.2.3 Bicyclist Direction and Initial Approach Paths Questions

The *"Narrative and diagram"* section was the only source of information for PBCAT questions related to bicyclist direction and initial approach paths.

3.2.4 Circumstances Prior to Crash Questions

The *"Narrative and diagram"* section was the only source of information for PBCAT questions related to the circumstance prior to a crash that involved a pedestrian or a bicyclist.

3.2.5 PBCAT Crash Typing Output

The research team reviewed narrative and diagrams in all crash reports that were identified from the Crash Record Information System (CRIS). As Figure 3.7 shows, 7,084 pedestrian crashes and 2,948 pedalcyclist crashes were identified from CRIS based on person type, unit description, and harmful event. Out of the 7,084 pedestrian crashes identified in CRIS, 7,042 were assigned a pedestrian crash type, 21 were assigned a pedalcyclist crash type, and 21 crashes were excluded from the analysis. Similarly, out of the 2,948 pedalcyclist crashes, 2,937 were associated with pedalcyclist crash types, 4 were assigned a pedestrian crash type, and 7 crashes were excluded.

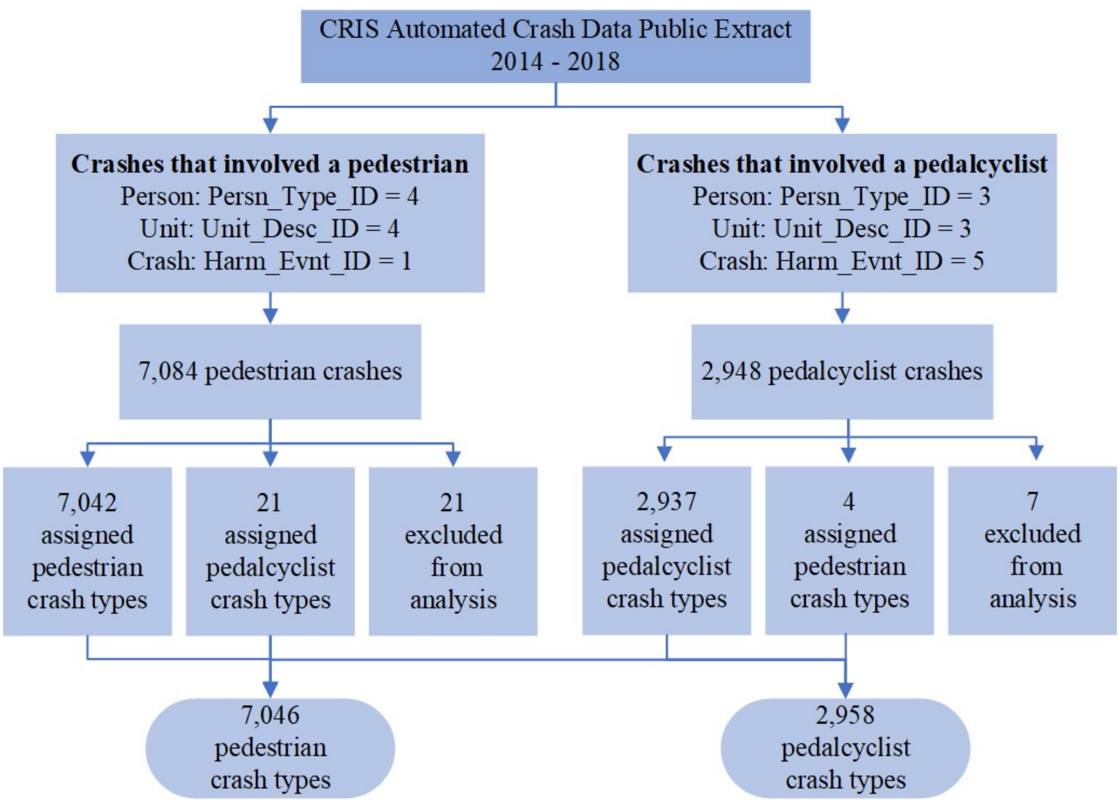


Figure 3.7 Pedestrian and Pedalcyclist Crashes Analyzed in Project 0-6983.

It took approximately 5 minutes to review the narrative and diagram in each CR-3 crash report form and to answer PBCAT questions related to the crash location, bicyclist/pedestrian position, direction, and approach paths. The time varied based on the complexity of the crash or due to missing or contradicting information that usually required a more thorough review.

3.3 PBCAT Crash Typing Results

This section offers an overview of the PBCAT crash typing results that were obtained once the PBCAT questions were answered based on manual review of CR-3 crash form's narrative and diagram section.

The upcoming section shows the most common:

- Pedestrian crash location
- Pedestrian position
- Pedestrian crash groups (at/nearby intersection, non-intersection, non-roadway)
- Pedestrian crash scenarios at intersections
- Pedalcyclist crash location and direction
- Pedalcyclist position
- Pedalcyclist crash groups (at/nearby intersection, non-intersection, non-roadway)

These PBCAT results were further analyzed during the statistical analysis, when the researchers will investigate which actions prior to crash are more common in serious injury and fatal crashes, as well as what roadway characteristics were present in those crashes.

Table 3.17 shows the number of pedestrian and pedalcyclist crashes that were analyzed. From the total of 7,046 pedestrian crashes, 22% occurred in year 2017. The year with highest number of pedalcyclist crashes was 2016, when 22% of the total 2,958 pedalcyclist crashes occurred. These crashes included all severities—fatal incapacitating injury, non-incapacitating injury, possible injury, and property-damage-only crashes.

Table 3.17 Pedestrian and Pedalcyclist Crashes in North Central Texas Analyzed in 0-6983.

Year	Number of Pedestrian Crashes	Number of Pedalcyclist Crashes
2014	1,287	540
2015	1,368	597
2016	1,539	584
2017	1,501	656
2018	1,351	581
Total	*7,046*	*2,958*

3.3.1 Pedestrian Crash Location

Figure 3.8 shows that pedestrian crash locations were almost equally distributed between non-intersection locations (3,455 crashes), and intersection/intersection-related locations (3,431 crashes). Non-intersection locations included midblock or locations more than 50 feet from an intersection, while crashes that occurred at an intersection or within 50 feet from the corners of an intersection were categorized as intersection / intersection-related. A small percentage (2%) of crashes occurred at non-roadway locations which included parking lots, driveways, and alleys.

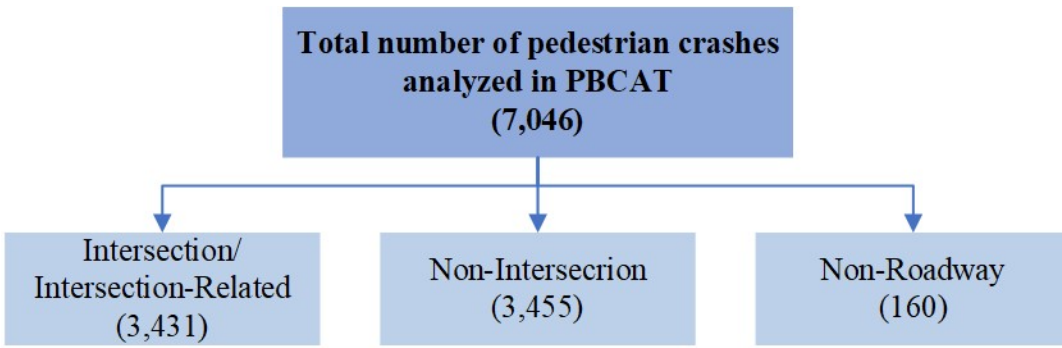


Figure 3.8 Pedestrian Crash Location (All Crash Severities).

3.3.2 Pedestrian Position

Figure 3.9 describes the pedestrian's position at the time of the collision. At intersection/intersection-related locations the most common pedestrian position was within the crosswalk area. At non-intersection location the most common pedestrian position was in a travel lane and for non-roadway locations the most frequent pedestrian location was at a parking lot.

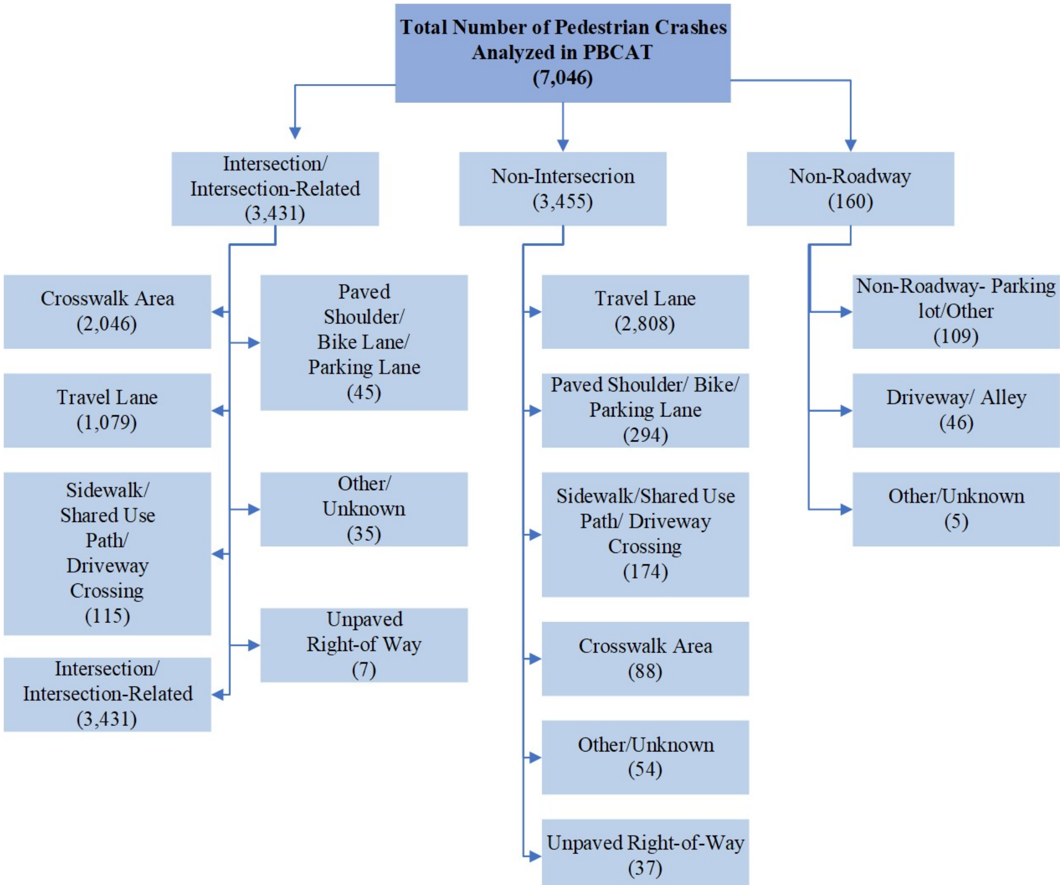


Figure 3.9 Pedestrian Position (All Crash Severities).

3.3.3 Pedestrian Crash Groups

The most common pedestrian crash groups are shown for three location types: at/nearby intersections, non-intersection, and non-roadway. Additional information about the crash groups and crash types can be found in Appendix E.

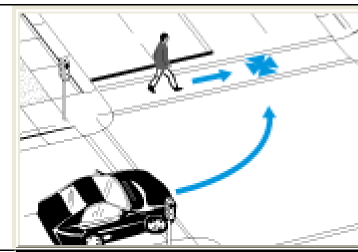
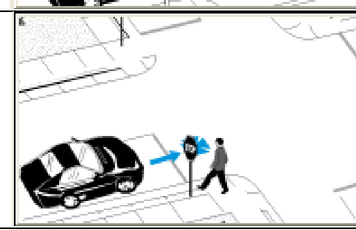
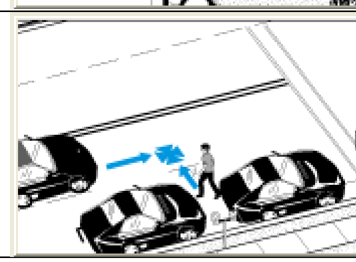
Table 3.18 shows the top 5 most common crash groups that accounted for 89% of all intersection/intersection-related pedestrian crashes:

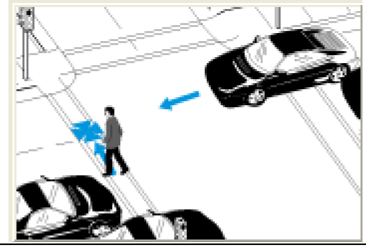
- **Crossing roadway – vehicle turning**: included actions such as motorist turning left, turning right, or merging prior to colliding with a pedestrian who was most often walking in a parallel path.
- **Crossing roadway – vehicle not turning:** caused by failure to yield right of way, either by motorist or by pedestrian.
- **Unusual circumstances:** included a diverse range of actions that lead to a crash. From pedestrians struck as a result of a prior vehicle-to-vehicle crash, to cases where motor vehicle lost control, or cases where pedestrian (previous occupant of a motorized vehicle

that was disabled due to a crash or stalling) was near or next to the vehicle when stuck by another motorized vehicle.

- **Dash/dart-out:** included crashes where a pedestrian walked into the roadway and collided with a motorized vehicle, whose view was obstructed (dart-out) or not (dash).
- **Multiple threat/trapped:** included crashes where pedestrian got trapped at a signalized crosswalk when traffic light changed.

Table 3.18 Most Common Pedestrian Crash Groups at Intersection/Intersection-Related Locations (All Crash Severities).

Top 5 Pedestrian Crash Groups	**Number of Pedestrian Crashes at Intersection/ Intersection-Related Locations (Total: 3,431)**	**Examples of Crash Groups** (FHWA, n.d.-d)
Crossing Roadway - Vehicle Turning	1,487 (43%)	
Crossing Roadway - Vehicle Not Turning	1,034 (30%)	
Unusual Circumstances	250 (7%)	
Dash / Dart-Out	223 (6%)	

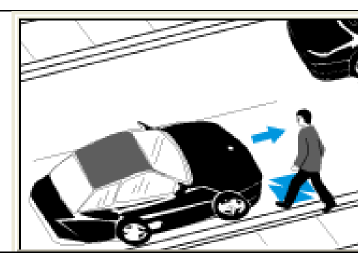
Top 5 Pedestrian Crash Groups	Number of Pedestrian Crashes at Intersection/ Intersection-Related Locations (Total: 3,431)	Examples of Crash Groups
Multiple Threat / Trapped	62 (2%)	

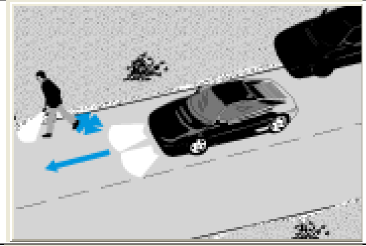
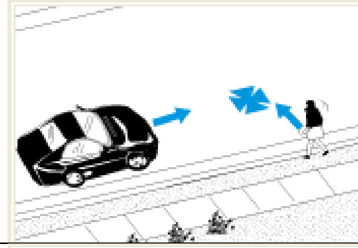
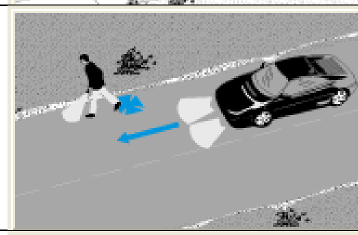
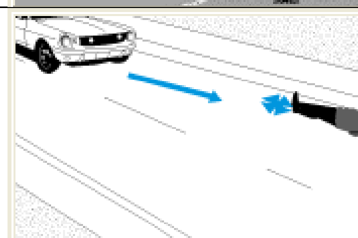
Note: Crash group example images from FHWA (n.d.-d).

Table 3.19 summarizes the top 5 most common crash groups that account for 89% of all non-intersection-related pedestrian crashes:

- **Crossing roadway – vehicle not turning:** in majority of cases a pedestrian failed to yield right to way to a motorized vehicle.
- **Unusual circumstances:** disabled vehicle-related crashes occurred frequently, as well as crashes where motor vehicle lost control and collided with a pedestrian.
- **Dash/dart-out**: included crashes where a pedestrian walked into the roadway and was struck by a motorized vehicle, whose view was obstructed (dart-out) or not (dash).
- **Walking along roadway:** majority of crashes in this crash group occurred when a pedestrian was walking along roadway with traffic and was stuck by a motorized vehicle from behind.
- **Pedestrian in roadway (circumstances unknown):** this crash group includes cases where a crash report indicated that a pedestrian was standing, walking, or lying in the roadway, but did not provide information about how the pedestrian got there.

Table 3.19 Most Common Pedestrian Crash Groups at Non-Intersection Locations (All Crash Severities).

Top 5 Pedestrian Crash Groups	Number of Pedestrian Crashes at Non-Intersection Locations (Total: 3,455)	Examples of Crash Groups
Crossing Roadway – Vehicle Not Turning	1054 (30%)	

Top 5 Pedestrian Crash Groups	Number of Pedestrian Crashes at Non-Intersection Locations (Total: 3,455)	Examples of Crash Groups
Unusual Circumstances	741 (21%)	
Dash / Dart-Out	451 (13%)	
Walking Along Roadway	341 (10%)	
Pedestrian in Roadway – Circumstances Unknown	182 (5%)	

Note: Crash group example images from FHWA (n.d.-d).

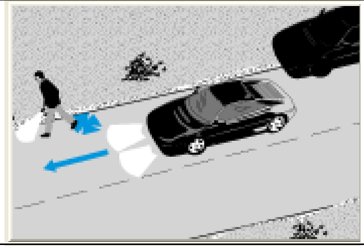
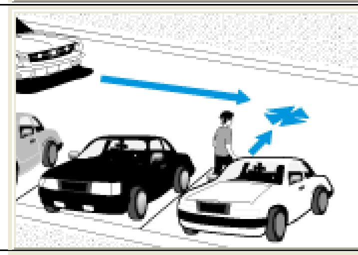
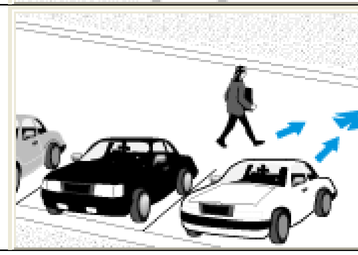
Table 3.20 summarizes the most common crash groups at non-roadway locations:

- **Unusual circumstances:** Actions prior to crash included mostly motor vehicle loss of control and cases where a pedestrian was struck as a result of a prior vehicle-to-vehicle crash.

- **Off roadway:** Off-roadway crashes included collisions between pedestrians and motorized vehicles at parking lots and other locations.

- **Backing vehicle:** Majority of these crashes occurred when a motorized vehicle was backing in a driveway.

Table 3.20 Most Common Pedestrian Crash Groups at Non-Roadway Locations (All Crash Severities).

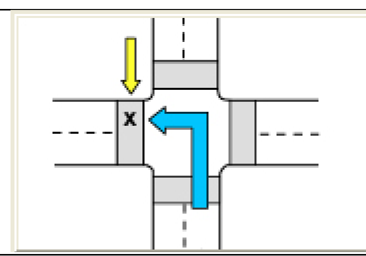
Pedestrian Crash Groups	Number of Pedestrian Crashes at Non-Roadway Locations (Total: 160)	Examples of Crash Groups
Unusual Circumstances	99 (62%)	
Off Roadway	40 (25%)	
Backing Vehicle	21 (13%)	

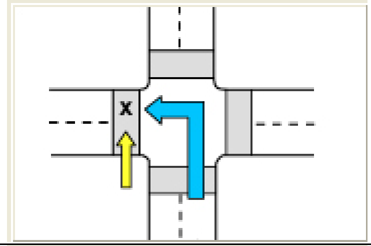
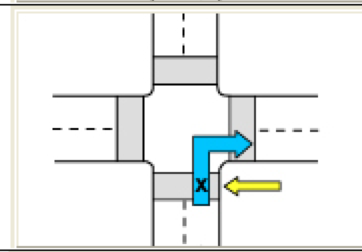
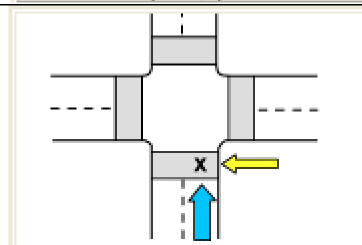
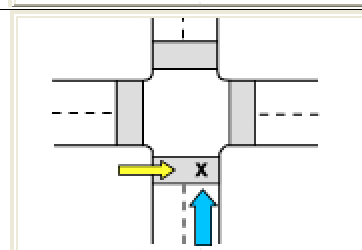
Note: Crash group example images from FHWA (n.d.-d).

3.3.4 Pedestrian Crash Scenarios at Intersections

Table 3.21 shows the top 5 most common pedestrian scenarios at intersections out of the total 36 scenarios that PBCAT considers. In 18% of all crashes that occurred between a pedestrian and a motorized vehicle at intersections, the pedestrian was within a crosswalk walking in a direction opposite to motorists while the motorized vehicle was turning left.

Table 3.21 Most Common Pedestrian Crash Scenarios at Intersections (All Crash Severities).

Pedestrian Crash Scenario	Number of Pedestrian Crashes at Intersections (Total: 2,560)	Examples of Scenarios
11b. Pedestrian within crosswalk area, approach direction opposite motorist's	472 (18%)	

Pedestrian Crash Scenario	Number of Pedestrian Crashes at Intersections (Total: 2,560)	Examples of Scenarios
11a. Pedestrian within crosswalk area, approach direction same as motorist's	224 (9%)	
5b. Pedestrian within crosswalk area, traveled from motorist's right	219 (9%)	
1b. Pedestrian within crosswalk area, traveled from motorist's right	203 (8%)	
1a. Pedestrian within crosswalk area, traveled from motorist's left.	185 (7%)	

Note: Scenario example images from FHWA (2006).

3.3.5 Pedalcyclist Crash Location and Direction

Figure 3.10 shows that 63% of all pedalcyclist crashes occurred at an intersection or within 50 feet from the corners of an intersection, followed by non-intersection locations represented in 36% of occurrences. A small percentage of crashes (less than 1%) were reported at on-roadway locations, such as a driveway, or an alley. PBCAT crash typing also asks about the direction that the pedalcyclist was riding, whether with traffic or against traffic. In the analyzed dataset, more than half of all crashes occurred when pedalcyclists were riding in the same direction as traffic. Crashes where a pedalcyclist was riding facing traffic occurred mostly at intersection/intersection-related locations.

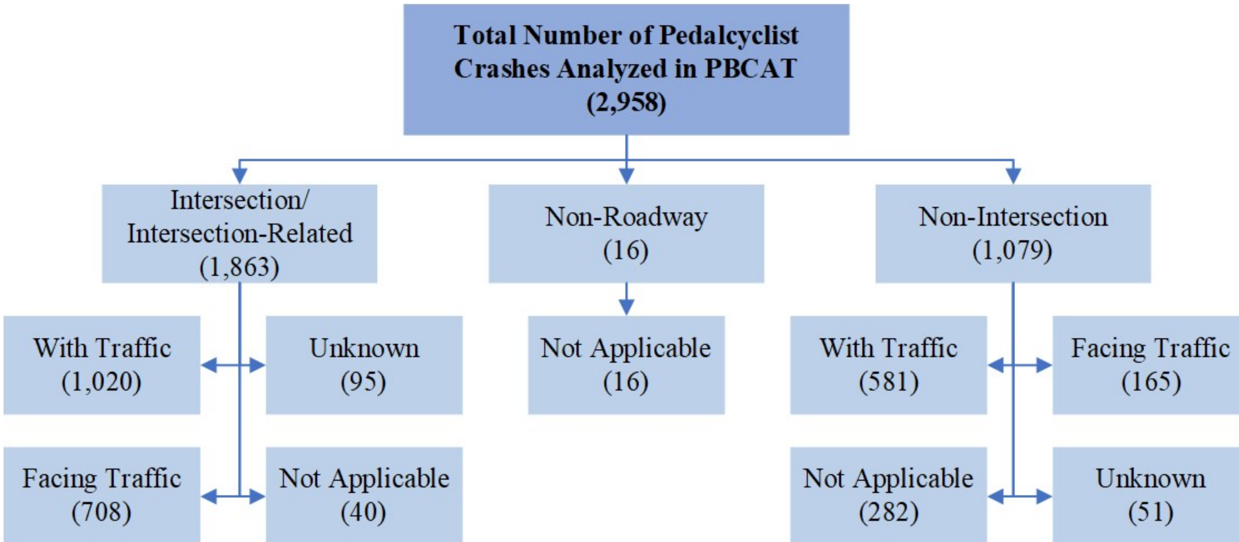


Figure 3.10 Pedalcyclist Crash Location and Direction (All Crash Severities).

3.3.6 Pedalcyclist Position

Figure 3.11 shows that for crashes that occurred at or nearby intersections, the pedalcyclists were most commonly riding on a sidewalk, within a crosswalk, or crossing a driveway. For crashes at non-intersection locations the pedalcyclists were most frequently riding in a travel lane. Crashes that occurred where bicycle facilities (such as bicycle lanes, paved shoulders, or multi-use trails) were present accounted for 4% of all crashes.

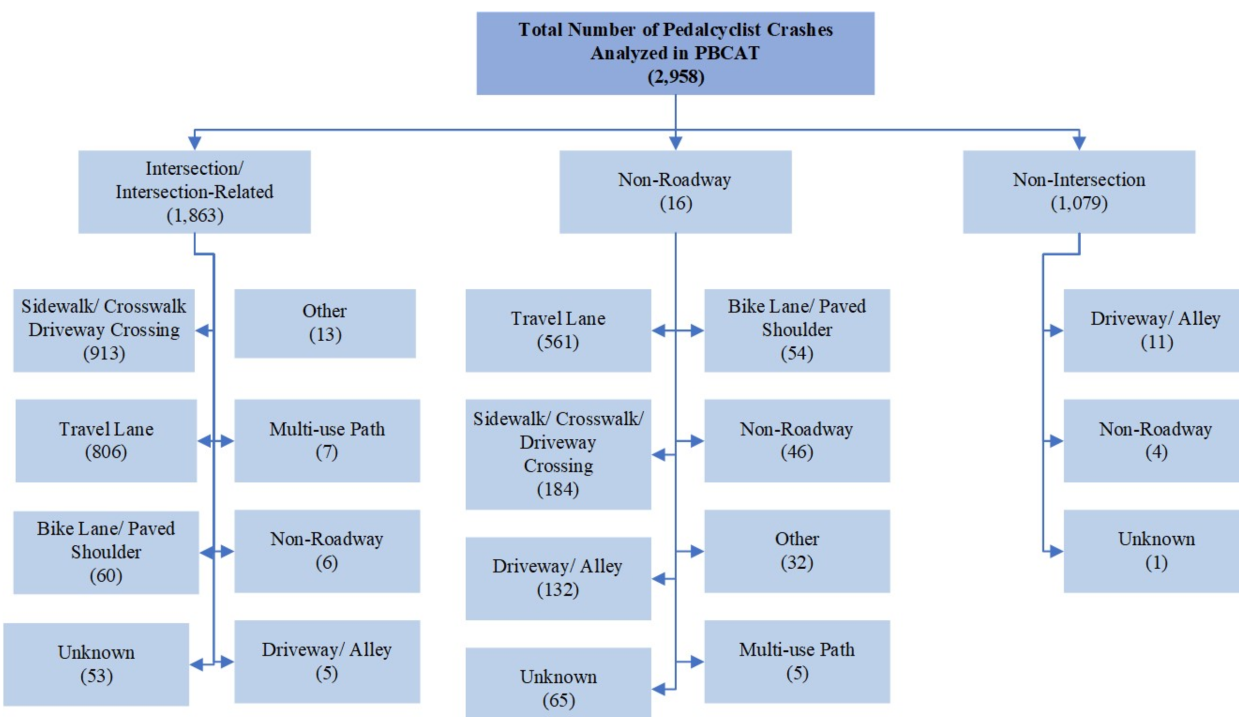


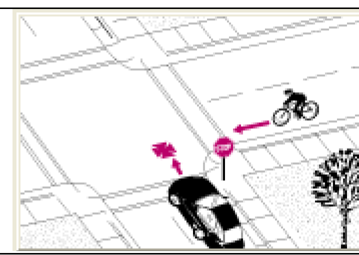
Figure 3.11 Pedalcyclist Crash Position (All Crash Severities).

3.3.7 Pedalcyclist Crash Groups

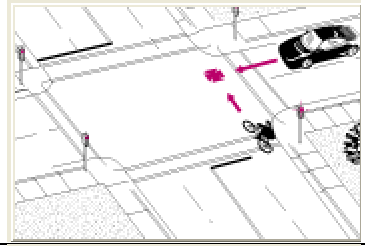
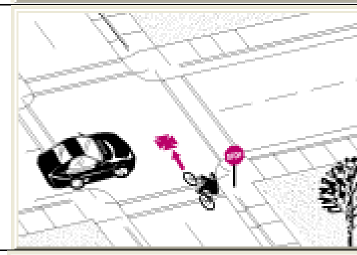
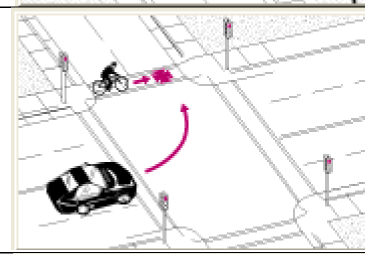
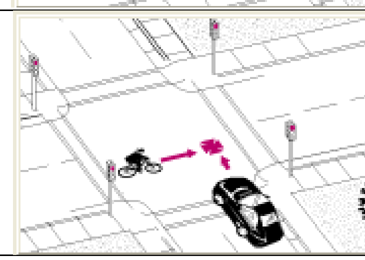
Table 3.22 shows the top 5 most common crash groups[7] that accounted for 73% of all pedalcyclist crashes at or nearby intersections:

- **Motorist failed to yield – sign-controlled intersection:** included crashes where motorist obeyed the sign but failed to yield a right of way to a pedalcyclist, which lead to a collision.
- **Bicyclist failed to yield – signalized intersection:** majority of these crashes occurred when pedalcyclist disobeyed a signal, rode into an intersection, and collided with a motorized vehicle.
- **Bicyclist failed to yield – sign-controlled intersection:** majority of these crashes occurred when pedalcyclist disobeyed a sign, rode into an intersection, and collided with a motorized vehicle.
- **Motorist left turn / merge:** majority of these crashes occurred when motorist was turning left and did not yield to a pedalcyclist riding in the opposite direction.
- **Motorist failed to yield – signalized intersection:** In this crash group, the most common action prior to crash was a motorized vehicle turning right on red signal and colliding with a pedalcyclist.

Table 3.22 Most Common Pedalcyclist Crash Groups at Intersection/Intersection-Related Locations (All Crash Severities).

Top 5 Pedalcyclist Crash Groups	Number of Pedalcyclist Crashes at Intersection/ Intersection-Related Locations (Total: 1,863)	Examples of Crash Groups
Motorist Failed to Yield - Sign-Controlled Intersection	451 (24%)	

[7] Definitions of PBCAT crash groups can be found in *PBCAT—Pedestrian and Bicycle Crash Analysis Tool Version 2.0. Application Manual, Appendix F* (FHWA, 2006) available at http://www.pedbikeinfo.org/pbcat_us/pbcat_manual/PBCAT_Manual.pdf

Top 5 Pedalcyclist Crash Groups	Number of Pedalcyclist Crashes at Intersection/ Intersection-Related Locations (Total: 1,863)	Examples of Crash Groups
Bicyclist Failed to Yield - Signalized Intersection	234 (13%)	
Bicyclist Failed to Yield - Sign-Controlled Intersection	239 (13%)	
Motorist Left Turn / Merge	236 (13%)	
Motorist Failed to Yield - Signalized Intersection	192 (10%)	

Note: Crash group example images from FHWA (n.d.-d).

Table 3.23 summarizes the top 5 most common crash groups that accounted for 79% of all pedalcyclist crashes at non-intersection locations.

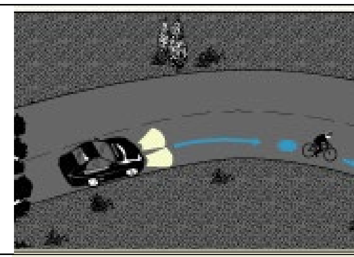
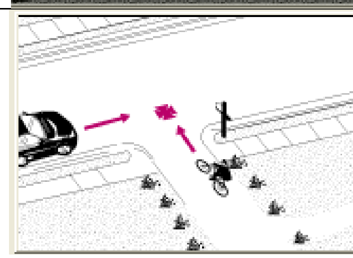
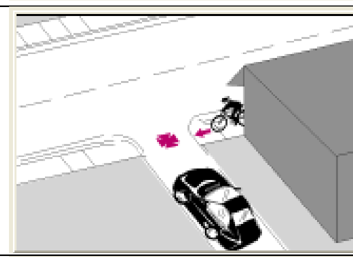
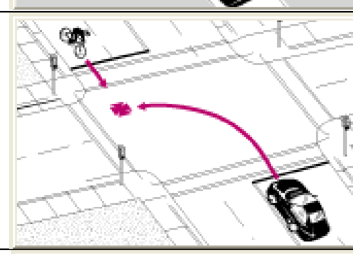
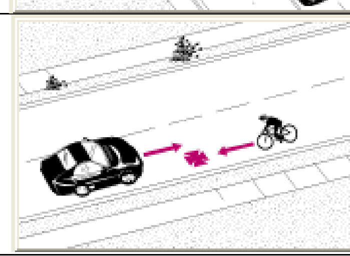
- **Motorist overtaking bicyclist:** While PBCAT crash types include possible explanations for the actions that led to a crash while motorist was overtaking a pedalcyclist, such as not detecting the cyclist, misjudging space, or cyclist swerving, majority of these crashes in the NCTCOG area did not belong to any of these categories and the actions prior to crash were categorized as "Motorist overtaking – other/unknown". It was due to either not sufficient information in the crash narrative, or due to actions other than the three listed above.

- **Bicyclist failed to yield – midblock:** majority of thee crashes occurred when bicyclist rode into the roadway from adjacent driveway (residential or commercial) or from other location.

- **Motorist left turn/merge:** these crashes mostly occurred when motorist was making a left turn and collided with a cyclist coming from the opposite direction.

- **Head-on:** most common actions prior to crash in this group included cases where a pedalcyclist was riding on a wrong side of roadway and collided head-on with a motorized vehicle.

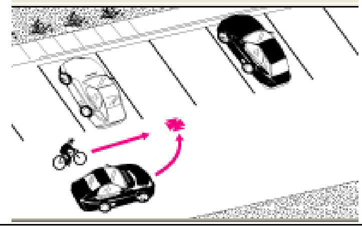
Table 3.23 Most Common Pedalcyclist Crash Groups at Non-Intersection Locations (All Crash Severities).

Top 5 Pedalcyclist Crash Groups	Number of Pedestrian Crashes at Non-Intersection Locations (Total: 1,079)	Examples of Crash Groups
Motorist Overtaking Bicyclist	329 (30%)	
Bicyclist Failed to Yield-Midblock	278 (26%)	
Motorist Failed to Yield - Midblock	143 (13%)	
Motorist Left Turn/Merge	63 (6%)	
Head-On	48 (4%)	

Note: Crash group example images from FHWA (n.d.-d).

For non-roadway locations, PBCAT classifies all pedalcyclist crashes into one crash group, as Table 3.24 shows. This non-roadway crash group includes any crashes that occurred at non-roadway locations, such as parking lots, driveways, and alleys.

Table 3.24 Pedalcyclist Crash Group at Non-Roadway Locations (All Crash Severities).

Pedalcyclist Crash Group	Number of Pedalcyclist Crashes at Non-Roadway Locations (Total: 16)	Examples of Crash Groups
Non-Roadway	16 (100%)	

Note: Crash group example images from FHWA (n.d.-d).

CHAPTER 4. STATISTICAL ANALYSIS TO IDENTIFY HIGH-RISK INCIDENCE CRASH CORRIDORS

4.1 Descriptive Trend Safety Risk Factor Analysis

This section describes the overall pedestrian and pedalcyclist crash patterns and trends in North Central Texas. It discusses various conditions, roadway elements, and actions prior to crash.

Pedestrian and pedalcyclist crash statistics are summarized by injury severity, using the following KABCO injury classification scale (FHWA, n.d.-d):

- K – "Killed: Died due to injuries sustained from the crash, within 30 days of the crash." (FHWA, n.d.-d)
- A – "Incapacitating Injury: Severe injury which prevents continuation of normal activities; includes broken or distorted limbs, internal injuries, crushed chest, etc." (FHWA, n.d.-d)
- B – "Non-Incapacitating Injury: Evident injury such as bruises, abrasions, or minor lacerations which do not incapacitate." (FHWA, n.d.-d)
- C – "Possible Injury: Injury which is claimed, reported, or indicated by behavior, but without visible wounds; includes limping or complaint of pain." (FHWA, n.d.-d)
- O – "Not Injured: The person involved in crash did not sustain an A, B, or C injury." (FHWA, n.d.-d) This injury severity category is also called 'Property Damage Only' or PDO.
- Unknown – "Unknown: Unable to determine whether injuries exist." (FHWA, n.d.-d)

The descriptive trend analysis was based on five years of pedestrian and pedalcyclist crash data from years 2014-2018 in North Central Texas.

Figure 4.1. shows that the highest number of pedestrian crashes occurred in year 2016 but by 2018 pedestrian crashes have declined by 12 percent, despite a substantial population growth in the

region. The highest number of pedalcyclist crashes occurred in year 2017 and by 2018 also pedalcyclist crashes have declined by 11 percent.

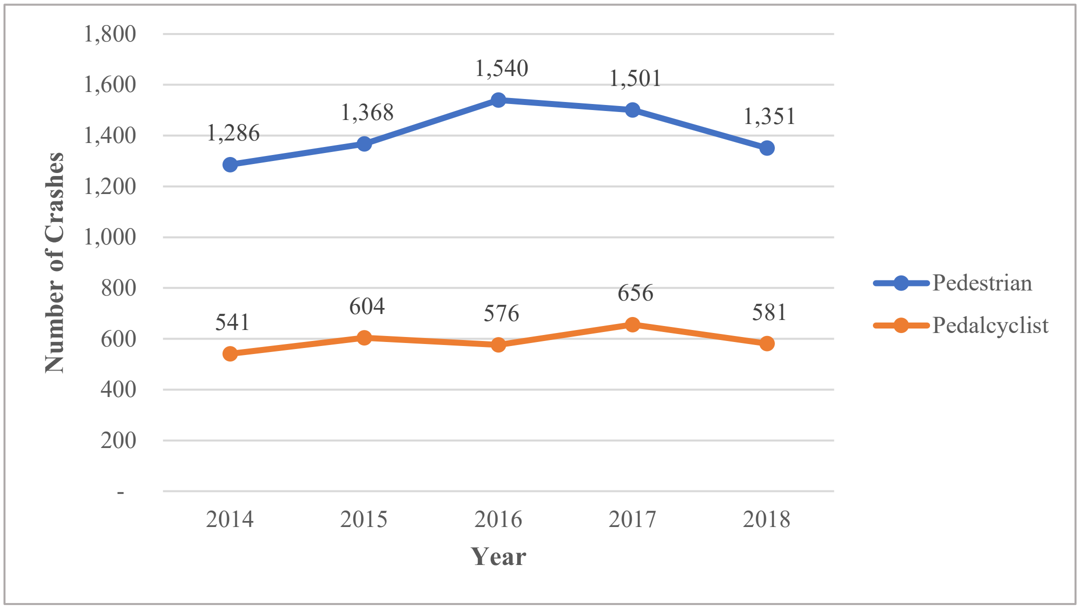


Figure 4.1 Pedestrian and Pedalcyclist Crashes, by Year.

During the five-year period, approximately 31% of pedestrian crashes resulted in fatal or serious injuries. The annual number of pedestrian K/A crashes ranged from 363 in 2014 to 493 in 2016, as Figure 4.2 shows.

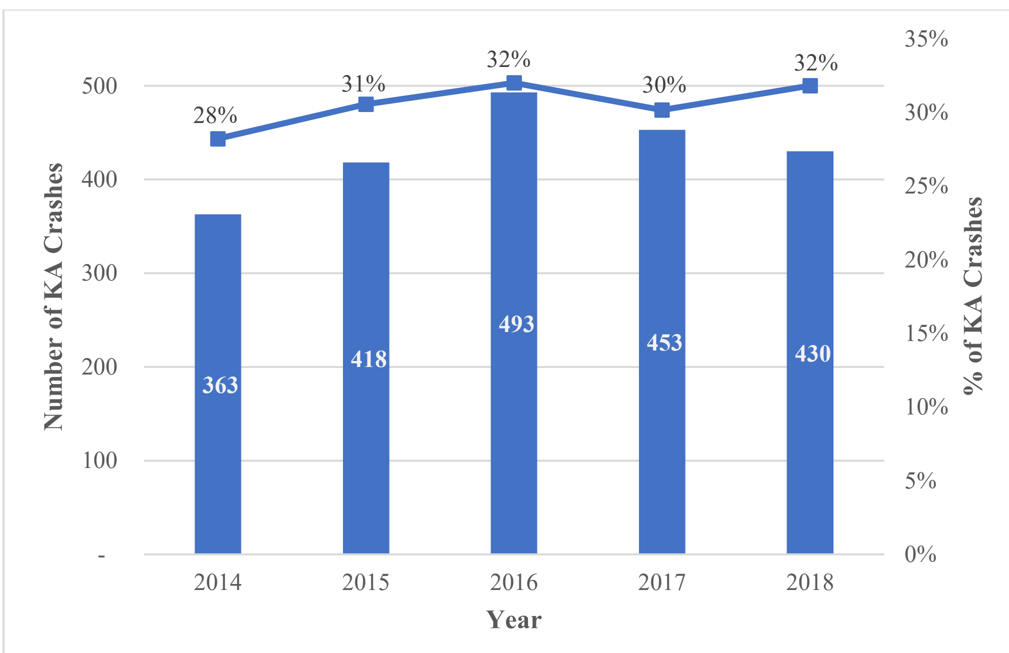


Figure 4.2 Pedestrian K/A Crashes by Year.

Figure 4.3 shows the rate of pedalcyclist K/A crashes during the five-year period, when approximately 15% of all crashes that involved a pedalcyclist resulted in fatal or serious injuries.

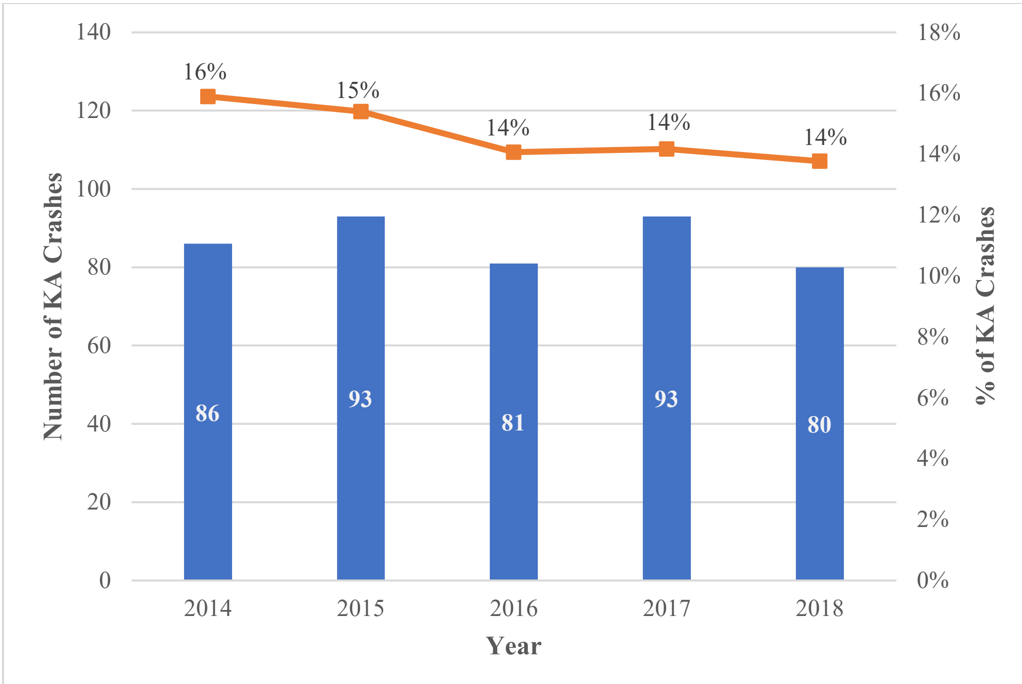


Figure 4.3 Pedalcyclist K/A Crashes by Year.

The descriptive trend analysis focused on selected roadway elements, conditions, and actions:

- Conditions
  - Month
  - Day of week
  - County
  - Light conditions
  - Vehicle type
  - Urban rural
- Roadway elements
  - Speed
  - Number of lanes
  - Crash location
- Actions
  - Impairment
  - Hit and run
  - PBCAT crash group

4.1.1 Conditions

Month

As Figure 4.4 shows, over the five-year period, the month with the highest number of pedestrian crashes was October and for pedalcyclists, and the month with the most crashes was September. Overall, pedestrian crashes were highest during months of September through January, while pedalcyclist crashes were highest from March through October.

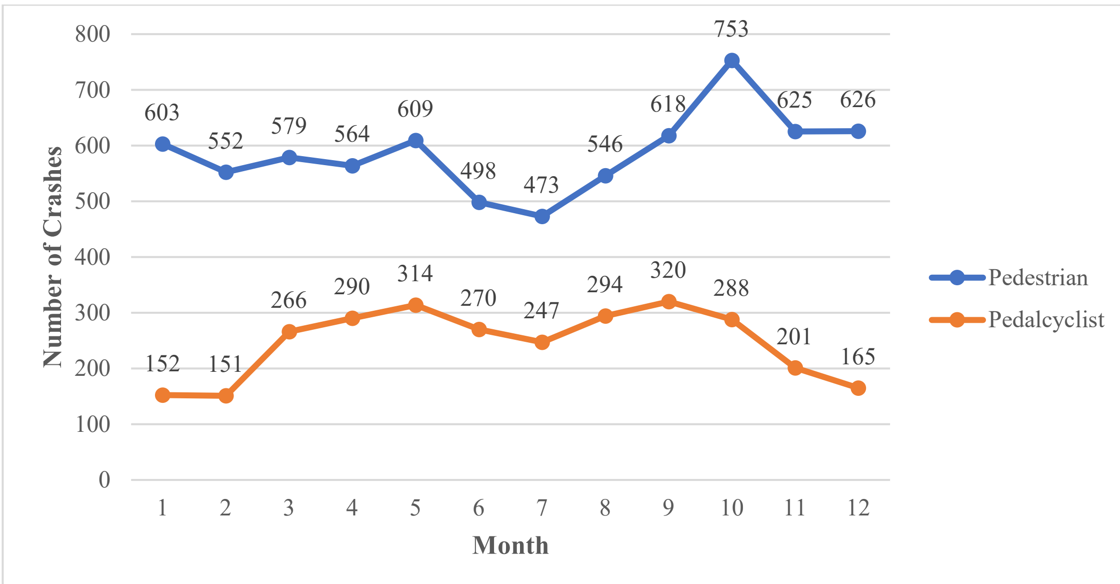


Figure 4.4 Pedestrian and Pedalcyclist Crashes by Month.

Day of Week

Pedestrian crashes occurred most frequently on Fridays and were lowest on Sundays. Pedalcyclist crashes were higher during workdays and lowest on weekends, as Figure 4.5 shows.

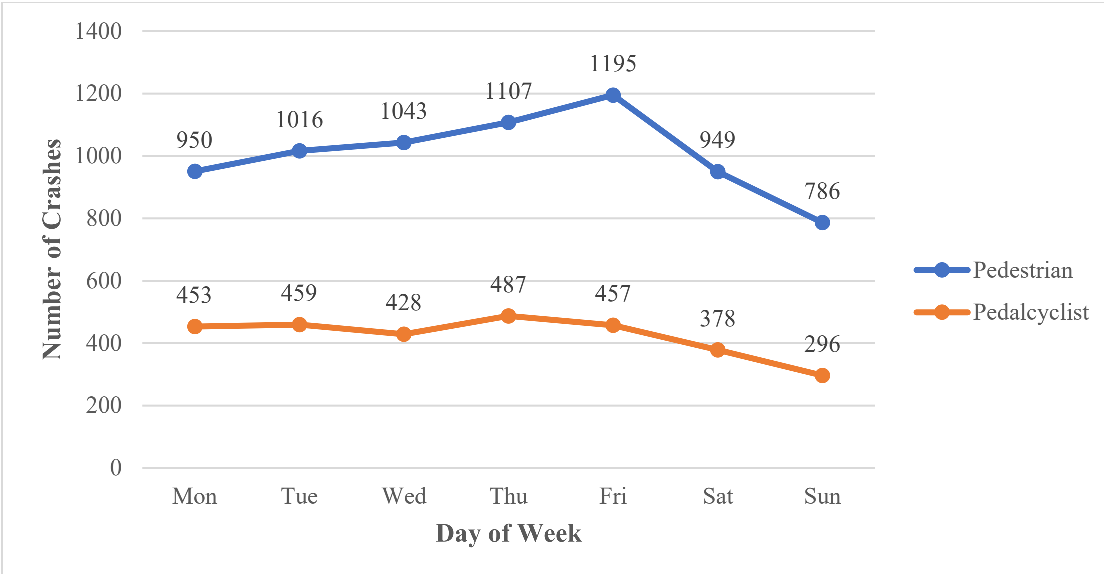


Figure 4.5 Pedestrian and Pedalcyclist Crashes by Day of Week.

County

Tables 4.1 and 4.2 provide pedestrian and pedalcyclist crash statistics by county. As Table 4.1 shows, almost 95% of all pedestrian crashes and 92% of K/A crashes occurred in only four counties: Dallas, Tarrant, Denton, and Collin, while only 88% of the region's population resides in these counties. For comparison, at the national level, the fatality rate (pedestrians killed in traffic crashes in the U.S. per 100,000 population) reported by (NHTSA, 2019) based on 2017 data was 1.84.

Table 4.1 Pedestrian Crash Statistics by County and Total Population.

County	**Total Pedestrian Crashes**	**K/A Pedestrian Crashes**	**Total Population** (U.S. Census 2017a)	**Crash Rate per 100,000 Population**	**K/A Crash Rate per 100,000 Population**
Dallas	3,855	1,169	2,552,213	151	46
Tarrant	1,928	589	1,983,675	97	30
Denton	448	127	781,321	57	16
Collin	432	103	914,075	47	11
Ellis	88	40	164,092	54	24
Johnson	74	31	160,173	46	19
Hunt	71	33	90,322	79	37
Kaufman	44	23	114,852	38	20
Parker	37	15	125,963	29	12
Rockwall	28	11	90,414	31	12
Hood	22	6	55,418	40	11
Wise	19	10	63,247	30	16

Pedalcyclist crashes by county are summarized in Table 4.2. Similar to pedestrian crashes, the majority of pedalcyclist crashes (95% of all crashes and 92% of K/A crashes) occurred in only four counties: Dallas, Tarrant, Denton, and Collin. For comparison, at the national level, the fatality rate (pedalcyclists killed in traffic crashes in the U.S. per 100,000 population) reported by (NHTSA, 2019) based on 2017 data was 2.4.

Table 4.2 Pedalcyclist Crash Statistics by County and Total Population.

County	Total Pedalcyclist Crashes	K/A Pedalcyclist Crashes	Total Population (U.S. Census 2017a)	Crash Rate per 100,000 Population	K/A Crash Rate per 100,000 Population
Dallas	1,197	179	2,552,213	47	7
Tarrant	890	122	1,983,675	45	6
Denton	365	51	914,075	40	6
Collin	333	45	781,321	43	6
Ellis	43	8	160,173	27	5
Johnson	38	13	164,092	23	8
Hunt	26	3	114,852	23	3
Kaufman	19	5	90,322	21	6
Parker	17	1	90,414	19	1
Rockwall	13	2	55,418	23	4
Hood	12	2	125,963	10	2
Wise	4	2	63,247	6	3

Light Conditions

Figure 4.6 gives pedestrian crash statistics by light conditions[8] and crash severity. While many fatal and serious pedestrian crashes occurred during daylight (36%), more than a half (60%) occurred in dark (lighted and not lighted) conditions.

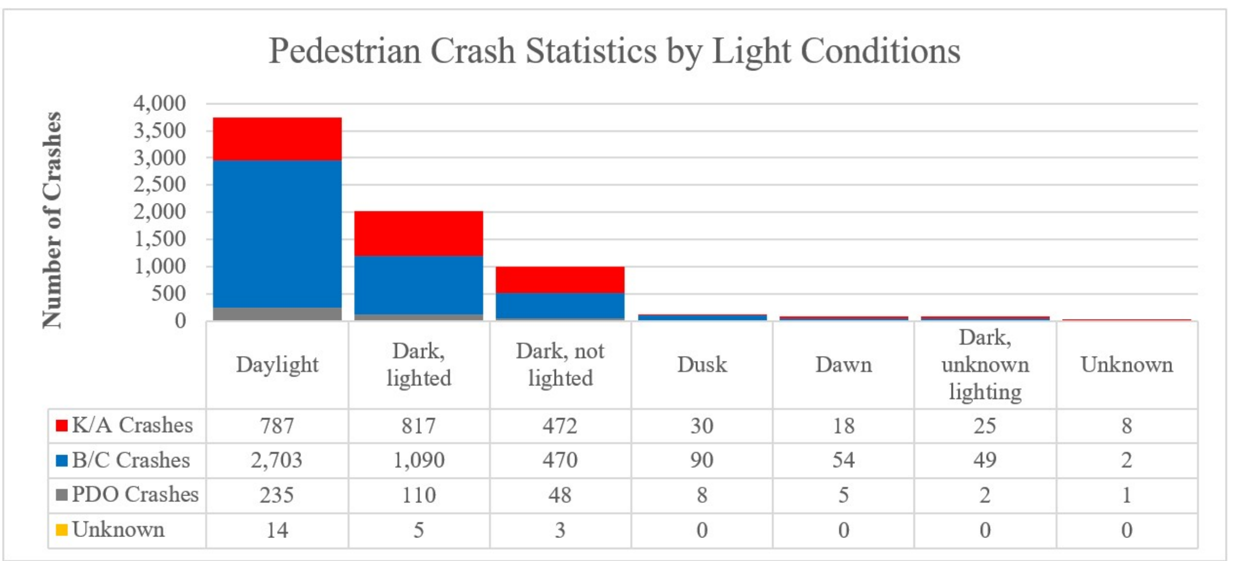
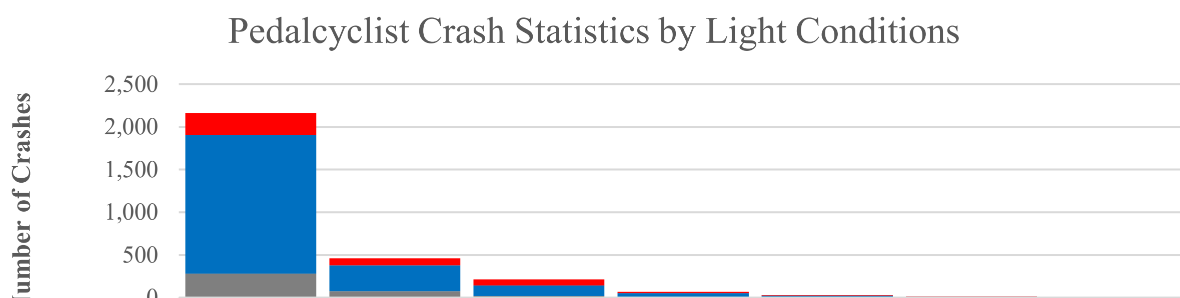


Figure 4.6 Pedestrian Crash Statistics by Light Conditions.

[8] Light conditions as reported in crash reports, refer to presence of lighting in the roadway, not pedestrian-scale lighting.

Figure 4.7 provides pedalcyclist crash statistics by light conditions[9] and crash severity. The majority of fatal and serious pedalcyclist crashes occurred during daylight (59%). The crash frequency of fatal and serious pedalcyclist crashes was similar in dark but lighted conditions (19%) and in not-lighted conditions (16%).

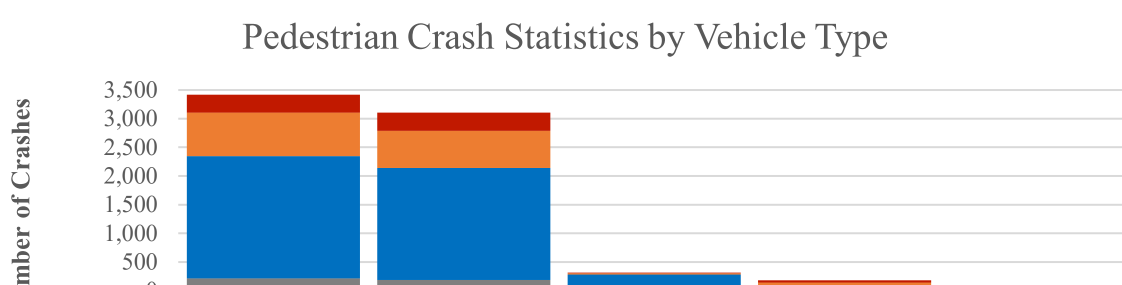


	Daylight	Dark, lighted	Dark, not lighted	Dusk	Dawn	Dark, unknown lighting	Unknown
K/A Crashes	257	81	69	15	6	5	0
B/C Crashes	1,622	305	124	46	19	12	2
PDO Crashes	280	74	20	8	6	1	0
Unknown	3	2	0	1	0	0	0

Figure 4.7 Pedalcyclist Crash Statistics by Light Conditions.

Vehicle Type

As Figure 4.8 shows, more than 93% of crashes with passenger vehicles, SUV/van/truck, or freight trucks resulted in injuries (K/A/B/C). About one third of crashes with passenger vehicles (31%)



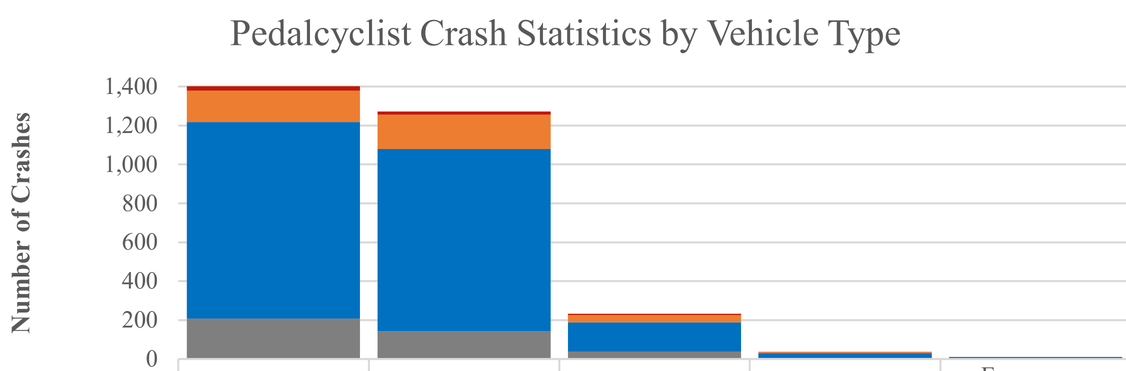
	Passenger Car	SUV/Van/Truck	Unknown	Freight Truck	Emergency Vehicle
K Crashes	315	319	16	42	3
A Crashes	755	650	17	52	4
B/C Crashes	2137	1,953	266	76	26
PDO Crashes	204	178	12	10	5
Unknown	7	8	5	1	1

Figure 4.8 Pedestrian Crash Statistics by Vehicle Type.

[9] Light conditions as reported in crash reports, refer to presence of lighting in the roadway, not pedalcyclist-scale lighting.

and SUV/van/truck (31%) resulted in fatal or serious injuries, while half of crashes (52%) between pedestrians and freight trucks resulted in fatalities and serious injuries.

While a majority of crashes between pedalcyclists and motorized vehicles resulted in injuries (B/C), about 13% of crashes with passenger vehicles were fatal or serious (15% for SUV/van/truck and 19% for freight trucks).

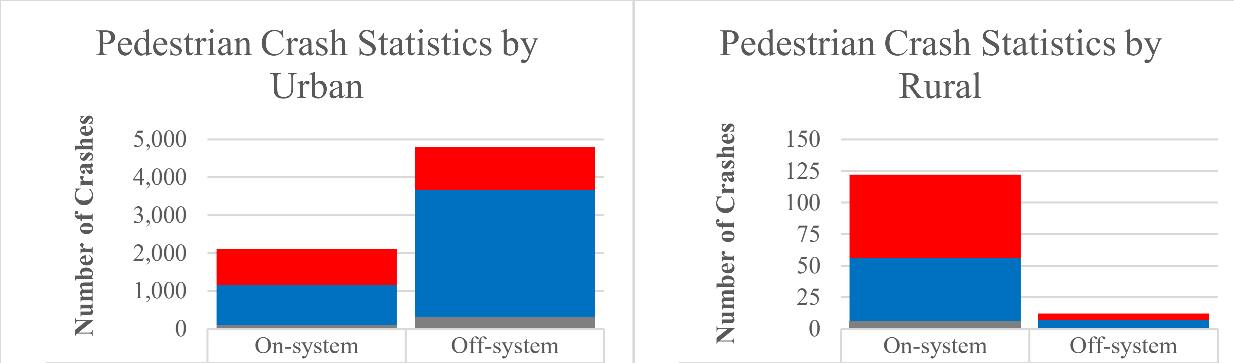


	Passenger Car	SUV/Van/Truck	Unknown	Freight Truck	Emergency Vehicle
K Crashes	27	16	7	1	0
A Crashes	161	177	38	6	0
B/C Crashes	1,010	936	150	25	9
PDO Crashes	206	143	34	5	1
Unknown	2	0	4	0	0

Figure 4.9 Pedalcyclist Crash Statistics by Vehicle Type.

Urban/Rural

Figure 4.10 provides pedestrian crash statistics by crash severity for on-system and off-system crashes in rural and urban conditions. In rural areas, majority of fatal and serious crashes occurred on-system roadways. In urban areas, majority of pedestrian crashes that resulted in injuries (B/C) were off-system, however fatal and serious injury crashes were almost as high on-system (954) as off-system (1,132).



Pedestrian Crash Statistics by Urban

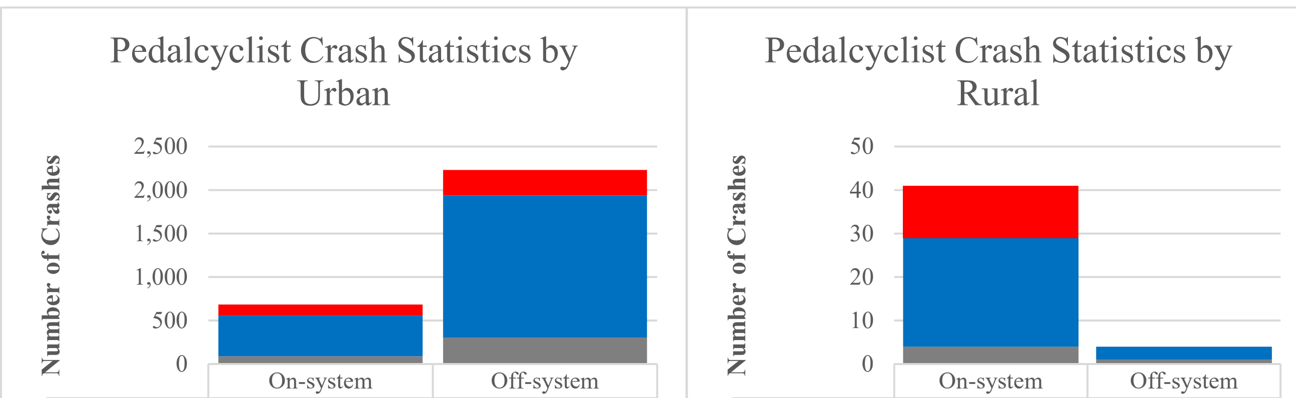
	On-system	Off-system
K/A Crashes	954	1,132
B/C Crashes	1,055	3,346
PDO Crashes	96	307
Unknown	6	16

Pedestrian Crash Statistics by Rural

	On-system	Off-system
K/A Crashes	66	5
B/C Crashes	50	7
PDO Crashes	6	0
Unknown	0	0

Figure 4.10 Pedestrian Crash Statistics by Rural and Urban.

Figure 4.11 summarizes pedalcyclist crash statistics by crash severity for on-system and off-system crashes in rural and urban conditions. In rural areas, all fatal and serious pedalcyclist crashes occurred on-system roadways. In urban areas, majority of pedalcyclist crashes that resulted in injuries (B/C) were off-system, however fatal and serious injury crashes off-system (293) were more than double of those on-system (128).



Pedalcyclist Crash Statistics by Urban

	On-system	Off-system
K/A Crashes	128	293
B/C Crashes	466	1,636
PDO Crashes	86	298
Unknown	3	3

Pedalcyclist Crash Statistics by Rural

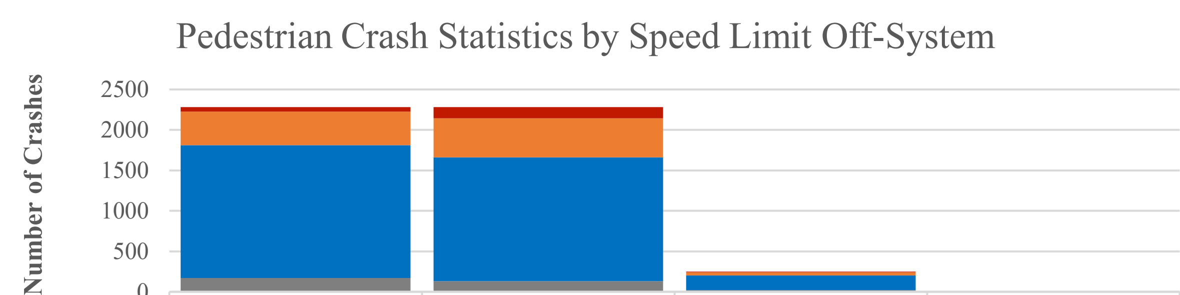
	On-system	Off-system
K/A Crashes	12	0
B/C Crashes	25	3
PDO Crashes	4	1
Unknown	0	0

Figure 4.11 Pedalcyclist Crash Statistics by Rural and Urban.

4.1.2 Roadway Elements

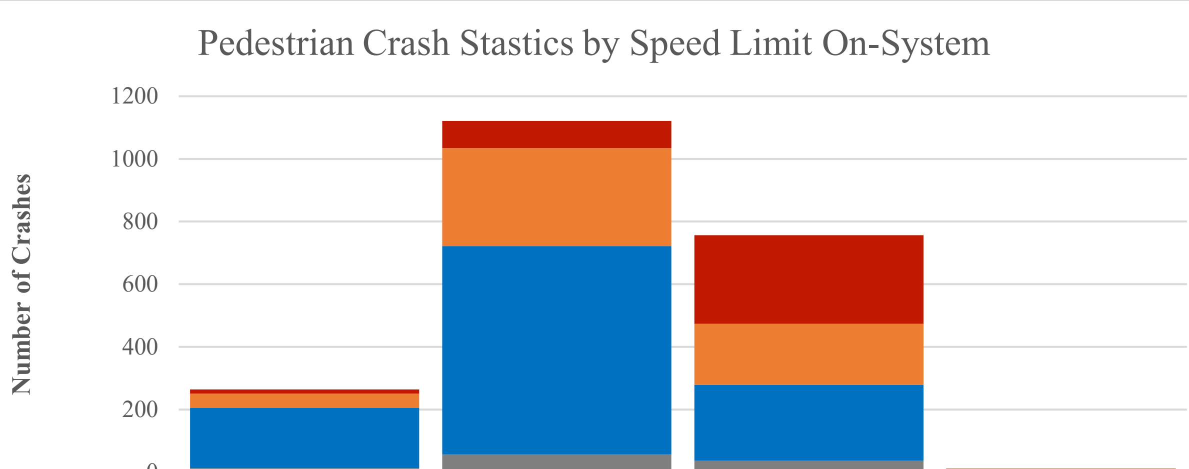
Speed

Figures 4.12 and 4.13 summarize pedestrian crash statistics by speed limit for on-system and off-system roadways. Off-system roadways with speed limit at or below 30 mph had the lowest pedestrian fatality and serious injury rate of 21%. The fatality rate appears to be rising with posted speed, with the highest fatality rate of 63% on on-system roadways with speed limits over 50 mph.



	Up to 30 mph	30-50 mph	Unknown	Over 50 mph
K Crashes	54	138	8	0
A Crashes	414	483	39	1
B/C Crashes	1,642	1,529	180	2
PDO Crashes	161	130	16	0
Unknown	9	2	5	0

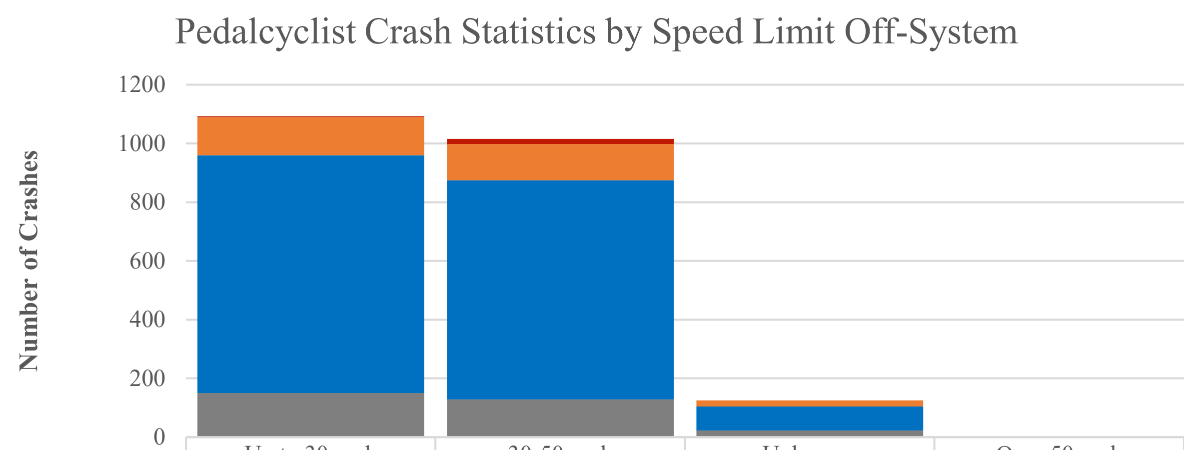
Figure 4.12 Pedestrian Crash Statistics by Speed Limit, Off-System.



	Up to 30 mph	30-50 mph	Over 50 mph	Unknown
K Crashes	13	87	283	1
A Crashes	46	312	196	3
B/C Crashes	192	665	242	6
PDO Crashes	9	55	36	2
Unknown	4	2	0	0

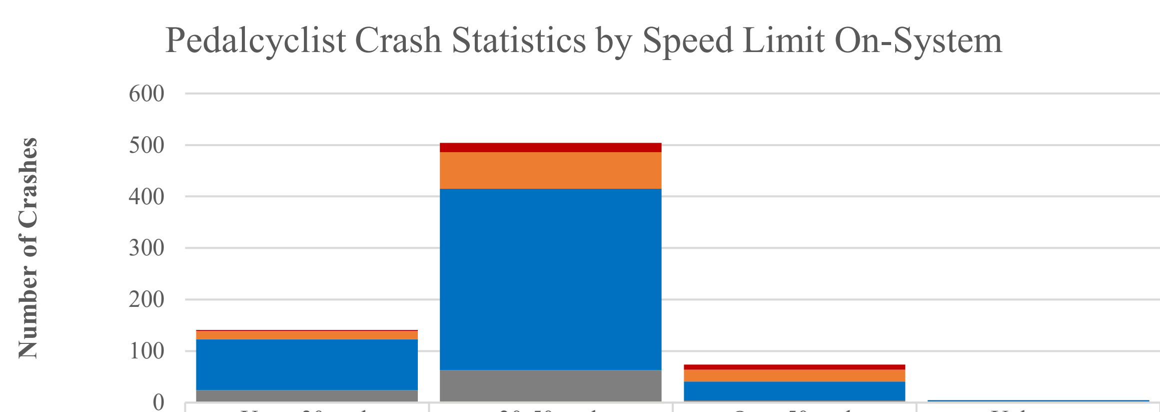
Figure 4.13 Pedestrian Crash Statistics by Speed Limit, On-System.

Figures 4.14 and 4.15 summarize pedalcyclist crash statistics by speed limit for on-system and off-system roadways. Similar to pedestrian statistics, pedalcyclist statistics show that off-system roadways with speed limit at or below 30 mph had the lowest fatality and serious injury rate of 12%. Also, the pedalcyclist fatality rate appears to be rising with posted speed, with the highest fatality rate of 45% on on-system roadways with speed limits over 50 mph.



	Up to 30 mph	30-50 mph	Unknown	Over 50 mph
K Crashes	4	17	0	0
A Crashes	129	123	20	0
B/C Crashes	810	746	82	1
PDO Crashes	149	127	23	0
Unknown	1	2	0	0

Figure 4.14 Pedalcyclist Crash Statistics by Speed Limit Off-System.

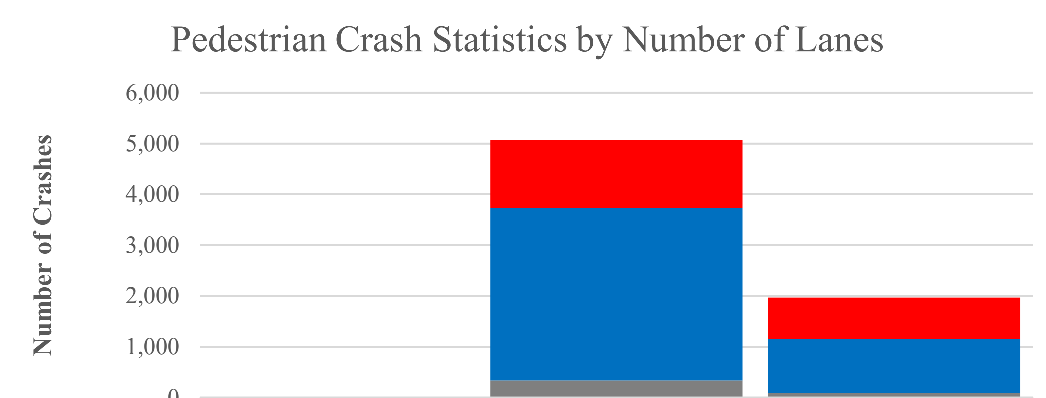


	Up to 30 mph	30-50 mph	Over 50 mph	Unknown
K Crashes	2	18	10	0
A Crashes	16	71	23	0
B/C Crashes	99	352	37	3
PDO Crashes	24	61	3	2
Unknown	0	2	1	0

Figure 4.15 Pedalcyclist Crash Statistics by Speed Limit On-System.

Number of Lanes

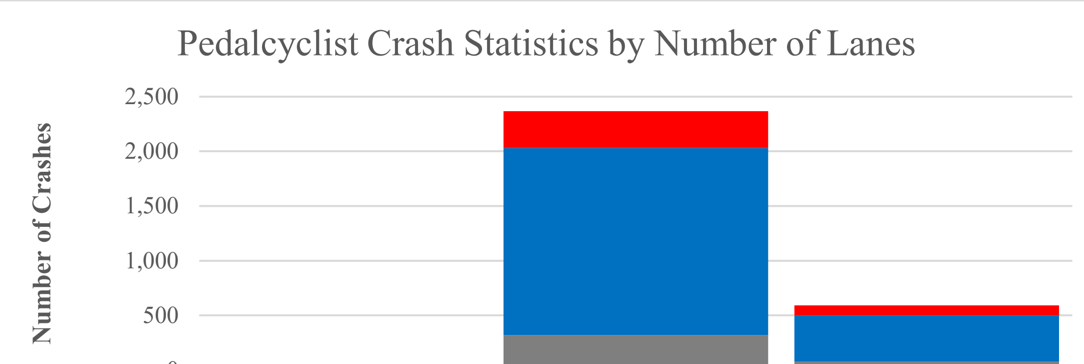
Figure 4.16 gives pedestrian crash statistics by crash severity for number of travel lanes. A majority of pedestrian crashes occurred on roadways with 2 to 4 lanes (72%) and 28% of all crashes occurred on roadways with more than 4 lanes.



	1 lane	2 – 4 lanes	More than 4 lanes
K/A Crashes	3	1,336	818
B/C Crashes	5	3,395	1,058
PDO Crashes	1	316	92
Unknown	0	19	3

Figure 4.16 **Pedestrian Crash Statistics by Number of Lanes.**

Figure 4.17 provides pedalcyclist crash statistics by crash severity for number of travel lanes. Roadways with 2 to 4 lanes experienced the highest proportion of pedalcyclist crashes (80%) and 20% of all crashes occurred on roadways with more than 4 lanes.

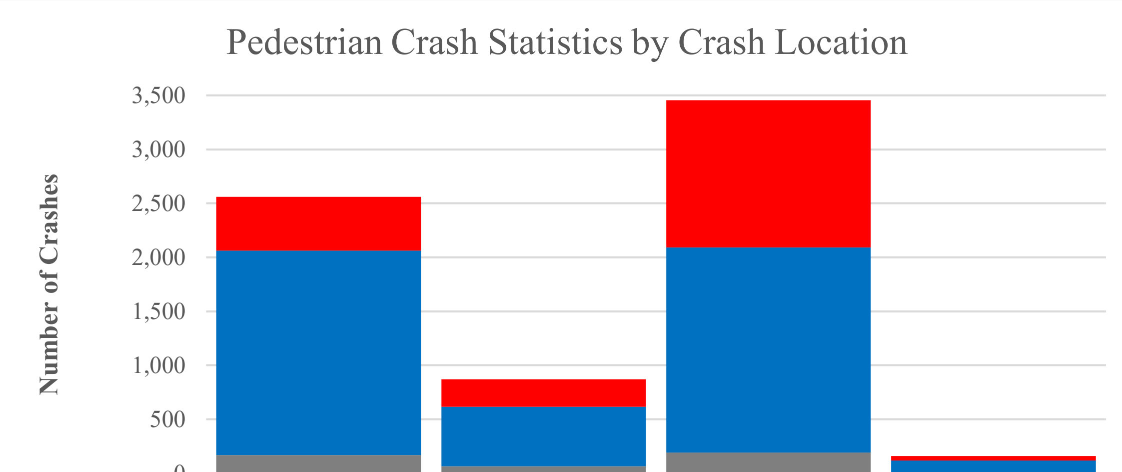


	1 lane	2 – 4 lanes	More than 4 lanes
K/A Crashes	0	338	95
B/C Crashes	0	1,710	420
PDO Crashes	0	315	74
Unknown	0	4	2

Figure 4.17 Pedalcyclist Crash Statistics by Number of Lanes.

Crash Location

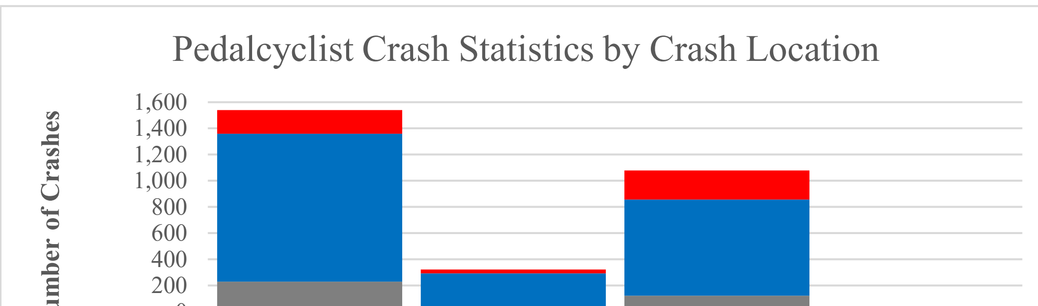
Figure 4.18 gives pedestrian crash statistics by crash severity for different crash locations. Majority of fatal and serious injury pedestrian crashes (40%) occurred at non-intersection locations.



	Intersection	Intersection-related	Non-intersection	Non-roadway
K/A Crashes	498	255	1,363	41
B/C Crashes	1,895	552	1,900	111
PDO Crashes	158	57	186	8
Unknown	9	7	6	0

Figure 4.18 Pedestrian Crash Statistics by Crash Location.

Figure 4.19 gives pedestrian crash statistics by crash severity for different crash locations. Most of fatal and serious injury pedalcyclist crashes occurred at non-intersection locations as well as directly at intersections.



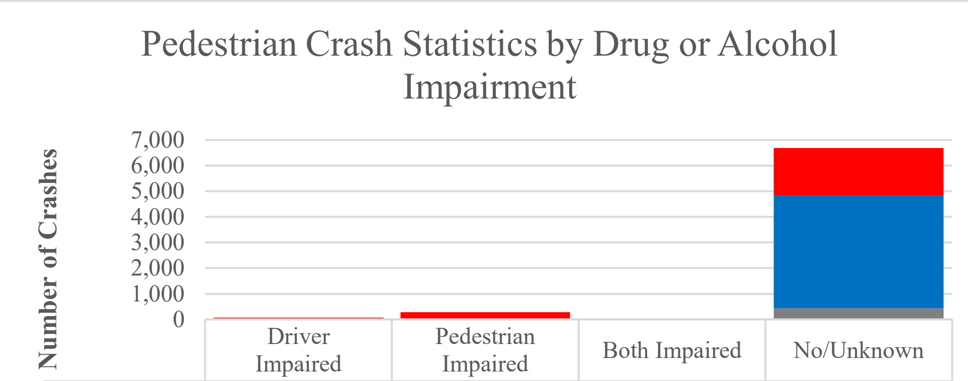
	Intersection	Intersection-related	Non-intersection	Non-roadway
K/A Crashes	180	30	221	2
B/C Crashes	1,130	253	734	13
PDO Crashes	227	40	121	1
Unknown	3	0	3	0

Figure 4.19 Pedalcyclist Crash Statistics by Crash Location.

4.1.3 Actions Prior to Crash

Impairment

Figure 4.20 shows pedestrian crash statistics for alcohol and drug impairment. From 281 crashes where a pedestrian was impaired, 275 of them (9%) resulted in fatal or serious injuries.



	Driver Impaired	Pedestrian Impaired	Both Impaired	No/Unknown
K/A Crashes	40	275	11	1830
B/C Crashes	26	3	0	4427
PDO Crashes	2	3	0	404
Unknown	0	0	0	25

Figure 4.20 Pedestrian Crash Statistics by Drug and Alcohol Impairment.

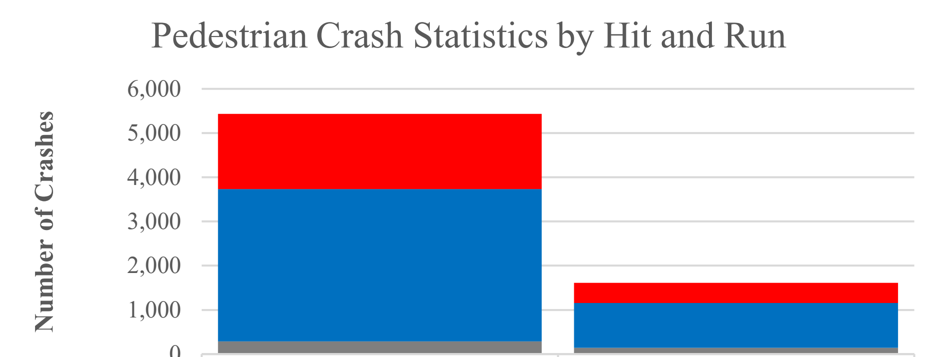
Figure 4.21 shows pedalcyclist crash statistics for alcohol and drug impairment. Crashes where a driver was impaired accounted for 0.4% (13 out of 2958 crashes) and a pedalcyclist was impaired in 10 crashes that resulted in serious or fatal injuries. The crash database indicated a negative or unknown impairment in majority of the crashes.

	Driver Impaired	Pedalcyclist Impaired	Both Impaired	No/Unknown
K/A Crashes	5	10	0	418
B/C Crashes	7	0	0	2123
PDO Crashes	1	0	0	387
Unknown	0	0	0	7

Figure 4.21 Pedalcyclist Crash Statistics by Drug and Alcohol Impairment.

Hit and Run

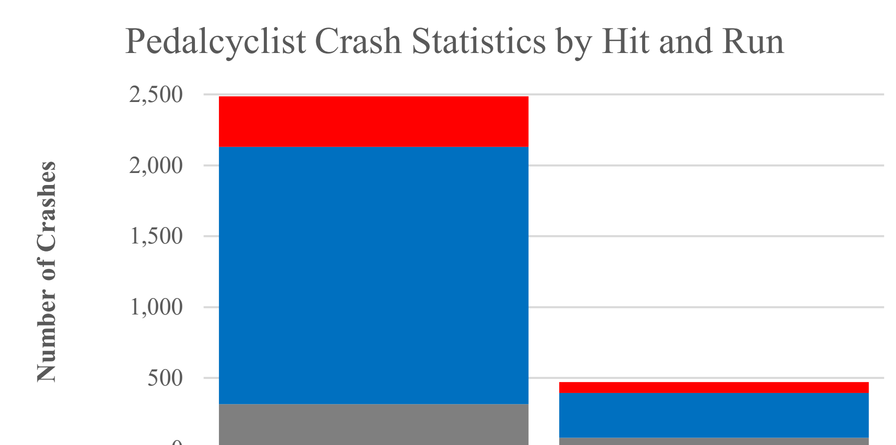
Figure 4.22 shows pedestrian crash statistics for hit and run crashes. During the five-year period, a total of 1,609 pedestrian crashes (23%) were identified as a hit and run.



	Not Hit and Run	Hit and Run
K/A Crashes	1,706	451
B/C Crashes	3,440	1,018
PDO Crashes	286	123
Unknown	5	17

Figure 4.22 Pedestrian Crash Statistics by Hit and Run.

Figure 4.23 gives pedalcyclist crash statistics for hit and run crashes. During the five-year period, a total of 471 pedalcyclist crashes (16%) were identified as a hit and run.

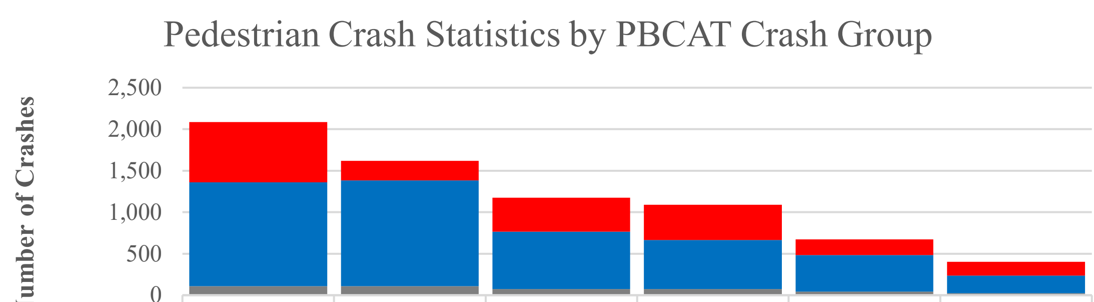


	Not Hit and Run	Hit and Run
K/A Crashes	356	77
B/C Crashes	1,816	314
PDO Crashes	314	75
Unknown	1	5

Figure 4.23 Pedalcyclist Crash Statistics by Hit and Run.

PBCAT Crash Group / Most Common Crash Types

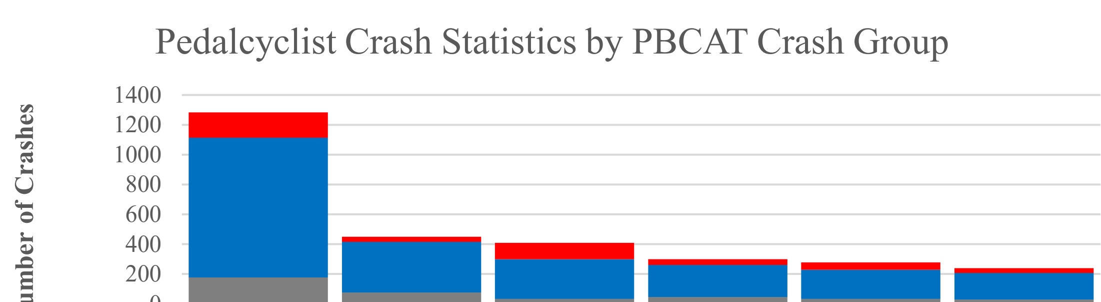
Figure 4.24 provides pedestrian crash statistics by crash severity for PBCAT crash groups that summarize the actions prior to crash. Crossing roadway (with vehicles not turning or turning) lead to the highest number of fatal and serious crashes, as well as unusual circumstances, such as disabled-vehicle related crashes. Crossing expressway resulted in fatal and serious injuries in 70% of crashes.



	Crossing Roadway-Vehicle Not Turning	Crossing Roadway-Vehicle Turning	All Other PBCAT Crash Groups	Unusual Circumstances	Dash/Dart-Out	Walking Along Roadway
K/A Crashes	729	236	409	425	190	168
B/C Crashes	1,251	1,275	691	588	441	212
PDO Crashes	102	101	70	75	40	21
Unknown	6	6	4	1	3	2

Figure 4.24 Pedestrian Crash Statistics by PBCAT Crash Group.

Figure 4.25 shows pedalcyclist crash statistics by crash severity for PBCAT crash groups that summarize the actions prior to crash. Motorist overtaking bicyclist lead to the highest number of fatal and serious crashes.



	All Other PBCAT Crash Groups	Motorist Failed to Yield-Sign-Controlled Intersection	Motorist Overtaking Bicyclist	Motorist Left Turn/Merge	Bicyclist Failed to Yield-Midblock	Bicyclist Failed to Yield-Sign-Controlled Intersection
K/A Crashes	169	35	109	39	49	32
B/C Crashes	936	338	267	213	197	179
PDO Crashes	173	77	32	47	32	28
Unknown	5	0	1	0	0	0

Figure 4.25 Pedalcyclist Crash Statistics by PBCAT Crash Group.

4.1.4 Summary of the Results

The descriptive trend analysis was based on a total of 7,046 pedestrian and 2,958 pedalcyclist crashes that occurred during 2014-2018 in North Central Texas. The key findings include:

- The highest number of pedestrian crashes occurred in year 2015 but by 2018 pedestrian crashes have declined by 12 percent. The highest number of pedalcyclist crashes occurred in year 2017 and by 2018 also pedalcyclist crashes have declined by 11 percent.

- During the five-year period, approximately 31% of pedestrian crashes resulted in fatal or serious injuries. Approximately 15% of all crashes that involved a pedalcyclist resulted in fatal or serious injuries.

- The month with the highest number of pedestrian crashes was October and for pedalcyclists the month with the most crashes was September. Overall, pedestrian crashes were highest during months of September through January, while pedalcyclist crashes were highest from March through October.

- Pedestrian crashes occurred most frequently on Fridays and were lowest on Sundays. Pedalcyclist crashes were higher during workdays and lowest on weekends.

- Almost 95% of all pedestrian crashes and 92% of K/A crashes occurred in only four counties: Dallas, Tarrant, Denton, and Collin, while only 88% of the region's population resides in these counties. Majority of pedalcyclist crashes (95% of all crashes and 92% of K/A crashes) occurred in only four counties: Dallas, Tarrant, Denton, and Collin.

- While many fatal and serious pedestrian crashes occurred during daylight (36%), more than a half (60%) occurred in dark (lighted and not lighted) conditions. The majority of fatal and serious pedalcyclist crashes occurred during daylight (59%). The crash frequency of fatal and serious pedalcyclist crashes was similar in dark but lighted conditions (19%) and in not lighted (16%).

- More than 93% of crashes with passenger vehicles, SUV/van/truck, or freight trucks resulted in injuries (K/A/B/C). About one third of crashes with passenger vehicles (31%) and SUV/van/truck (31%) resulted in fatal or serious injuries, while half of crashes (52%) between pedestrians and freight trucks resulted in fatalities and serious injuries. While majority of crashes between pedalcyclists and motorized vehicles resulted in injuries (B/C), about 13% of crashes with passenger vehicles were fatal or serious (15% for SUV/van/truck and 19% for freight trucks).

- In rural areas, majority of fatal and serious crashes occurred on-system roadways. In urban areas, majority of pedestrian crashes that resulted in injuries (B/C) were off-system, however fatal and serious injury crashes were almost as high on-system (954) as off-system (1,132).

- In rural areas, all fatal and serious pedalcyclist crashes occurred on-system roadways. In urban areas, majority of pedalcyclist crashes that resulted in injuries (B/C) were off-system, however fatal and serious injury crashes off-system (293) were more than double of those on-system (128).

- Off-system roadways with speed limit at or below 30 mph had the lowest pedestrian fatality and serious injury rate of 21 percent. The fatality rate appears to be rising with posted speed, with the highest fatality rate of 63% on on-system roadways with speed limits over 50 mph. Similar to the pedestrian statistics, the pedalcyclist statistics show that off-system roadways with speed limit at or below 30 mph had the lowest fatality and serious injury rate of 12%. Also, the pedalcyclist fatality rate appears to be rising with posted speed, with the highest fatality rate of 45% on on-system roadways with speed limits over 50 mph.

- A majority of pedestrian crashes occurred on roadways with 2 to 4 lanes (72%) and 28% of all crashes occurred on roadways with more than 4 lanes. Roadways with 2 to 4 lanes experienced the highest proportion of pedalcyclist crashes (80%) and 20% of all crashes occurred on roadways with more than 4 lanes.

- A majority of fatal and serious injury pedestrian crashes (40%) occurred at non-intersection locations, while most of fatal and serious injury pedalcyclist crashes occurred at non-intersection locations as well as directly at intersections.

- From 425 crashes where either driver or pedestrian was impaired, 389 (92%) of them resulted in fatal or serious injuries. Of 24 crashes where either driver or pedalcyclist was impaired, 16 (67%) of them resulted in fatal or serious injuries. The crash database indicated unknown impairment.

- During the five-year period, a total of 1,609 pedestrian crashes (23%) were identified as a hit and run. During the five-year period, a total of 471 pedalcyclist crashes (16%) were identified as a hit and run.

- *Crossing roadway* (with vehicles not turning or turning) lead to the highest number of fatal and serious crashes, as well as unusual circumstances such as *Disabled-Vehicle* related crashes. *Crossing expressway* resulted in fatal and serious injuries in 70% of crashes. For pedalcyclists, *Motorist overtaking bicyclist* led to the highest number of fatal and serious crashes.

4.2 Statistical Crash Analytical Modelling

The primary objective of the crash analytical modelling is to reduce "severe and fatal" pedestrian and pedalcyclist crashes. This section describes the final multinomial logit (MNL) model adopted for this research study. Logistic regression (Logit model) is used to measure the categorical dependent variable (Y) as a linear combination of multiple independent variables (X) by using the logit transfer function. In a binary logistic regression model, the dependent variable has two levels. Outputs with more than two values are modeled by multinomial logistic regression or MNL or by ordinal logistic regression. MNL based random and fixed effects models has been most commonly used for similar crash severity analysis (Chen, Zhen, & Fan, 2019; Wang, Jun, Chen, & Xiaofei, 2018; Haleem, Kirolos, & Gan, 2013; Wahab, Lukuman, & Jiang, 2019; Ye, Fan, & Lord, 2014; Salon, Deborah, & McIntyre, 2018; Pour-Rouholamin, Mahdi, & Huaguo, 2016; Aziz, Abdul, Ukkusuri Satish, & Hasan, 2013). MNL models are useful in determining the factors that contribute to the Severity of a crash. Other modeling methods based on tree algorithms (Bernard 2017; Park et al. 2016), and Bayesian belief networks (Bernard, 2017; Zong, et al., 2019; Cheng, et al., 2017) have also been used. It may be noted that the tree-based method (random forest and classification and regression tree) and Bayesian belief network modeling was also tested in this analysis but performed inadequately and have not been presented

4.2.1 Data Preparation and Modeling Method

For this analysis, the crash data set described in Chapter 3 was used. Figure 4.26 summarizes the steps of data processing and modeling. Crashes that involved pedestrian and pedalcyclists were separated into two datasets with 7,047 and 2,958 crash data points, respectively. In the preliminary data wrangling, all data set was coded and converted to ordinal or nominal categorical data, as discussed in the earlier sections. The crash *severity* was further characterized by two groups *"Fatal/Serious"* crashes and "*others*." Fatal/Serious (K/A) crashes represent the Severity that this project seeks to minimize.

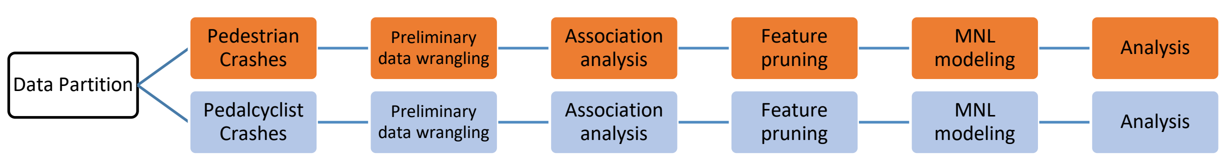


Figure 4.26 Summary of Steps in Data Preparation and Modeling.

The dataset was also analyzed for *"association"* using the Cramér's V measure. Measures of association (similar to correlation for continuous data) help to identify factors that may be similar to other factors. To improve regression performance, some highly associated factors that were thought to be measuring similar underlying phenomena were dropped from the final analysis to avoid high correlations among independent variables. The association analysis will also aid in grouping the factors together for planning the countermeasures in the later stages.

Finally, two MNL models were developed, one for the pedestrian dataset and another for the pedalcyclist dataset. Some factors were dropped due to a lack of statistical significance ($p<0.1$) and engineering judgment. The False Discovery Rate (FDR) "LogWorth," a process which gives the statistical significance of each factor, was used to correct for multiple comparisons of factors. The "*FDR LogWorth*" attribute of each effect (features) along with the *"Odds Ratio"* was used to understand the effect of each factor and level. LogWorth for each model effect, defined as $-\log_{10}$(p-value). This transformation adjusts p-values to provide an appropriate scale for graphing. A value that exceeds 2 is significant at the 0.01 level and exceeding one is significant at 0.1. FDR LogWorth shows the False Discovery Rate (FDR) LogWorth for each model effect, defined as $-\log_{10}$(FDR p-value). This is the best statistic for plotting and assessing significance. False Discovery Rate p-value for each model effect was calculated using the Benjamini-Hochberg technique. This technique adjusts the p-values to control the false discovery rate for multiple tests.

For two-level response modeling, as is the case here with levels of "fatal or serious, K/A" and "others," the MNL is as follows:

$$\log\left(\frac{Prob(\text{fatal or serious})}{Prob(not\ fatal\ or\ serious)}\right) = Xb$$

(Eq. 4-1)

Where X is the vector of effects, and b is the vector of regression coefficients. The odds as reported are

$$\frac{Prob(\text{fatal or serious})}{Prob(not\ fatal\ or\ serious)} = e^{Xb} = e^{b_0}.\, e^{b_1X_1}.\, e^{b_2X_2} \ldots e^{b_iX_i}$$

(Eq. 4-2)

4.2.2 Pedestrian Crash Analysis

The contingency table for pedestrian crashes that summarizes the factors and levels used for this analysis after preliminary data wrangling can be found in Appendix A. These factors have been further grouped into three broad categories Roadway Elements (E), Actions (A), and Conditions (C). Contingency tables help understand the distribution of crashes in the data set. For example, looking at *Driver Age* (from contingency table in Appendix A) and level "<16," we see that there were 16 crashes that involved drivers under the age of 16 and 8 of the 16 (50%) resulted in severe or fatal injuries.

The measure of association between all factors considered is in Figure 4.27. A high degree of association suggests that the factors may be representing the same underlying phenomenon. It may be seen that *Severity* is not closely associated with one factor. Table 4.3 shows the factors that have a high association (>0.6). Most associations are expected and may be explained. Associations between *Roadway-Roadway Type* and *Roadway-Straight/Curve* are extremely high (>0.9).

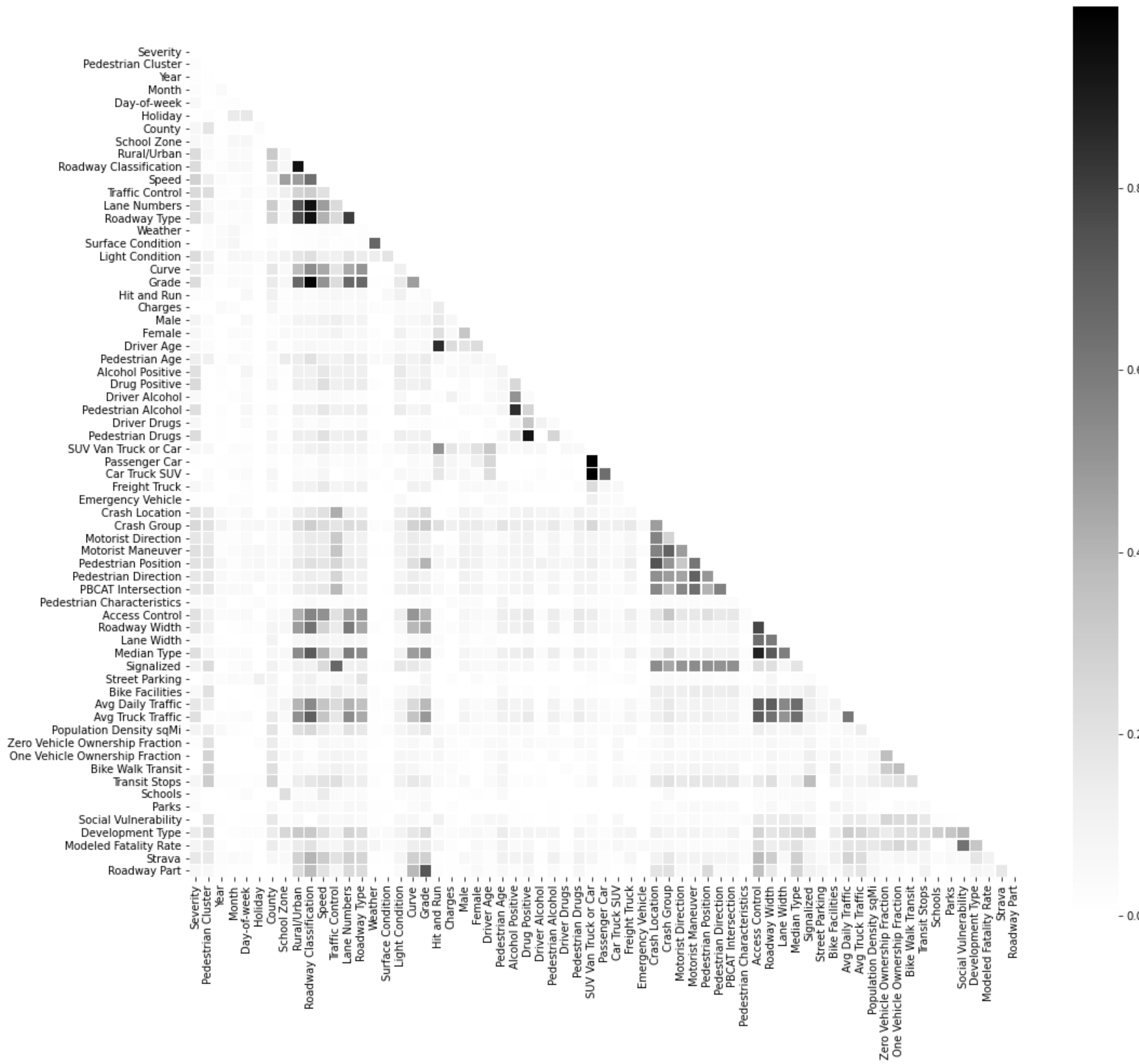


Figure 4.27 Degree of Association Among Feature Pairs for the Pedestrian Crash Dataset.

Table 4.3 Factors Showing a Cramer-V Association of >0.6 for the Pedestrian Dataset.

Feature	Associated Feature	Degree
Access Control	Median Type	0.89
Access Control	Roadway Width	0.78
Access Control	Avg Truck Traffic	0.71
Access Control	Avg Daily Traffic	0.70
Access Control	Lane Width	0.64
Alcohol Positive	Pedestrian Alcohol	0.84
Avg Daily Traffic	Roadway Width	0.71
Avg Daily Traffic	Access Control	0.70
Avg Daily Traffic	Median Type	0.65
Avg Daily Traffic	Avg Truck Traffic	0.61
Avg Truck Traffic	Access Control	0.71
Avg Truck Traffic	Roadway Classification	0.70
Avg Truck Traffic	Median Type	0.64
Avg Truck Traffic	Roadway Width	0.63
Avg Truck Traffic	Avg Daily Traffic	0.61
Car Truck SUV	Passenger Car	0.64
Crash Group	Motorist Maneuver	0.68
Crash Location	Pedestrian Position	0.74
Driver Age	Hit and Run	0.85
Drug Positive	Pedestrian Drugs	0.93
Grade	Roadway Part	0.73
Grade	Roadway Type	0.67
Grade	Rural/Urban	0.67
Grade	Lane Numbers	0.66
Hit and Run	Driver Age	0.85
Lane Numbers	Roadway Classification	0.94
Lane Numbers	Roadway Type	0.81
Lane Numbers	Rural/Urban	0.73
Lane Numbers	Grade	0.66
Lane Width	Access Control	0.64
Lane Width	Roadway Width	0.60
Median Type	Access Control	0.89
Median Type	Roadway Width	0.72
Median Type	Roadway Classification	0.72
Median Type	Avg Daily Traffic	0.65
Median Type	Avg Truck Traffic	0.64
Modeled Fatality Rate	Social Vulnerability	0.63
Motorist Maneuver	Pedestrian Direction	0.69
Motorist Maneuver	Crash Group	0.68

Feature	Associated Feature	Degree
Motorist Maneuver	PBCAT Intersection	0.64
Motorist Maneuver	Pedestrian Position	0.62
Passenger Car	Car Truck SUV	0.64
PBCAT Intersection	Motorist Maneuver	0.64
Pedestrian Alcohol	Alcohol Positive	0.84
Pedestrian Direction	Motorist Maneuver	0.69
Pedestrian Drugs	Drug Positive	0.93
Pedestrian Position	Crash Location	0.74
Pedestrian Position	Motorist Maneuver	0.62
Roadway Classification	Roadway Type	0.94
Roadway Classification	Rural/Urban	0.94
Roadway Classification	Lane Numbers	0.94
Roadway Classification	Median Type	0.72
Roadway Classification	Avg Truck Traffic	0.70
Roadway Classification	Speed	0.64
Roadway Classification	Roadway Width	0.62
Roadway Part	Grade	0.73
Roadway Type	Roadway Classification	0.94
Roadway Type	Lane Numbers	0.81
Roadway Type	Rural/Urban	0.77
Roadway Type	Grade	0.67
Roadway Width	Access Control	0.78
Roadway Width	Median Type	0.72
Roadway Width	Avg Daily Traffic	0.71
Roadway Width	Avg Truck Traffic	0.63
Roadway Width	Roadway Classification	0.62
Roadway Width	Lane Width	0.60
Rural/Urban	Roadway Classification	0.94
Rural/Urban	Roadway Type	0.77
Rural/Urban	Lane Numbers	0.73
Rural/Urban	Grade	0.67
Signalized	Traffic Control	0.67
Social Vulnerability	Modeled Fatality Rate	0.63
Speed	Roadway Classification	0.64
Surface Condition	Weather	0.67
Traffic Control	Signalized	0.67
Weather	Surface Condition	0.67

Thirteen out of the sixty-three factors were considered significant and included in the final model. The MNL model developed was found to be significant, with a log-likelihood reduction of 775 and 71 degrees of freedom (Table 4.4). The McFadden's R squared measure, *RSquare(U)*, is 0.18; other studies explaining Severity have suggested >0.1 as a good measure.

Drug Positive, Alcohol Positive, Speed, Pedestrian Age, Light Condition, Traffic Control, Driver Age, Crash Group, Motorist Maneuver, PBCAT Intersection, Freight Truck, and Pedestrian Position were statistically significant effects identified by the analysis ($p < 0.01$, 99% level). Transit Stops are statistically significant at $\alpha = 0.1$ ($p<0.1$ and LogWorth >1) may be useful for designing countermeasures. Comprehensive odds ratio and model coefficients are presented in Appendix A for the full model with all factors. The final model with 13 factors is in Appendix C. Comparing effect summary between two models will help guard against accidentally dropping a major factor. Table 4.5 also classifies the factors in the three broad groups of Actions, Conditions, and Roadway Elements.

Table 4.4 Whole Model Test Results for the Pedestrian Crash MNL.

Model	LogLikelihood	DF	ChiSquare	Prob>ChiSq
Difference	775.4454	71	1550.891	<.0001*
Full	3565.0450			
Reduced	4340.4904			
RSquare (U)	0.1787			
AICc	7279.68			
BIC	7785.76			
Observations	7047			

Table 4.5 Effect Summary for the Pedestrian Dataset.

Source	FDR LogWorth	Statistical Significance (99%)	FDR PValue	Class
Drug Positive	39.845		0.00000	Actions
Alcohol Positive	19.462		0.00000	Actions
Speed	18.641		0.00000	Rdwy Elements
Pedestrian Age	17.742		0.00000	Conditions
Light Condition	12.511		0.00000	Conditions
Traffic Control	4.131		0.00007	Rdwy Elements
Crash Group	3.904		0.00012	Actions
Driver Age	3.724		0.00019	Conditions
Motorist Maneuver	3.010		0.00098	Actions
Freight Truck	2.545		0.00285	Conditions
PBCAT Intersection	2.347		0.00449	Actions
Pedestrian Position	2.304		0.00496	Actions
Transit Stops	1.882		0.01311	Conditions

Note: The blue line indicates statistical significance at a 99% level.

From Table 4.6, lower speeds (1-23 and 24-32 mph) are less likely to result in K/A crash. Speed levels (indicating mph) of 59+, 51-58, 43-50, 33-42, and 24-32, when compared with speed level of 1-23 mph, are likely to increase the probability of a K/A crash by 6.5, 3.8, 4.1, 2.7, and 2.3 times respectively. Similar trends of increasing probability of a K/A crash are observed when levels 59+, 51-58, 43-50, and 33-42 are compared to 24-32 level. However, no significant difference in K/A crashes was observed when comparing levels 51-58 and 33-42.

Table 4.6 Selected Odds Ratio for "Speed" in the Pedestrian MNL Model.

Level1	Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
59+	1−23	6.49	<.0001*	4.03	10.46
51-58	1−23	3.81	<.0001*	2.12	6.84
43-50	1−23	4.09	<.0001*	2.60	6.43
33-42	1−23	2.72	<.0001*	1.78	4.17
24-32	1−23	2.31	0.0001*	1.51	3.54
1−23	24-32	0.43	0.0001*	0.28	0.66
59+	24-32	2.81	<.0001*	2.16	3.64
51-58	24-32	1.65	**0.0230***	1.07	2.53
43-50	24-32	1.77	<.0001*	1.44	2.18
33-42	24-32	1.18	**0.0315***	1.01	1.37
24-32	33-42	0.85	**0.0315***	0.73	0.99
1−23	33-42	0.37	<.0001*	0.24	0.56
59+	33-42	2.38	<.0001*	1.86	3.05
51-58	33-42	1.40	0.1193	0.92	2.13
43-50	33-42	1.50	<.0001*	1.24	1.82
33-42	43-50	0.67	<.0001*	0.55	0.81
24-32	43-50	0.56	<.0001*	0.46	0.70
1−23	43-50	0.24	<.0001*	0.16	0.38
59+	43-50	1.59	0.0010*	1.21	2.09
51-58	43-50	0.93	0.7464	0.60	1.44
43-50	51-58	1.08	0.7464	0.69	1.67
33-42	51-58	0.72	0.1193	0.47	1.09
24-32	51-58	0.61	**0.0230***	0.40	0.93
1−23	51-58	0.26	<.0001*	0.15	0.47
59+	51-58	1.70	**0.0174***	1.10	2.65
51-58	59+	0.59	**0.0174***	0.38	0.91
43-50	59+	0.63	0.0010*	0.48	0.83
33-42	59+	0.42	<.0001*	0.33	0.54
24-32	59+	0.36	<.0001*	0.27	0.46
1−23	59+	0.15	<.0001*	0.10	0.25

Note: The full odd ratio table is in Appendix C. Odds of >1 show a higher chance of a K/A crash when comparing among levels.

The odds ratio for *Light Condition* (Table 4.7), suggest some statistically significant evidence that the dark conditions (dark_not_lighted and dark_lighted) increase the probability of a K/A crash compared to daylight, and dusk. Dark (dark_not_lighter and dark_lighted) increase the probability of a K/A crash 1.7-1.8 times over daylight, over 1.7-1.9 times over dusk, and over 1.5-1.6 times over dawn (not statistically significant). There was not much evidence of a substantial difference between dawn vs. daylight and dark-not-lighted vs. dark-lighted.

Table 4.7 The Odds Ratio for "Light Conditions" in the Pedestrian MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
dark not lighted	dark lighted	1.07	0.4864	0.89	1.28
dark unknown lighting	dark lighted	0.82	0.4688	0.48	1.40
dawn	dark lighted	0.65	0.1562	0.35	1.18
daylight	dark lighted	0.60	<.0001*	0.52	0.69
dusk	dark lighted	0.57	**0.0172***	0.36	0.91
dark unknown lighting	dark not lighted	0.77	0.3471	0.44	1.33
dawn	dark not lighted	0.61	0.1088	0.33	1.12
daylight	dark not lighted	0.57	<.0001*	0.47	0.68
dusk	dark not lighted	0.54	0.0097*	0.34	0.86
dark lighted	dark not lighted	0.94	0.4864	0.78	1.12
dawn	dark unknown lighting	0.79	0.5583	0.36	1.75
daylight	dark unknown lighting	0.74	0.2658	0.43	1.26
dusk	dark unknown lighting	0.70	0.3135	0.35	1.40
dark lighted	dark unknown lighting	1.22	0.4688	0.71	2.09
dark not lighted	dark unknown lighting	1.30	0.3471	0.75	2.25
daylight	dawn	0.93	0.823	0.51	1.70
dusk	dawn	0.89	0.7546	0.42	1.86
dark lighted	dawn	1.55	0.1562	0.85	2.83
dark not lighted	dawn	1.65	0.1088	0.89	3.04
dark unknown lighting	dawn	1.27	0.5583	0.57	2.81
dusk	daylight	0.95	0.8296	0.61	1.49
dark lighted	daylight	1.66	<.0001*	1.44	1.91
dark not lighted	daylight	1.77	<.0001*	1.48	2.11
dark unknown lighting	daylight	1.36	0.2658	0.79	2.33
dawn	daylight	1.07	0.823	0.59	1.95
dark lighted	dusk	1.74	**0.0172***	1.10	2.75
dark not lighted	dusk	1.86	0.0097*	1.16	2.97
dark unknown lighting	dusk	1.43	0.3135	0.71	2.85
dawn	dusk	1.13	0.7546	0.54	2.36
daylight	dusk	1.05	0.8296	0.67	1.65

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

Drivers of age <16 are more likely to be in a K/A crash. The probability of a K/A crash increases by about four times if the driver is under 16 compared to all other age groups (Table 4.8). Majority of cases where driver age is <16 are crashes where driver age is 0, likely from an incomplete crash report. "Unknown" driver age corresponds to mostly a "hit-and-run" incident in over 93% of cases as likely the driver has fled the scene and no details are known.

Table 4.8 The Odds Ratio for "Driver Age" in the Pedestrian MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
driver_>60	driver_<16	0.26	**0.0109***	0.09	0.73
unknown	driver_<16	0.18	0.0013*	0.06	0.51
driver_16_25	driver_<16	0.25	0.0087*	0.09	0.70
driver_26_60	driver_<16	0.24	0.0072*	0.09	0.68
unknown	driver_>60	0.71	0.0023*	0.56	0.88
driver_16_25	driver_>60	0.97	0.7754	0.78	1.21
driver_26_60	driver_>60	0.94	0.5497	0.78	1.14
driver_<16	driver_>60	3.88	**0.0109***	1.37	11.01
driver_26_60	driver_16_25	0.97	0.7396	0.83	1.14
driver_<16	driver_16_25	4.01	0.0087*	1.42	11.30
driver_>60	driver_16_25	1.03	0.7754	0.83	1.29
unknown	driver_16_25	0.73	0.0013*	0.60	0.88
driver_<16	driver_26_60	4.12	0.0072*	1.47	11.54
driver_>60	driver_26_60	1.06	0.5497	0.87	1.29
unknown	driver_26_60	0.75	0.0004*	0.64	0.88
driver_16_25	driver_26_60	1.03	0.7396	0.88	1.20
driver_16_25	unknown	1.37	0.0013*	1.13	1.66
driver_26_60	unknown	1.34	0.0004*	1.14	1.57
driver_<16	unknown	5.49	0.0013*	1.95	15.50
driver_>60	unknown	1.42	0.0023*	1.13	1.77

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

From Table 4.9, pedestrians over the age of 60 (level >60) show a statistically significant chance of having a K/A crash compared to all other groups. They are 2.3, 2.4, and 1.6 times more likely to have a K/A crash than <16, 16-25, and 26–60 year-old pedestrians, respectively. Pedestrians 26-60 also are more likely to have a K/A crash compared to <16 and 16-25.

Table 4.9 The Odds Ratio for "Pedestrian Age" in the Pedestrian MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
pedestrian_>60	pedestrian_<16	2.34	<.0001*	1.86	2.95
pedestrian_16_25	pedestrian_<16	0.97	0.7901	0.78	1.20
pedestrian_26_60	pedestrian_<16	1.47	<.0001*	1.22	1.77
pedestrian_16_25	pedestrian_>60	0.41	<.0001*	0.33	0.51

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
pedestrian_26_60	pedestrian_>60	0.63	<.0001*	0.52	0.75
pedestrian_<16	pedestrian_>60	0.43	<.0001*	0.34	0.54
pedestrian_26_60	pedestrian_16_25	1.51	<.0001*	1.29	1.78
pedestrian_<16	pedestrian_16_25	1.03	0.7901	0.83	1.28
pedestrian_>60	pedestrian_16_25	2.41	<.0001*	1.95	2.99
pedestrian_<16	pedestrian_26_60	0.68	<.0001*	0.56	0.82
pedestrian_>60	pedestrian_26_60	1.59	<.0001*	1.33	1.91
pedestrian_16_25	pedestrian_26_60	0.66	<.0001*	0.56	0.78

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

For *Motorist Maneuvers* (Table 4.10), there is a statistically significant effect on the Severity when going straight vs. turning (both left or right). A crash where the motorist maneuver is straight opposed to left turn increases the probability of a K/A pedestrian crash 1.8 times. A motorist maneuver of straight vs. right-turn increases the probability of a K/A pedestrian crash 2.2 times. This may be due to the fact that turning movement slows the car down, so injury levels are less severe.

Table 4.10 The Odds Ratio for "Motorist Maneuver" in the Pedestrian MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
right_turn	left_turn	0.81	0.2053	0.58	1.12
straight	left_turn	1.78	0.0015*	1.25	2.54
straight	right_turn	2.20	<.0001*	1.49	3.27
left_turn	right_turn	1.24	0.2053	0.89	1.72
left_turn	straight	0.56	0.0015*	0.39	0.80
right_turn	straight	0.45	<.0001*	0.31	0.67

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

Having 3+ *Transit Stops* within 300 ft. from crash location, compared to other levels (0, 1-2), decreases the probability of a K/A crash (Table 4.11). The effect is not very strong but statistically significant.

Table 4.11 The Odds Ratio for "Transit Stops" in the Pedestrian MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
1_2	0	0.94	0.3896	0.82	1.08
3+	0	0.71	0.0038*	0.57	0.90
3+	1_2	0.76	**0.0187***	0.60	0.95
0	1_2	1.06	0.3896	0.93	1.22
0	3+	1.40	0.0038*	1.12	1.76
1_2	3+	1.32	**0.0187***	1.05	1.66

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

Having 3 or more transit stops, compared to other levels (0, 1-2), decreases the probability of a K/A crash (Table 4.31). The effect is not very strong but statistically significant.

For significant levels in Traffic Controls, Alcohol Positive, Drug Positive, Freight Truck, Crash Group, PBCAT Intersection, and Pedestrian Positions factors, please refer to odds ratio tables in Appendix C.

For *Traffic Controls, Crash Group*, and *Pedestrian Position,* no significant trends were observed. Some levels were statistically significant. Please refer to the Odds ratio in Appendix C for a detailed comparison of various levels.

Alcohol Positive for any person involved in the crash was found to increase the probability of K/A crash by six times. *Alcohol Positive* has a strong association with *Pedestrian Alcohol*. Similarly, a *Drug Positive* for any person involved was found to increase the probability of a K/A crash about 34 times. A separate analysis was performed to separate the effects of driver and pedestrian, alcohol, and drugs. It was estimated that *Pedestrian Alcohol* is likely to increase the probability of K/A crashes 33 times. *Driver Alcohol* had no statistically significant effect on K/A crash. For Drugs, both *Driver Drugs* and *Pedestrian Drugs* can increase the probability of a K/A crash by 10 and 53 times, respectively.

Presence of a *Freight Truck* increased the probability of a K/A crash 1.7 times.

If the *PBCAT Intersection* is far vs. near (crashes that occurred when pedestrian is at far side of the intersection), the probability of a K/A crash increases by 1.5 times.

4.2.3 Pedalcyclist Crash Analysis

As with pedestrian analysis, the Contingency table showing the count of crashes at various effect levels is in Appendix B.

Figure 4.28 and Table 4.12 show the degree of association between various features. As with the pedestrian crash dataset, Severity is not closely associated with any other factor. Most of the associations observed in Table 4.12 (>0.6) may be explained and are expected.

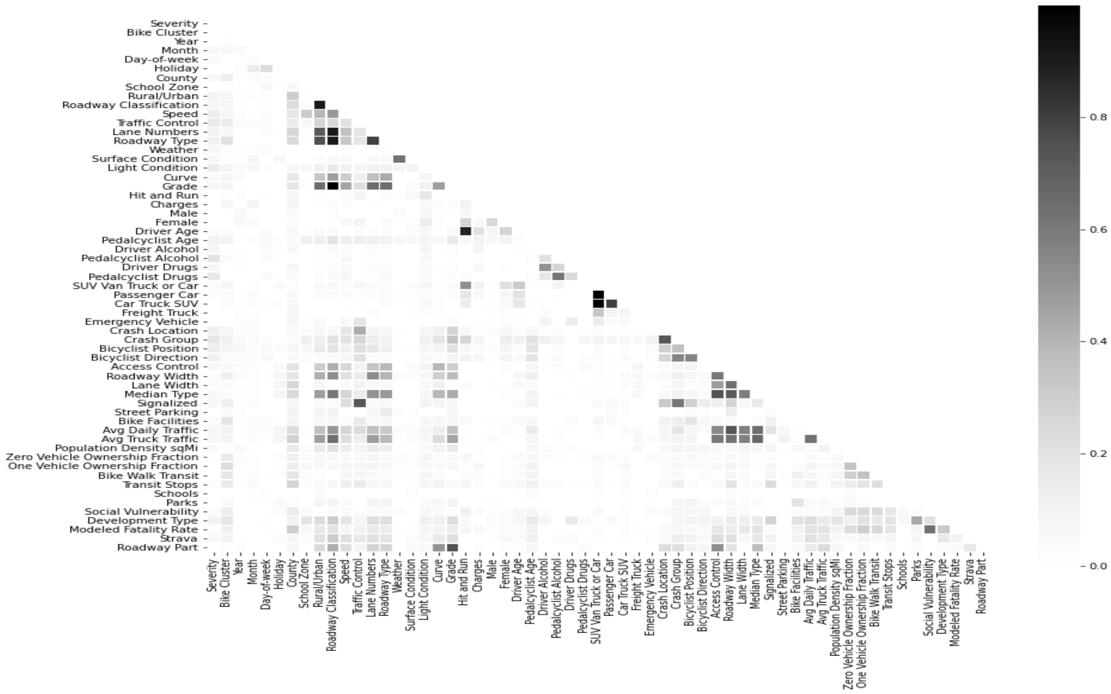


Figure 4.28 Degree of Association Between Feature Pairs for the Pedalcyclist Dataset.

Table 4.12 Factors Showing a Cramer-V Association of >0.6 for the Pedalcyclist Dataset.

Feature	Associated Feature	Degree
Access Control	Roadway Width	0.61
Access Control	Median Type	0.75
Access Control	Avg Truck Traffic	0.61
Avg Daily Traffic	Roadway Width	0.73
Avg Daily Traffic	Median Type	0.64
Avg Daily Traffic	Avg Truck Traffic	0.62
Avg Truck Traffic	Roadway Classification	0.64
Avg Truck Traffic	Access Control	0.61
Avg Truck Traffic	Roadway Width	0.63
Avg Truck Traffic	Median Type	0.67
Avg Truck Traffic	Avg Daily Traffic	0.62
Car Truck SUV	Passenger Car	0.79
Crash Group	Crash Location	0.73
Crash Group	Signalized	0.61
Crash Location	Crash Group	0.73
Driver Age	Hit and Run	0.89
Grade	Rural/Urban	0.65
Grade	Lane Numbers	0.65
Grade	Roadway Type	0.65
Grade	Roadway Part	0.75

Feature	Associated Feature	Degree
Hit and Run	Driver Age	0.89
Lane Numbers	Rural/Urban	0.72
Lane Numbers	Roadway Classification	0.91
Lane Numbers	Roadway Type	0.80
Lane Numbers	Grade	0.65
Lane Width	Roadway Width	0.63
Median Type	Roadway Classification	0.61
Median Type	Access Control	0.75
Median Type	Roadway Width	0.72
Median Type	Avg Daily Traffic	0.64
Median Type	Avg Truck Traffic	0.67
Modeled Fatality Rate	Social Vulnerability	0.63
Passenger Car	Car Truck SUV	0.79
Pedalcyclist Alcohol	Pedalcyclist Drugs	0.62
Pedalcyclist Drugs	Pedalcyclist Alcohol	0.62
Roadway Classification	Rural/Urban	0.91
Roadway Classification	Lane Numbers	0.91
Roadway Classification	Roadway Type	0.91
Roadway Classification	Median Type	0.61
Roadway Classification	Avg Truck Traffic	0.64
Roadway Part	Grade	0.75
Roadway Type	Rural/Urban	0.76
Roadway Type	Roadway Classification	0.91
Roadway Type	Lane Numbers	0.80
Roadway Type	Grade	0.65
Roadway Width	Access Control	0.61
Roadway Width	Lane Width	0.63
Roadway Width	Median Type	0.72
Roadway Width	Avg Daily Traffic	0.73
Roadway Width	Avg Truck Traffic	0.63
Rural/Urban	Roadway Classification	0.91
Rural/Urban	Lane Numbers	0.72
Rural/Urban	Roadway Type	0.76
Rural/Urban	Grade	0.65
Signalized	Traffic Control	0.73
Signalized	Crash Group	0.61
Social Vulnerability	Modeled Fatality Rate	0.63
Surface Condition	Weather	0.62
Traffic Control	Signalized	0.73
Weather	Surface Condition	0.62

The model was developed with six significant factors out of fifty-eight and was found to be statistically significant, with a loglikelihood reduction of 118 and 44 degrees of freedom (Table 4.13). The McFadden's R-squared measure, *RSquare(U)*, is 0.1.

Pedalcyclist Age, Speed, Light Condition, Crash Group, and Bicyclist Direction were significant factors at the 99% level (Table 4.14). *Driver Age* was significant at α = 0.1 (p<0.1 and LogWorth >1). Comprehensive odds ratio and model coefficients of the full model (with fifty-eight factors) are presented in Appendix B, and the reduced model is presented here is in Appendix D.

Table 4.13 Whole Model Test Results for the Pedalcyclist Crash MNL.

Model	LogLikelihood	DF	ChiSquare	Prob>ChiSq
Difference	118.0150	44	236.0301	<.0001*
Full	1113.6454			
Reduced	1231.6604			
RSquare (U)	0.0958			
AICc	2318.71			
BIC	2586.94			
Observations (or Sum Wgts)	2958			

Table 4.14 Effects Summary for the Pedalcyclist Crash MNL.

Source	LogWorth	Statistical Significance (99%)	PValue	Class
Pedalcyclist Age	6.050		0.00000	Conditions
Bicyclist Direction	3.658		0.00022	Actions
Speed	3.577		0.00027	Rdwy Elements
Crash Group	3.333		0.00046	Actions
Light Condition	3.247		0.00057	Conditions
Driver Age	1.234		0.05836	Conditions

Note: Blue line shows significance at 99%.

As with the pedestrian model, Speed Limits in 1-23 level (mph) reduce the odds of K/A crash (Table 4.15). The probability of a K/A crash is 11, 5, 3, 3, and 3 times higher for speed levels 59+, 51-58, 43-50, 33-42, and 24-32, respectively, when compared to level 1-23. Speed level of 59+ also consistently increases the probability of a K/A crash. All other levels do not show a significant difference.

Table 4.15 The Odds Ratio for "Speed Limits" in the Pedalcyclist MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
59+	1–23	11.434912	<.0001*	3.6178577	36.142164
51-58	1–23	4.8217414	0.0090*	1.4798934	15.710044
43-50	1–23	3.2636722	**0.0178***	1.2271819	8.6796882
33-42	1–23	2.6522256	**0.0435***	1.0289472	6.8364058

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
24-32	1–23	2.7473117	**0.0355***	1.0708017	7.048664
1–23	24-32	0.3639922	**0.0355***	0.1418709	0.9338797
59+	24-32	4.1622186	<.0001*	2.0495041	8.4528077
51-58	24-32	1.7550762	0.1486	0.8181527	3.7649361
43-50	24-32	1.1879512	0.3482	0.8289428	1.7024433
33-42	24-32	0.9653894	0.7926	0.7424754	1.255229
24-32	33-42	1.0358514	0.7926	0.7966674	1.3468459
1–23	33-42	0.3770418	**0.0435***	0.1462757	0.9718672
59+	33-42	4.3114401	<.0001*	2.1377895	8.6952039
51-58	33-42	1.8179982	0.1175	0.8600338	3.843009
43-50	33-42	1.230541	0.2284	0.8779624	1.7247105
33-42	43-50	0.8126507	0.2284	0.5798074	1.1390009
24-32	43-50	0.8417854	0.3482	0.5873911	1.2063559
1–23	43-50	0.3064033	**0.0178***	0.1152115	0.8148751
59+	43-50	3.5036949	0.0009*	1.6702279	7.349822
51-58	43-50	1.4773976	0.3268	0.6772041	3.2231102
43-50	51-58	0.6768659	0.3268	0.3102593	1.4766596
33-42	51-58	0.5500555	0.1175	0.2602128	1.162745
24-32	51-58	0.5697758	0.1486	0.2656088	1.2222657
1–23	51-58	0.207394	0.0090*	0.0636535	0.6757243
59+	51-58	2.3715315	0.0851	0.8875656	6.3366156
51-58	59+	0.4216684	0.0851	0.157813	1.1266773
43-50	59+	0.285413	0.0009*	0.1360577	0.5987207
33-42	59+	0.2319411	<.0001*	0.1150059	0.4677729
24-32	59+	0.2402565	<.0001*	0.1183039	0.4879229
1–23	59+	0.0874515	<.0001*	0.0276685	0.2764067

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

For *Light Conditions,* 'Dark not lighted' increased the probability of a K/A crash compared to 'Dark lighted' level by about 1.8 times (Table 4.16). Also, "daylight" was found to reduce the probability of K/A crash compared to "dark not lighted" conditions. No other level comparisons were significant.

Table 4.16 The Odds Ratio for "Light Conditions" in the Pedalcyclist MNL model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
dark not lighted	dark lighted	1.76	0.0070*	1.17	2.66
dark unknown lighting	dark lighted	1.54	0.4366	0.52	4.61
dawn	dark lighted	1.34	0.558	0.51	3.53
daylight	dark lighted	0.77	0.0782	0.57	1.03
dusk	dark lighted	1.35	0.3695	0.70	2.58

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
dark unknown lighting	dark not lighted	0.88	0.8155	0.29	2.66
dawn	dark not lighted	0.76	0.5855	0.28	2.05
daylight	dark not lighted	0.44	<.0001*	0.30	0.63
dusk	dark not lighted	0.76	0.4408	0.39	1.51
dark lighted	dark not lighted	0.57	0.0070*	0.38	0.86
dawn	dark unknown lighting	0.87	0.8428	0.21	3.58
daylight	dark unknown lighting	0.50	0.205	0.17	1.46
dusk	dark unknown lighting	0.87	0.8272	0.26	2.97
dark lighted	dark unknown lighting	0.65	0.4366	0.22	1.93
dark not lighted	dark unknown lighting	1.14	0.8155	0.38	3.47
daylight	dawn	0.57	0.2521	0.22	1.48
dusk	dawn	1.01	0.9898	0.33	3.06
dark lighted	dawn	0.75	0.558	0.28	1.98
dark not lighted	dawn	1.32	0.5855	0.49	3.56
dark unknown lighting	dawn	1.15	0.8428	0.28	4.78
dusk	daylight	1.75	0.0715	0.95	3.23
dark lighted	daylight	1.30	0.0782	0.97	1.75
dark not lighted	daylight	2.30	<.0001*	1.60	3.30
dark unknown lighting	daylight	2.01	0.205	0.68	5.92
dawn	daylight	1.74	0.2521	0.67	4.50
dark lighted	dusk	0.74	0.3695	0.39	1.42
dark not lighted	dusk	1.31	0.4408	0.66	2.59
dark unknown lighting	dusk	1.15	0.8272	0.34	3.90
dawn	dusk	0.99	0.9898	0.33	3.02
daylight	dusk	0.57	0.0715	0.31	1.05

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

Driver Age analysis shows that "driver >60" are generally involved in less K/A crashes (Table 4.17). However, a statistically significant difference was observed with the "driver 16-25" group. "Unknown" group corresponds with 'hit-and-run' incidents in over 93% of crashes. As with the pedestrian model, "unknown" are less likely to be in a K/A crash except for "driver > 60" group.

Table 4.17 The Odds Ratio for "Driver Age" in the Pedalcyclist MNL model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
driver_>60	driver_<16	0.52	0.5619	0.06	4.72
unknown	driver_<16	0.58	0.6233	0.06	5.19
driver_16_25	driver_<16	0.89	0.918	0.10	7.99
driver_26_60	driver_<16	0.70	0.7519	0.08	6.25
unknown	driver_>60	1.11	0.6411	0.72	1.69
driver_16_25	driver_>60	1.71	0.0078*	1.15	2.54

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
driver_26_60	driver_>60	1.35	0.0854	0.96	1.90
driver_<16	driver_>60	1.92	0.5619	0.21	17.37
driver_26_60	driver_16_25	0.79	0.1067	0.59	1.05
driver_<16	driver_16_25	1.12	0.918	0.13	10.05
driver_>60	driver_16_25	0.58	0.0078*	0.39	0.87
unknown	driver_16_25	0.65	**0.0240***	0.44	0.94
driver_<16	driver_26_60	1.42	0.7519	0.16	12.64
driver_>60	driver_26_60	0.74	0.0854	0.53	1.04
unknown	driver_26_60	0.82	0.2376	0.59	1.14
driver_16_25	driver_26_60	1.27	0.1067	0.95	1.69
driver_16_25	Unknown	1.55	**0.0240***	1.06	2.26
driver_26_60	unknown	1.22	0.2376	0.88	1.69
driver_<16	unknown	1.73	0.6233	0.19	15.61
driver_>60	unknown	0.90	0.6411	0.59	1.38

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

Pedalcyclist Age was tested at four levels: <16, 16-25, 26-60, and >60. Pedalcyclists >60 have an increased probability of a K/A crash compared to other age categories (Table 4.18). The odds ratio for a K/A crash for >60 vs <16 is 2.6; thus, the pedalcyclist of age >60 has 2.6 times more likely to have a K/A crash than <16 years old. Similarly, >60 pedalcyclist has 2.2 times more likely to have a K/A crash than a 16–25-year-old. The odds ratios for 26-60 vs <16 and 16-25 are significant, with magnitudes of 1.9 and 1.6, respectively.

Table 4.18 The Odds Ratio for "Pedalcyclist Age" in the Pedalcyclist MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
pedalcyclist_>60	pedalcyclist_<16	2.57	<.0001*	1.66	3.97
pedalcyclist_16_25	pedalcyclist_<16	1.19	0.3796	0.81	1.75
pedalcyclist_26_60	pedalcyclist_<16	1.89	0.0001*	1.37	2.61
pedalcyclist_16_25	pedalcyclist_>60	0.46	0.0006*	0.30	0.72
pedalcyclist_26_60	pedalcyclist_>60	0.74	0.1037	0.51	1.06
pedalcyclist_<16	pedalcyclist_>60	0.39	<.0001*	0.25	0.60
pedalcyclist_26_60	pedalcyclist_16_25	1.59	0.0038*	1.16	2.17
pedalcyclist_<16	pedalcyclist_16_25	0.84	0.3796	0.57	1.24
pedalcyclist_>60	pedalcyclist_16_25	2.16	0.0006*	1.39	3.34
pedalcyclist_<16	pedalcyclist_26_60	0.53	0.0001*	0.38	0.73
pedalcyclist_>60	pedalcyclist_26_60	1.36	0.1037	0.94	1.96
pedalcyclist_16_25	pedalcyclist_26_60	0.63	0.0038*	0.46	0.86

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

For *Bicyclist Direction* (Table 4.19), traveling with-traffic increases the probability of a K/A crash 2 times compared to going facing-traffic. This is due to the fact that majority of pedalcyclists follow the law and ride with traffic, therefore the crash dataset included more observations of K/A crashes for riding with traffic than facing traffic.

Table 4.19 The Odds Ratio for "Bicyclist Direction (PBCAT)" in the Pedalcyclist MNL Model.

Level1	/Level2	Odds Ratio	Prob>Chisq	Lower 95%	Upper 95%
with_traffic	facing_traffic	1.92	0.0001*	1.38	2.68
facing_traffic	with_traffic	0.52	0.0001*	0.37	0.72

Note: Odds of >1 show a higher chance of a K/A crash when comparing among levels.

For *Crash Group,* refer to the odds ratio tables in Appendix D.

4.2.4 Summary of the Results

The key findings from the multinomial logit (MNL) model include:

- 7,047 pedestrian crashes and 2,958 pedalcyclist crashes were analyzed using several MNL models to identify significant factors that may contribute to the Severity of a crash.
- For both pedestrian and pedalcyclist datasets, the Severity of a crash was not directly related to any other factor and limited association (correlation) among other factors was observed.
- Models for both pedestrians and pedalcyclist datasets were found to be significant at the 99% level.
- Thirteen factors were considered significant for the Pedestrian MNL model these include Drug Positive, Alcohol Positive, Speed, Pedestrian Age, Light Condition, Traffic Control, Driver Age, Crash Group, Motorist Maneuver, PBCAT Intersection, Freight Truck, and Pedestrian Position.
- Other pedestrian crash assessment:
    - A Speed Limit of 60 mph (59+) is more likely to result in a K/A crash and speed limit of <24 mph is likely to reduce (statistically significantly) the Severity of the crash when compared with any other speed limit.
    - Dark light conditions (dark_not_lighter and dark_lighted) increase the probability of a K/A crash compared to daylight, dusk, and dawn. There is a very small difference between levels dark-not-lighted and dark-lighted.
    - Drivers of age <16 are more likely to be in a K/A crash.

- Pedestrians over the age of 60 show a statistically significant chance of having a K/A crash compared to all other age groups. Pedestrians 26-60 also are more likely to have a K/A crash compared to <16 and 16-25.

- A crash where the Motorist Maneuver is straight opposed to left-turn or right-turn increases the probability of a K/A pedestrian crash.

- Having 3+ Transit Stops within 300ft. from crash location, compared to other levels (0, 1-2), decreases the probability of a K/A crash (Table 4.11). The effect is weak but statistically significant.

- Alcohol Positive for any person involved in the crash was found to increase the probability of K/A crash. Alcohol Positive has a strong association with Pedestrian Alcohol. Pedestrian Alcohol is likely to increase the probability of K/A crashes. Driver Alcohol had no statistically significant effect on K/A crash.

- A Drug Positive for any person involved was found to increase the probability of a K/A crash. Drugs positive, both driver and pedestrian, can increase the probability of a K/A crash.

- Crashes involving freight trucks have a higher probability of a K/A crash.

- If the *PBCAT Intersection* is far vs. near (crashes where pedestrian is at far side of the intersection), the probability of a K/A crash increases.

* Six factors were considered significant for the Pedalcyclist MNL model these include: Pedalcyclist Age, Speed, Light Condition, Crash Group, Bicyclist Direction, and Driver Age.

* Other pedalcyclist crash assessment:

    - A Speed Limit of 60 mph (59+) increases the probability of a K/A crash. A speed limit of 20 mph (<24) reduces the probability of a K/A crash. However, there is limited evidence of differences between levels 24-32, 43-50, and 51-58.

    - Lighting Conditions ‘Dark not lighted’ increased the probability of a K/A crash compared to ‘Dark lighted’ level.

    - A Driver Age of >60 is likely to reduce the probability of a K/A crash compared to all levels.

- Pedalcyclists of age >60 have an increased probability of a K/A crash compared to <16 and 16-25 age categories. There is no statistically significant effect for levels >60 and 26-60.

- Traveling with traffic increase the probability of a K/A crash 2 times compared to traveling facing traffic. This may be biased by the fact that majority of pedalcyclists follow the law and ride “with traffic”.

CHAPTER 5. GUIDELINES FOR SAFETY COUNTERMEASURES

This chapter presents guidelines to enhance pedestrian and pedalcyclist safety by adopting a comprehensive approach to select cost-effective countermeasures to reduce the frequency of crashes. These guidelines should assist state, regional, and local organizations in the development of strategic plans to foster safety management practices at the network level. Specific objectives are described for each countermeasure including the level of effectiveness according to the associated risk factors and crash type. The comprehensive approach involves a process of four steps:

Step 1. Identify high-risk crash locations

Step 2. Determine risk safety factors and crash types

Step 3. Select cost-effective safety countermeasures

Step 4. Implement countermeasures and monitor for safety effectiveness

5.1 Identify High-Risk Crash Locations.

High-risk crash locations are identified based on data analyses conducted at different scales. Safety data can be grouped into three main categories: crash data, roadway characteristics, and exposure. Table 5.1 shows safety data, but not limited, in each category as well as additional data that may be useful for further analysis.

Table 5.1 Safety Data Groups

Crash Data	Roadway Characteristics	Exposure	Additional Data
Crash type	Location Type	Vehicle miles travelled (VMT)	Citizens Observations
Number of lanes	Location on Roadway	Average annual daily traffic (AADT)	Law enforcement observations
Country of crash	Road Surface Type	Road segment length	Trauma center data
Coordinates of crash location	Type Shoulder	Vehicle Volume	Physical Condition of persons involved in the Crash
Time of Crash	Traffic control devices	Pedestrian/ Biker Volume	Alcohol/Drug Use
Vehicle/Unit	Functional classes	Movement specifications	Safety Equipment In use/not in use
Person Specifications	Number of legs	Total travel distance (in person-miles of travel)	Pedestrian/Biker Actions
Severity of Crash	No median/median island	Total travel time (in person-hours of travel)	Subsequent Harmful Event
Pedestrian Age	Number of transit stops	Motorist Direction	Land use/development
Driver age	Presence of on-street parking	Motorist Maneuver	Light Condition
Pedestrian impairment	Presence of signal	Pedestrian/Biker Direction	-

Crash Data	Roadway Characteristics	Exposure	Additional Data
Vehicle type	Presence of four or more through lanes	Point of Impact on vehicle	-
Speed limit	Lack of separate turning moments	High-turning volume	-
Traffic control type	-	Proportion of truck/bus traffic in traffic stream	-
-	-	Vehicle speed	-
-	-	Number of driveways	-

Safety data can be gathered from different sources including State Departments of Transportation (DOTs), public agencies, universities, and police reports. Roadway characteristics data can be retrieved from electronic databases of roadway features, traffic characteristics, aerial photographs, street views, video logs, and traffic control device inventories. Exposure data to measure the number of opportunities for a crash to occur can be obtained from State, local and regional agencies.

5.1.1 Safety Data Analysis Scales

A number of scales can be used to evaluate the safety data related to crashes depending on the scope of the analysis and applications. Safety analysis can be performed to evaluate specific point locations (e.g., intersections or crosswalks), or to assess a larger area of interest. Table 5.2 shows safety data analysis scale options with their corresponding categories.

Table 5.2 Safety Data Analysis Scales

Scale	Categories
Intersection(points)	• Surface Street intersections • Signalized Intersections • Two-way stop-controlled intersections • All-way top-controlled intersections • Roundabouts • Ramp Terminals • Midblock Crosswalks
Segments	• Segment after Ramp Terminals • Segment after Roundabouts • Segment after Ramp Terminals • Others
Facilities	• Length of Roadways • Bicycle Paths • Freeway facilities
Area	• Interconnected transportation facilities • Adjoining areas
System	• All transportation facilities • Models within a particular region

5.1.2 Crash Risk Performance Measures

Once the data analysis scale is defined, performance measures are calculated depending on the objectives of the safety evaluation. Table 5.3 shows performance measures for safety analysis describing their strengths and weaknesses.

Table 5.3 Crash Risk Performance Measures

Performance Measure	Strengths	Weakness
Crash Frequency-Count	• Number of crashes/Period of time • For locations with higher volumes	• Lack of reliable pedestrian/ pedalcyclists volume data • Limited ability to calculate crash rate
Crash Frequency-Density	• Identify high concentration of Ped/ Biker Crashes • Ped/Biker Crash Frequency/Unit Area or length • Circular search areas	• Size of area can vary
Crash Rate	• Number of Crashes/Unit of Exposure • Normalizes the Crash Frequency Based on Exposure • Easy to Apply if Volume of Traffic is Known	• Bias Toward Low-Volume Locations • linear relationship even though not always behaves linearly
Crash Type Distribution	• Used to separate crashes into categories	• May focus on a specific Crash type
Crash-Severity Distribution	• Use of degree of severity for identifying high crash locations • Distribution of crash severity can also be used to rank sites	• Mainly focuses on the most severe crashes

5.1.3 Crash Risk Screening Methods

A screening method is applied to finally identify the high-risk crash location using the performance measures previously selected. Table 5.4 shows the screening methods with a description of their strengths and weaknesses.

Table 5.4 Crash Risk Location Screening Methods

Screening Method	Strengths	Weakness
Simple Ranking	Orders intersections, segments or facilities based on the numerical value	Sites with highest values are identified for further study Bias may be present for high-volume intersections or segments

Screening Method	Strengths	Weakness
Sliding Window	Used to identify locations within a roadway facility that show the most potential for safety improvements P.M. with a specific length of 0.5mi and the S.W. with 0.1mi SW can be automized by ArcGIS.	Only applicable for segment-based screening Window evaluates segments per 0.1mi (PM=0.5, SW=0.1*5)
Peak Searching	Segments subdivided into windows (0.1mi) Auto desired precision of level, it increases the window until desired precision is reached if 0.1mi is too small.	Only applicable for segment-based screening
Grid	Creates a grid for the entire network Score could be based on a number of characteristics (crash severity, etc.) Scores can be shown as a crash density map.	-
Polygons	Help Visualize crash concentration more fairly The smaller the polygon, the higher the concentration of crashes around the area	-
Visual	Can be done by reviewing a plot of crash locations Heat maps can apply as a technique of providing appreciation Different symbols representing number of crashes is another technique	Techniques to provide appreciation for multiple crashes are needed
Kernel Density Estimation (KDE)	This method identifies clusters of crashes within a roadway network by estimating statistical significance of line features with points or events along them. KDE can analyse patterns to check if the features are clustering and ranks the resulting significant clusters.	In rural areas, it is recommended to exclude the point events located at intersections when analysing traffic crashes in the KDE and the user can leave points at intersections without affecting the outcome. In urban areas, it is recommended to include intersections in the analysis.

The performance measure criterion established by the agency is finally used to identify high-risk crash locations. The analysis can be conducted at different data scales for a single or multiple performance measures. Different tools are available to conduct this analysis including:

- **GIS**: Geographic information systems are used for coding, displaying, and analyzing of gathered data in relation to geolocation. Layers containing different types of crash data can be overlapped for analysis.

- **United States road assessment program:** risk-mapping protocol used to expose the roads with the lowest and highest safety risk based on different crash types and severities.

- **Safety analyst**: software used for highway safety management following six main steps: network screening, diagnosis, countermeasure selections, economical appraisal, priority ranking and countermeasure evaluation.

- **ActiveTrans priority tool (APT)**: planners and agencies use this tool to prioritize pedestrian and bicyclist improvements at different locations. The tool methodology combines crash data with demand, connectivity, or equity as determined by the user.

5.2 Determine Risk Safety Factors and Crash Types

Risk factors and crash types are determined for the crash locations identified in the previous steps. The objective is to reduce the reduce the risk factors with cost-effective countermeasures. In most of the cases, there is no single factor that causes the crashes but rather the combination of multiple factors that result in injuries or fatalities. Table 5.5 shows risks factors organized by groups.

Table 5.5 Risk Safety Factors.

Risk Factor Group	Risk Factors
Driver	• Alcohol/drug use • Driver skills, vision, reflex • Distracted driving, texting • Driver experience • Vehicle type
Demographic, cultural and social	• Immigrant populations • Cultural customs and traditions
Pedestrian/Pedal-cyclist	• Alcohol/drug use • User age • Pedestrian/Biker Volume • Behavior • Disabilities
Infrastructure related	• Land use and zoning • Vehicle speeds • Roadway geometry • Signals
Other	• Infrastructure policies • Enforcement policies

Note: Table from Chang (2019).

A number of approaches are used to determine risk factors for the different crash types. A brief description recommended approaches with the applicability and limitations of each approach is shown in Table 5.6.

Table 5.6 Approaches to determine risk safety factors.

Approach	Applicability	Limitations
Count Models (SPFs): Development of SPFs by using negative binomial regression or tree modelling.	• Uses network data • Provides estimates that can be used to determine high risk crash locations • Identifies risks while controlling factors such as traffic and pedestrian volume • Risks based on crash prediction • Provides ability to estimate crashes for prioritization, economic analysis, and treatment evaluation.	• Requires effort during Step 2 to compile or estimate pedestrian volume data from different sources (roadway, crash, and other). Otherwise, data needs are similar to other methods. • Requires more modelling expertise than other methods. • May provide misleading identification of risk factors or a biased list of sites if important variables are missing from the data and modelling
Prior Research and Expert Knowledge: Determining risk factors from a combination of prior research and local knowledge. Pre-determined risk factors can be used.	• Does not require local crash data of matched locations • Uses local roadway characteristics for screening • Simple to perform initially • Smaller jurisdictions can assess risks through road safety audits	• Assumes risk factors are similar to those from other studies or jurisdictions. • Requires local knowledge and expertise to deter mine risk factors. • Still requires compiling relevant data types to screen the network for risks. • May require more effort at later steps to compile additional data (to account for pedestrian demand/exposure) to prioritize zero-frequency crash locations (Step 6) if these measures are not included in the initial risk screening. • May require judgment to apply weighting factors for prioritization. • Does not produce crash estimates for project evaluation or economic analysis. • Does not produce SPFs that can be used to evaluate treatments.
Frequency-Based Method: Relies upon historical crash data of the system to identify crash locations across the network.	• Uses network data • More intuitive to apply • Make priori determination of crash types and roadway factors that are treatable for use in identifying systematic issues	• Expert judgment needed to make determinations of conditions relevant for counter measures application (e.g., traffic volume and speed). • Is not built on analysis of risk factors that may contribute to crashes across the network while controlling for other factors such as traffic volume. • May not account for regression-to-the mean/random effects. • Disaggregation may obscure risks for pedestrians, especially if based on vehicle concerns. • May identify sites having features correlated with high traffic and high pedestrian volumes but potentially miss other locations with elevated risk. • May require more effort at later steps to compile additional data (to account for pedestrian demand/exposure) to prioritize zero-frequency crash locations (Step 6) if these measures are not included in the initial risk screening. • Does not produce crash estimates to evaluate projects (economic analysis) or treatments.

Note: Table from NCHRP (2018

To determine the crash type, these guidelines adopt the Pedestrian and Bicycle Crash (PBCAT) type definitions that consider the risk factors previously discussed. Appendix E includes a list of PBCAT groups and flowcharts to determine the crash.

5.3 Select Cost-Effective Safety Countermeasures

Safety countermeasures are selected to reduce risk factors for the crash types identified in the risk safety crash locations. The countermeasures in these guidelines are organized in six groups:

a) Along Roadway

b) Intersection Crossing Locations

c) Maintenance

d) Traffic Calming and Management

e) Markings, Signs, Signals

f) Other Measures

As shown in Figures 5.1 and 5.2, FHWA PEDSAFE (FHWA, 2006) and FHWA BIKESAFE (FHWA, 2014) are the main references for the countermeasure groups recommended in these guidelines. FHWA BIKESAFE and FHWA PEDSAFE organize the countermeasures with eight different crash group categories which are included in the six groups described in these guidelines.

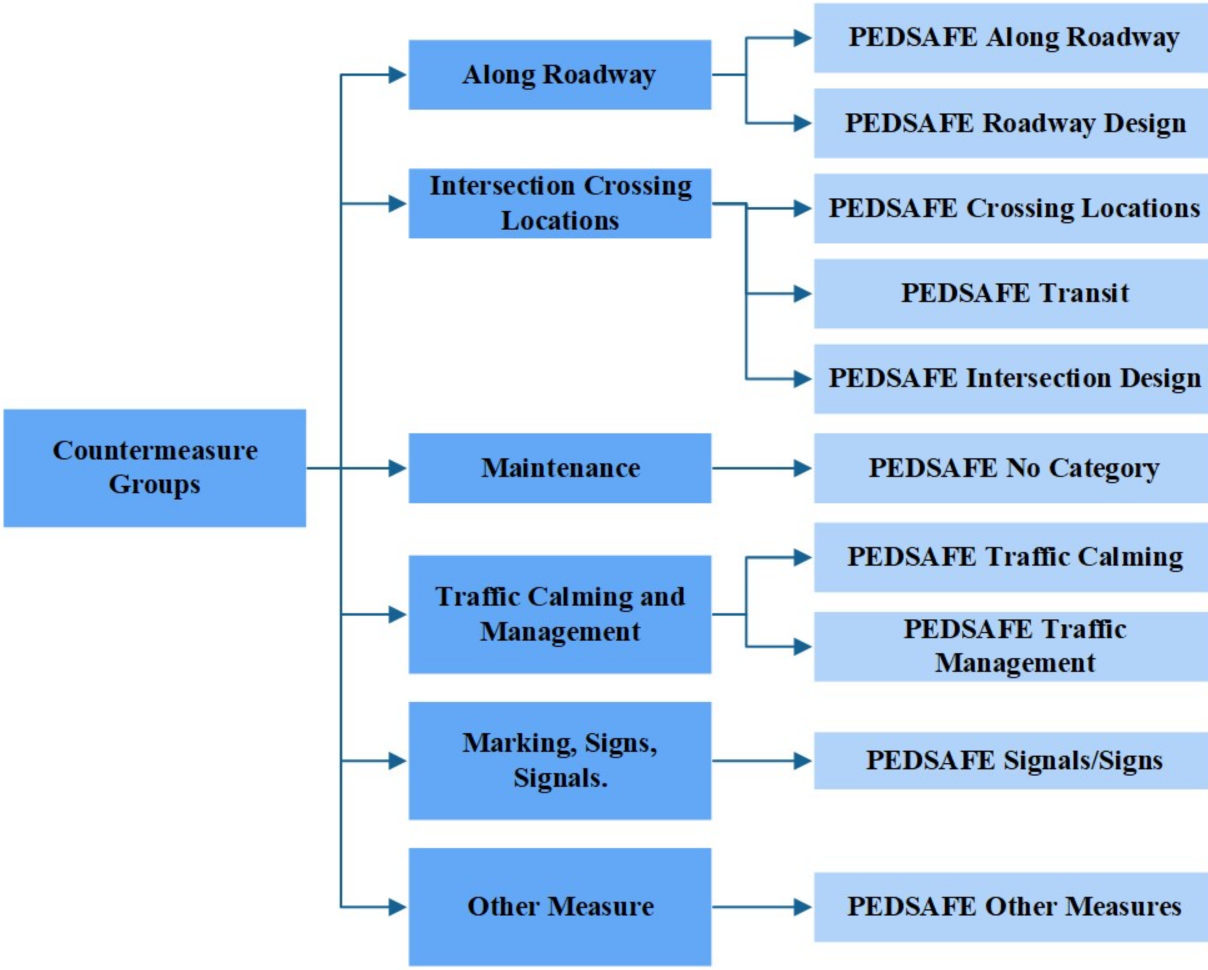


Figure 5.1 Pedestrian Countermeasure groups.

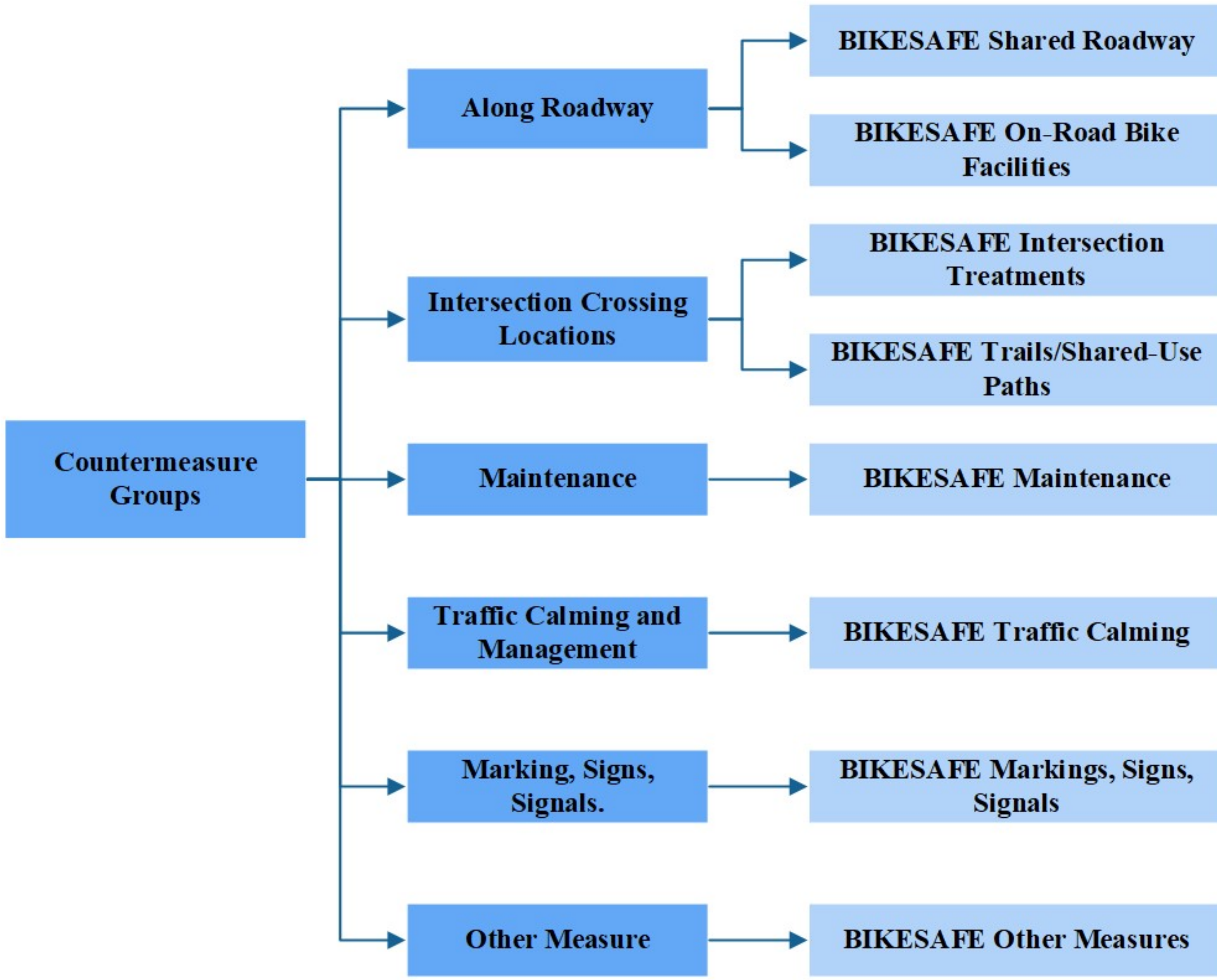


Figure 5.2 Pedalcycle Countermeasure groups

Tables 5.7 - 5.15 provide a comprehensive list of countermeasures for each group with the corresponding risk related factors (e.g., human, vehicle, road, environment) and crash group types. Countermeasures are divided into pedestrian and pedalcyclist.

Countermeasure effectiveness is expressed in terms of the Crash Modification Factor (CMF). CMFs are based on crash studies that provide evidence of much have crashed reduced since the application of a certain countermeasure. CMFs should be less than 1.0 representing the expected crash reduction as a result of the corresponding countermeasure. If CMF result in more than 1.0 it means crashes increased after the implementation of the countermeasure therefore not being suitable. In these guidelines, CMFs were taken from the *Highway Safety Improvement Manual* (TxDOT, 2015) and *Developing Methodology for Identifying, Evaluating, and Prioritizing Systemic Improvements* (TTI, 2015). When crash-based studies were not available for a specific countermeasure, CMFs from *Crash Modification Factors Clearinghouse* (FHWA). CMFs obtained from *Crash Modification Clearinghouse* are a reliable source as it is recommended on *Reliability of Safety Management Methods* (FHWA, 2016d).

Table 5.7 Pedestrian Along the Roadway Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Lane narrowing	Number of lanes, Number of conflict points, Traffic speed	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 400 Walking Along Roadway, 310 Working/Playing in Road	0.44[b]
Lane reductions (road diet)	Number of lanes, Number of conflict points, Traffic speed	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 310 Working/Playing in Road	0.75[a]
Driveway improvements	Number of conflict points, Conspicuity/Visibility	740 Dash/Dart-Out, 350 Unique Midblock, 400 Walking Along Roadway, 800 Off Roadway, 200 Backing Vehicle	0.9[b]
Raised medians	Number of traffic lanes, Traffic speed, Conflicts with turning traffic	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning	0.75[a]
One-way/Two-way street conversions	Traffic speed	750 Crossing Roadway-Vehicle Not Turning	0.75[a]
Improved right-turn slip-lane design	Turning speed at intersection, Number of conflict points, Conflicts at signalized locations, Conflicts with turning traffic	790 Crossing Roadway-Vehicle Turning, 215 Motorist Right Turn / Merge	0.6[a]
Curb ramps	Insufficient crossing time, Pedestrian delay	750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway	0.9[a]
Crossing islands	Number of traffic lanes, Traffic speed, Conflicts with turning traffic	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.74[b]
Raised pedestrian crossings	Number of traffic lanes, Traffic speed, Conflicts with turning traffic	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 750 Crossing Roadway-Vehicle Not Turning, 200 Backing Vehicle	0.9[b]
Lightning and illumination	Conspicuity/Visibility; Darkness	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway, 200 Backing Vehicle, 910 Crossing Expressway	0.6[a]
Parking restrictions	Conspicuity/Visibility	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road, 800 Off Roadway, 200 Backing Vehicle	0.21[b]
Pedestrian overpasses/underpasses	Traffic speed, Number of conflict points, Traffic volume, Insufficient crossing time, Pedestrian delay	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 790 Crossing Roadway-Vehicle Turning, 910 Crossing Expressway	0.05[a]
Access to transit	Conspicuity/Visibility	750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway	0.9[b]
Bus bulb outs	Conspicuity/Visibility	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.18[b]

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Bicycle lanes	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 340 Bus-Related, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway	0.72[b]
Sidewalks and paved shoulders	Conspicuity/Visibility, Compliance with crosswalks	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway, 200 Backing Vehicle	0.35[a]
Street furniture/walking environment	Traffic speed	740 Dash/Dart-Out, 340 Bus-Related, 400 Walking Along Roadway	TBD
Marked crosswalks and enhancements	Conspicuity (driver failure to notice); compliance with crosswalks (motorist and pedestrian	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.9[a]
In-pavement flashing lights	Conspicuity/Visibility, Darkness	740 Dash/Dart-Out, 340 Bus-Related, 400 Walking Along Roadway	TBD
Longitudinal rumble strips	Conspicuity/Visibility, Number of conflict points	400 Walking Along Roadway	0.5[a]
Safety edge	Conspicuity/Visibility, Width of crossing/surface texture	400 Walking Along Roadway	0.892[b]
Transverse rumble strips	Traffic speed, Traffic volume, Width of crossing/Surface texture	400 Walking Along Roadway	0.85[a]

Note. Data are from FHWA (2013a)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.8 Pedalcyclist Along the Roadway Countermeasures

Countermeasures	Risk Related Factor	Crash Group Types	CMF
Roadway surface improvements	Width of crossing/ Surface Texture	220 Bicyclist Left Turn / Merge, 230 Motorist Overtaking Bicyclist	0.7[a]
Bridge and overpass access	Traffic speed, Number of conflict points, Traffic volume, Insufficient crossing time	230 Motorist Overtaking Bicyclist	0.05[a]
Tunnel and underpass access	Traffic speed, Number of conflict points, Traffic volume, Insufficient crossing time	230 Motorist Overtaking Bicyclist	0.05[a]
Driveway improvements	Conspicuity/Visibility, Number of conflict points, Traffic speed, Conflicts with turning traffic	320 Motorist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 600 Backing Vehicle	0.9[b]
Lane reductions (road diet)	Number of lanes, Number of conflict points, Traffic speed	320 Motorist Failed to Yield - Midblock, 158 Bicyclist Failed to Yield - Signalized Intersection, 310 Bicyclist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.75[b]
Lane narrowing	Number of lanes, Number of conflict points, Traffic speed	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 310 Bicyclist Failed to Yield - Midblock, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.44[b]

Countermeasures	Risk Related Factor	Crash Group Types	CMF
Streetcar track treatments	Conflicts at signalized locations, Conflicts with turning traffic	220 Bicyclist Left Turn / Merge	0.84[b]
Separate shared-use paths	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	230 Motorist Overtaking Bicyclist, 240 Bicyclist Overtaking Motorist	0.75[a]
Bike lanes	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	310 Bicyclist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 240 Bicyclist Overtaking Motorist, 258 Head-On	0.72[b]
Wide curb lanes	Parking presence, conspicuity/visibility, Width of crossing	310 Bicyclist Overtaking Motorist	0.7[a]
Paved shoulders	Conspicuity/Visibility, Traffic speed	210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 310 Bicyclist Overtaking Motorist, 258 Head-On	0.75[a]
Shared bus-bike lanes	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 310 Bicyclist Overtaking Motorist	TBD
Contraflow bike lanes	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 310 Bicyclist Overtaking Motorist	TBD
Separated bike lanes	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	310 Bicyclist Failed to Yield - Midblock, 220 Bicyclist Left Turn / Merge	0.26[b]
Raised cycle tracks	Traffic speed, Number of traffic lanes, Number of Conflict points, Conflicts at signalized locations	310 Bicyclist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 240 Bicyclist Overtaking Motorist, 258 Head-On	1.43[b]
Through bike lanes	Conflicts with turning traffic, Conflicts at signalized locations, Turning speed at intersections	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 320 Motorist Failed to Yield - Midblock, 310 Bicyclist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	1.4[b]
Offset intersections	Conflicts with turning traffic, Conflicts at signalized locations, Turning speed at intersections	230 Motorist Overtaking Bicyclist, 240 Bicyclist Overtaking Motorist	0.74[b]
Colored pavement material guidance	Conspicuity/Visibility	150 Motorist Failed to Yield - Signalized Intersection , 158 Bicyclist Failed to Yield - Signalized Intersection , 320 Motorist Failed to Yield - Midblock , 210 Motorist Left Turn / Merge , 215 Motorist Right Turn / Merge , 220 Bicyclist Left Turn / Merge , 225 Bicyclist Right Turn / Merge , 240 Bicyclist Overtaking Motorist , 230 Motorist Overtaking Bicyclist , 600 Backing Vehicle , 140 Motorist Failed to Yield - Sign-Controlled Intersection , 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.61[b]

Note. Data are from FHWA (2014)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.9 Pedestrian Intersection Crossing Location Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Roundabouts	Number of conflict points, Traffic volume, Conflicts at signalized locations, Conflicts with turning traffic, Number of traffic lanes	750 Crossing Roadway-Vehicle Not Turning	0.6[a]
Intersection median barriers	Conflicts with turning traffic, Traffic volume, Width of crossing	720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning	0.45[a]
Curb radius reduction	Parking presence, conspicuity/visibility; width of crossing	750 Crossing Roadway-Vehicle Not Turning, 800 Off Roadway	0.45[b]
Modify skewed intersections	Conflicts with turning traffic, Width of crossing	750 Crossing Roadway-Vehicle Not Turning	0.9[b]
Pedestrian accommodations at complex	Compliance with crosswalk, Turning speed at intersections, Conflicts with turning traffic, Width of crossing	750 Crossing Roadway-Vehicle Not Turning	0.9[b]
Interchanges	Traffic speed, Traffic volume	750 Crossing Roadway-Vehicle Not Turning	0.35[a]
Curb extensions	Parking presence, conspicuity/visibility; width of crossing	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 800 Off Roadway, 200 Backing Vehicle	0.9[a]
Transit stop improvements	Conspicuity/Visibility	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.9[b]

Note. Data are from FHWA (2014)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.10 Pedalcyclist Intersection Crossing Location Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Curb radius reduction	Parking presence, conspicuity/visibility, Width of crossing	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection	0.45[b]
Roundabouts	Number of conflict points, Traffic volume, Conflicts at signalized locations, Conflicts with turning traffic, Number of traffic lanes, Traffic speed	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 220 Bicyclist Left Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.6[a]
Intersection markings	Number of traffic lanes, width of crossing, Conspicuity/Visibility, Conflicts at signalized locations, Conflicts with turning traffic	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection	0.8[a]
Sight Distance Improvements	Conspicuity/Visibility	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 220 Bicyclist Left Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.5[a]
Turning Restrictions	Conflicts with turning traffic	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge	0.23[b]
Merge and weave are redesign	Number of traffic lanes, Number of conflict points, Conspicuity/Visibility	210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.35[b]
Bike Boxes	Conflicts with turning traffic, Turning speed at intersections	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection	1.27[b]
Two-stage turn queue boxes	Conflicts with turning traffic, Turning speed at intersections	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge	TBD
Bicycle Boulevard	Number of conflict points, Conflicts at signalized locations	210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.37[b]
Bicycle-tolerable shoulder rumble strips	Conspicuity/Visibility	230 Motorist Overtaking Bicyclist	0.85[a]

Note. Data are from FHWA (2013a)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.11 Pedalcyclist Maintenance Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Repetitive/short-term maintenance	Width of crossing/ Surface Texture	220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 240	0.7[a]

Countermeasure	Risk Related Factor	Crash Group Types	CMF
		Bicyclist Overtaking Motorist, 600 Backing Vehicle, 258 Head-On	
Major maintenance	Width of crossing/ Surface Texture	220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 240 Bicyclist Overtaking Motorist, 600 Backing Vehicle	0.7[a]
Hazard identification program	Width of crossing/ Surface Texture	220 Bicyclist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 240 Bicyclist Overtaking Motorist, 600 Backing Vehicle	0.5[a]

Note. Data are from FHWA (2014)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.12 Pedestrian Traffic Calming and Management Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Diverters	Conflict with turning traffic, Turning speed at intersections	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD
Full Street Closure	Number of conflict points, Conflicts at signalized locations	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD
Partial street closure	Traffic volume, Number of conflict points	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD
Left turn prohibitions	Conflict with turning traffic, Turning speed at intersections	790 Crossing Roadway-Vehicle Turning, 750 Crossing Roadway-Vehicle Not Turning, 800 Off Roadway	0.36[b]
Temporary installations	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road, 800 Off Roadway	TBD
Chokers	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks, Width of crossing	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning	TBD
Chicanes	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	740 Dash/Dart-Out, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD
Mini-circles	Traffic speed, Traffic volume	750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD
Speed humps	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	740 Dash/Dart-Out, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	0.6[a]
Gateways	Traffic speed	740 Dash/Dart-Out, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	0.98[b]
Landscaping	Traffic speed	750 Crossing Roadway-Vehicle Not Turning, 800 Off Roadway, 200 Backing Vehicle	0.82[b]
Specific paving treatments	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	750 Crossing Roadway-Vehicle Not Turning	0.7[a]
Serpentine design	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD
Pedestrian street	Traffic speed, Conspicuity/Visibility,	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road	TBD

Countermeasure	Risk Related Factor	Crash Group Types	CMF
	Non-compliance with crosswalks		
Woonerf	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning	TBD
Radar Speed display	Traffic speed	400 Walking Along Roadway	0.86[b]
Clear zones	Number of conflict points	400 Walking Along Roadway	0.78[b]
School zone improvement	Number of traffic lanes, Traffic speed, Width of crossing, Traffic Volume, Pedestrian delay	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 800 Off Roadway	0.8[a]

Note. Data are from FHWA (2013a)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.13 Pedalcyclist Traffic Calming and Management Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Mini-circles	Traffic speed, Traffic volume, No traffic signal/Stop sign, Number of conflict points	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 225 Bicyclist Right Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	TBD
Chicanes	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 310 Bicyclist Failed to Yield - Midblock, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	TBD
Speed tables humps cushions	Traffic speed, Conspicuity/Visibility, Non-compliance with crosswalks	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 310 Bicyclist Failed to Yield - Midblock, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 600 Backing Vehicle	0.6[a]
Traffic diversion	Traffic speed, Conflict with turning traffic, Traffic volume	310 Bicyclist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist	TBD
Visual narrowing	Traffic speed	310 Bicyclist Failed to Yield - Midblock, 225 Bicyclist Right Turn / Merge, 230 Motorist Overtaking Bicyclist	0.5[a]
Wayfinding	Traffic volume	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge	0.984[b]

Note. Data are from FHWA (2014)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.14 Pedestrian Markings, Signs, and Signals Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Traffic signals	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.65[a]
Pedestrian signals	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.85[a]
Pedestrian signal timing	Conflicts at signalized locations, Insufficient crossing time, Pedestrian delay,	750 Crossing Roadway-Vehicle Not Turning	0.87[b]
Traffic signal enhancements	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway	0.5[a]
Right-turn-on-red restrictions	Conflicts with turning traffic, Turning speed at intersections	750 Crossing Roadway-Vehicle Not Turning	0.96[b]
Advanced stop lines at traffic signals	Number of traffic lanes; Conspicuity/Visibility	720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.85[a]
Left turn phasing	Conflicts at signalized locations; insufficient crossing time	790 Crossing Roadway-Vehicle Turning, 750 Crossing Roadway-Vehicle Not Turning, 800 Off Roadway	0.96[b]
Pedestrian hybrid beacon	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	720 Multiple Threat/Trapped, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.85[a]
Puffin crossing	Insufficient crossing time, Pedestrian delay	750 Crossing Roadway-Vehicle Not Turning	0.81[b]
Signing	Conspicuity/Visibility, Traffic speed, Traffic volume	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 790 Crossing Roadway-Vehicle Turning, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road, 800 Off Roadway, 910 Crossing an Expressway	0.8[a]
In-street pedestrian crossing sign	Conspicuity/Visibility, Traffic speed, Traffic volume	740 Dash/Dart-Out	0.9[a]
Automated pedestrian detection	Conflicts at signalized locations; insufficient crossing time, Pedestrian delay	790 Crossing Roadway-Vehicle Turning, 750 Crossing Roadway-Vehicle Not Turning	0.35[b]
Leading pedestrian interval	Conflicts at signalized locations, insufficient crossing time	720 Multiple Threat/Trapped, 790 Crossing Roadway-Vehicle Turning, 750 Crossing Roadway-Vehicle Not Turning	0.87[b]
Rectangular rapid flash beacon	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	720 Multiple Threat/Trapped, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning	0.65[a]
Pavement lighted markers	Conspicuity/Visibility, Traffic speed, Traffic volume	750 Crossing Roadway-Vehicle Not Turning	0.8[a]
Flashing yellow arrow for left turns	Conflict with turning traffic, Turning speed at intersections	790 Crossing Roadway-Vehicle Turning	0.85[a]

Note. Data are from FHWA (2013a)[a] and CMF Clearinghouse (n.d.)[b].

Table 5.15 Pedalcyclist Markings, Signs, and Signals Countermeasures.

Countermeasure	Risk Related Factor	Crash Group Types	CMF
Optimizing signal timing for bicyclists	Conflicts at signalized locations, insufficient crossing time	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 320 Motorist Failed to Yield - Midblock, 310 Bicyclist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 220 Bicyclist Left Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection	0.87[b]
Bike-activated signal detection	Conflicts at signalized locations	310 Bicyclist Failed to Yield - Midblock, 220 Bicyclist Left Turn / Merge, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.35[a]
Sign improvements for bicyclists	Conspicuity/Visibility, Traffic speed, Traffic volume, Conflicts with turning traffic	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 320 Motorist Failed to Yield - Midblock, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge, 230 Motorist Overtaking Bicyclist, 600 Backing Vehicle, 140 Motorist Failed to Yield - Sign-Controlled Intersection	0.9[a]
Pavement marking improvements	Conspicuity/Visibility, Traffic speed, Traffic volume, Conflicts with turning traffic	150 Motorist Failed to Yield - Signalized Intersection , 158 Bicyclist Failed to Yield - Signalized Intersection , 320 Motorist Failed to Yield - Midblock , 210 Motorist Left Turn / Merge , 215 Motorist Right Turn / Merge , 220 Bicyclist Left Turn / Merge , 225 Bicyclist Right Turn / Merge , 240 Bicyclist Overtaking Motorist , 230 Motorist Overtaking Bicyclist , 600 Backing Vehicle , 140 Motorist Failed to Yield - Sign-Controlled Intersection , 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.8[a]
School-zone improvements	Number of traffic lanes, Traffic speed, Width of crossing, Traffic Volume, Pedestrian delay	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 310 Bicyclist Failed to Yield - Midblock, 140 Motorist Failed to Yield - Sign-Controlled Intersection, 145 Bicyclist Failed to Yield - Sign-Controlled Intersection	0.95[a]
Rectangular rapid flashing beacons	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	310 Bicyclist Failed to Yield - Midblock	0.65[a]
Pedestrian hybrid beacon	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	310 Bicyclist Failed to Yield - Midblock	0.85[a]
Bicycle signal heads	Traffic volume, No traffic signal/Stop sign, Number of traffic lanes	150 Motorist Failed to Yield - Signalized Intersection, 158 Bicyclist Failed to Yield - Signalized Intersection, 210 Motorist Left Turn / Merge, 215 Motorist Right Turn / Merge	0.8[a]

Table 5.16 Other Measures.

Countermeasure	Risk Related Factor	Crash Group Types
USLIMITS2	Traffic speed	740 Dash/Dart-Out, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway
School zone improvement	Number of traffic lanes, Traffic speed, Width of crossing, Traffic volume, Pedestrian delay	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 800 Off Roadway
Neighborhood identity	Traffic speed, Traffic volume	350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway
Speed-monitoring	Traffic speed	740 Dash/Dart-Out, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway
On-street parking enhancements	Parking presence, Conspicuity/Visibility	740 Dash/Dart-Out, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway, 200 Backing Vehicle
Pedestrian/driver education	Number of traffic lanes, Traffic speed, Width of crossing, Traffic volume, Pedestrian delay, Width crossing, Conflicts at signalized locations, Number of conflict points, Parking presence, Number of traffic lanes	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway, 200 Backing Vehicle, 910 Crossing an Expressway
Police enforcement	Traffic speed, Traffic volume, Conflicts at signalized locations	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, 800 Off Roadway, 910 Crossing an Expressway
Automated enforcement systems	Traffic speed, Traffic volume	750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road
Pedestrian streets/malls	Traffic speed	740 Dash/Dart-Out, 750 Crossing Roadway-Vehicle Not Turning, 310 Working/Playing in Road
Pedestrian safety at railroad crossings	Width crossing	400 Walking Along Roadway
Shared streets	Traffic speed, Number of traffic lanes, Number of conflict points, Conflicts at signalized locations	740 Dash/Dart-Out, 310 Working/Playing in Road
Streetcar planning and design	Conflicts at signalized locations	400 Walking Along Roadway
Useful websites	Number of traffic lanes, Traffic speed, Width of crossing, Traffic volume, Pedestrian delay, Width crossing, Conflicts at signalized locations, Number of conflict points, Parking presence, Number of traffic lanes	740 Dash/Dart-Out, 720 Multiple Threat/Trapped, 350 Unique Midblock, 750 Crossing Roadway-Vehicle Not Turning, 340 Bus-Related, 790 Crossing Roadway-Vehicle Turning, 400 Walking Along Roadway, 310 Working/Playing in Road, Off Roadway, 200 Backing Vehicle, 910 Crossing an Expressway

5.4 Implement Countermeasures and Monitor for Safety Effectiveness

Countermeasures identified in Step 3 are for strategic network-level decision making and should be followed by "Roadway Safety Audits" to confirm the appropriate improvements in each location.

Besides, the implementation of the countermeasures at the strategic level should include safety awareness programs to reduce the frequency of pedestrian and biker related crashes, as well as a reliable data collection programs to support safety analysis at different management levels.

A combination approach is recommended to identify risk-high incident crash locations. This approach combines historical crash pattern analyses with predictive risk safety models, including Safety performance functions (SPFs), to estimate the number and frequency of crashes. Data recommended for the countermeasure selection are provided in these guidelines and summarize as follows:

- **Crash Data**: three to five years of police crash reports for the study location. Review of individual crash reports to identify contributing factors as reported by the police.
- **Traffic Volume Data**: three to five years of traffic volume data for the study location, as well as forecasted traffic volumes for the projected service life of contemplated countermeasures. A minimum of at least one historical estimate and one future estimate that represents a potential implementation year is needed.
- **Roadway Data (Site Conditions)**: including traffic operations, design elements, adjacent land use, driver demographics, and other elements.
- **SPFs**: Obtain appropriate SPFs for the study location. SPFs may be available for a given jurisdiction or borrowed from a jurisdiction with sites of similar conditions to the study location
- **Crash Costs**: To complete an economic appraisal, there is a need for average crash costs by crash type and severity level.
- **Countermeasure Details**: For each potential countermeasure, there is a need to identify the expected safety effects post implementation (for the specific site conditions) and reported contraindications (e.g., noise of rumble strips near residential developments). The Highway Safety Manual and CMF Clearinghouse provide CMFs with their applicability based on the site condition, crash type, and crash severity.

Safety data analysis can also consider land use, transit measures, and social environment to predict potential safety risks in order to anticipate the corresponding countermeasures. Expert knowledge is required to interpret the results to finally select cost-effective countermeasures. Countermeasures for each crash type are included in Appendix F of these guidelines.

Engineering, educational, enforcement and policy countermeasures must be combined to be more effective as shown Figure 5.3. Examples of engineering countermeasures include signs, traffic management, roadway design, and modified crossing locations among others. Educational and enforcement policy countermeasures include but not limited to educational campaigns, awareness through radio, TV, banners, police enforcement training, law enforcement.

Figure 5.3 Engineering, Education, Enforcement and Policy Countermeasures.

Report cards, like the one shown in Figure 5.4, are used to summarize information collected about each corridor and corresponding countermeasures. It contains an overview about where the crashes occurred, when they occurred, the roadway elements and conditions, as well as the PBCAT crash groups indicating the unsafe actions that lead to those crashes.

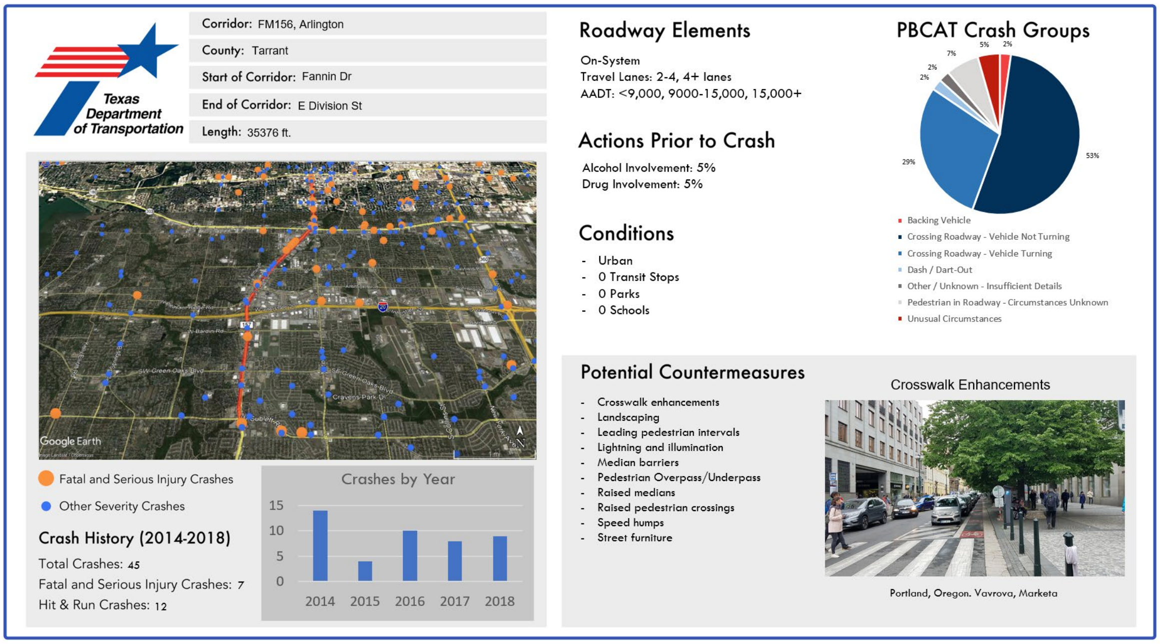


Figure 5.4 Example of a Report Card with Recommended Countermeasures for Implementation

5.5 Case Study

This section illustrates the application of the guidelines described in 5.4 with a case study for pedestrian and pedalcyclist crashes that occurred between 2014 and 2018 in the 12-county North Central Texas area, including the Wise, Denton, Collin, Hunt, Parker, Tarrant, Dallas, Rockwall, Kaufman, Hood, Johnson, and Ellis counties. The case study follows the four steps from the guidelines to identify countermeasures that may be considered at the identified high-incidence corridors.

Step 1. Identify high-risk crash locations

1.1 Safety Data Analysis Scale: The case study focused on the crash data group for the safety analysis and involved pedestrian and pedalcyclist crash incidences on roadways in the North Central Texas region.

1.2 Crash Risk Performance Measure: Crash frequency count was the method used to identify high-risk crash location. The total number of crashes over a 5-year crash incidence history (2014-2018) was used for the analysis.

1.3 Crash Risk Screening Method: The screening method focused on two scales that were combined.

- Area: the region was overlaid with a 1 sq. mi. grid and the number of crashes were counted to determine areas with high occurrence of incidents. ArcGIS® Optimized Hotspot Analysis indicated the areas with the highest number of crashes in the 1-mile grid.
- Segment: crashes were analyzed throughout the roadway network to identify clusters of crashes in the network. Kernel Density Estimation (KDE) method provided statistical significance of the crash clusters in the roadway network.

The screening was performed separately for pedestrian crashes and for pedalcyclist crashes.

Methodology for Pedestrian Dataset

- Crash dataset including 6,504 crashes was analyzed (non-roadway crashes and disabled vehicle-related crashes were removed from the dataset).
- Performed **ArcGIS® Optimized Hotspot Analysis** with 1-mile cells. Selected top 25% of cells in the 1-mile grid with the most crashes (these cells had between 18 and 119 crashes in each 1-mile cell).
- Employed **Kernel Density Estimation (KDE+)** (Bíl, 2019) and selected KDE crash clusters that are located within the top 25% of cells in the 1-mile grid.
- Crashes were grouped into corridors by manually reviewing each of the top 25% cells in the 1-mile grid and KDE crash clusters. There were two criteria that was used to assign crashes into clusters:
    - Crashes occurred on the same street.
    - Crashes were not more than 0.25 mile apart (in some unique cases this was extended up to 0.4 mile due to existence of significant KDE clusters nearby).

Figure 5.5 shows an example where 8 crashes were identified in Dallas N Washington Ave (all within 253 ft., which makes it the shortest corridor in the analysis of pedestrian crashes) but there were no other crashes within 0.4 miles on the same street that could be joined into that corridor.

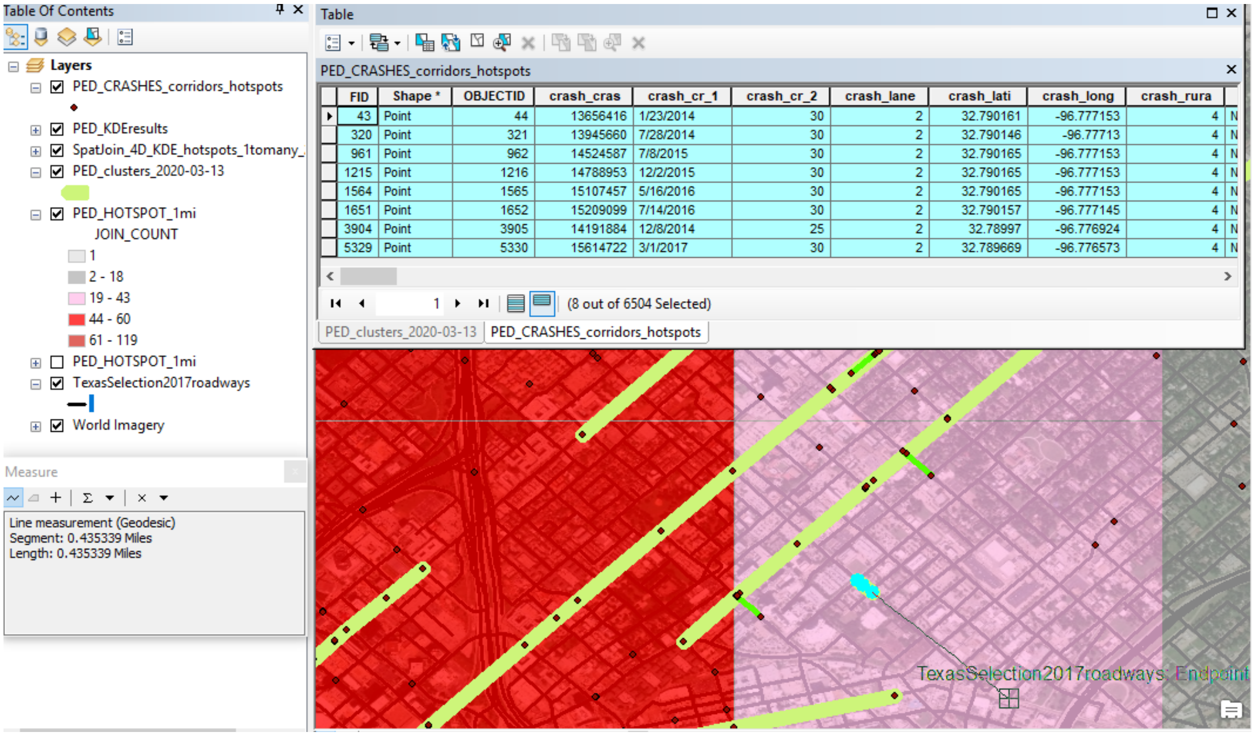


Figure 5.5 Example of a Corridor in Dallas N Washington Ave with 8 Crashes within 253 ft and No Other Crashes Around Within 0.4 Mile on the Same Street.

- The last step was to review each of the 1-mile grid cells that contain more than 20 crashes, to verify if there were any other crash corridors.
- This resulted in 59[10] pedestrian crash corridors that contained a total of 911 crashes, which means that 14% of total 6,504 crashes in the pedestrian dataset were assigned to a corridor.

Figure 5.6 shows an example of the 1-mile cell grid from the ArcGIS® Optimized Hotspot Analysis (in red, pink, and gray), KDE clusters (in dark green), crashes (dots), and the identified corridors (in light green).

[10] Two additional corridors in Richardson were added based of feedback from the PMC: E Arapaho Rd (US 75 to N. Grove Rd) and Spring Valley Rd (US 75 to N. Greenville Ave), which resulted in a total of 61 pedestrian crash corridors.

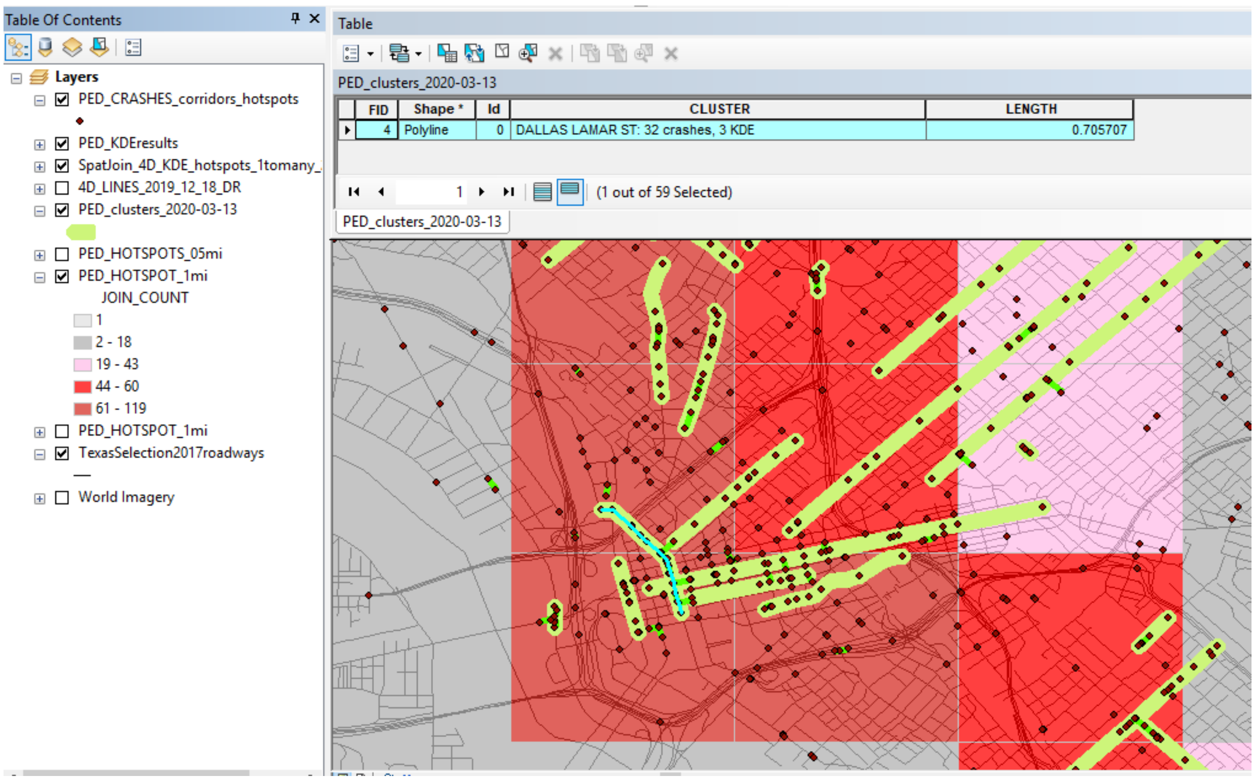


Figure 5.6 Example of Pedestrian High-Risk Corridors in downtown Dallas.

Methodology for Pedalcyclist Dataset:

- Crash dataset including 2,942 crashes was analyzed (non-roadway crashes were removed).
- Performed **ArcGIS® Optimized Hotspot Analysis** with 1-mile cells. Selected top 25% of cells in the 1-mile grid with the most crashes (these cells had between 6 and 30 crashes in each 1-mile cell).
- Employed **Kernel Density Estimation (KDE+)** (Bíl, 2019) to find KDE crash clusters located in the top 25% of cells in the 1-mile grid.
- Crashes were grouped into corridors by manually reviewing each of the top 25% cells in the 1-mile grid and KDE crash clusters. Two criteria were used to assign crashes into clusters:
    - Crashes occurred on the same street.
    - Crashes were not more than 1 mile apart (this longer distance when compared to the pedestrian dataset was established since the pedalcyclist dataset had only 2,942 crashes in the entire region, and there were 2 crashes located close to each other in many cases while any other crash in the proximity was much further).

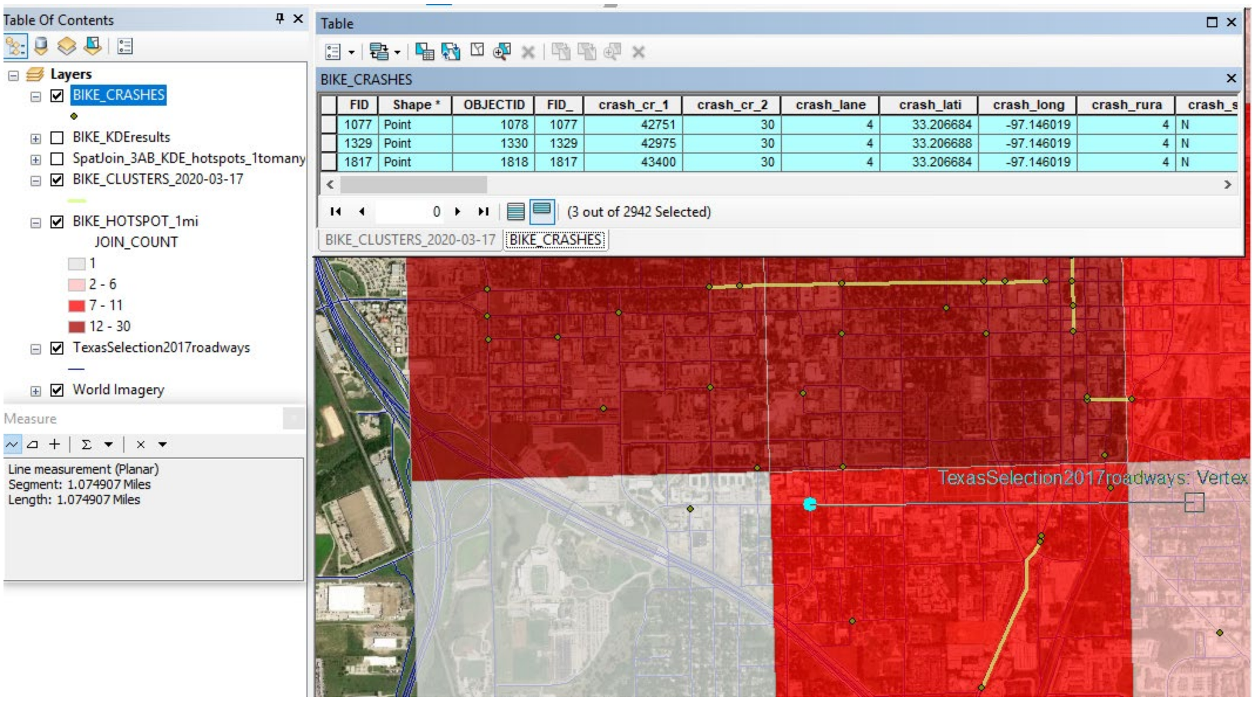


Figure 5.7 Example of a Corridor in Denton Eagle Dr with 3 Crashes Located within 1 ft from Each Other and No Other Crashes Around Within 1 Mile on the Same Street.

- The last step was to review each of the 1-mile grid cells that contain more than 11 crashes, to verify if there were any other crash corridors.
- This resulted in 44[11] pedalcyclist crash corridors that contained a total of 298 crashes, which means that 10% of total 2,942 crashes in the pedalcyclist dataset were assigned to a corridor.

Table 5.17 summarizes pedestrian high-risk corridors identified in the analysis. Corridors are listed by the city and street. The research team aimed to create the corridors as long as possible, however with the search radius for crashes within 0.25 mile (and sometimes even 0.4 mile), there were just no additional crashes within that distance of the crash clusters identified by the KDE analysis. As Table 5.17 shows the resulting corridor lengths range from 253 ft. to 35,376 ft. The corridors were ranked from the highest to the lowest crash/length ratio, which is the corridor the number of crashes

[11] One additional corridor in Richardson were added based of feedback from the PMC: Spring Valley Rd (US 75 to N. Greenville Ave), which resulted in a total of 45 pedalcyclist crash corridors.

divided by the corridor length. More details for the High-Risk Corridors are found in the Safety Corridor Report Cards in Appendix H.

Table 5.17 Pedestrian High-Risk Corridors.

Corridor Name	City	Begin of Corridor	End of Corridor	On/Off System	Total Crashes	Corridor Length [Feet]	Ratio = Crashes / Length [Miles]
N WASHINGTON AVE	DALLAS	Worth St	Shreveport St	Off	8	253	167
MCKINNEY AVE	DALLAS	Lemmon Ave	Lemmon Ave E	Off	8	464	91
MAIN ST	FORT WORTH	Between E 4th St and W 5th St	W Weatherford St	On	17	1200	75
LEMMON AVE	DALLAS	Lemmon Ave	Lemmon Ave E	On	9	680	70
JIM MILLER RD	DALLAS	Samuel Blvd	I-30 Frontage Road	Off	9	735	65
RIVERFRONT BLVD	DALLAS	Riverfront Blvd	Riverfront Blvd	Off	7	571	65
HOUSTON ST	DALLAS	Young St	Ross Ave	off	18	1988	48
LAMAR ST	DALLAS	Young St	Victory Ave	Off	32	3726	45
SPRING VALLEY RD	RICHARDSON	S Sherman St	Business Pkwy	Off	6	911	34
CEDAR SPRINGS RD	DALLAS	Sale St	Douglas Ave	Off	21	3356	33
COLE AVE	DALLAS	Lemmon Ave	Blackburn St	Off	8	1266	33
MCKINNEY AVE	DALLAS	Olive St	Oak Grove Ave	Off	20	3439	31
AL LIPSCOMB WAY	DALLAS	Meadow St	J B Jackson Jr Blvd	Off	6	1056	30
SL0012 BONNIE VIEW RD	DALLAS	Stoneport Dr	Jacobie Blvd	On	32	5928	28
MLK BLVD	DALLAS	Cedar Crest Blvd	Robert B Cullum Blvd	Off	40	7866	27
KNOX ST HENDERSON AVE	DALLAS	Homer St	Katy Trail	Off	17	3436	26
PINELAND DR	DALLAS	-	Holly Hill Dr	Off	10	2024	26
BELKNAP ST	FORT WORTH	Cherry St	Grove St	Off	13	2691	26
SL0012	DALLAS	Starlight Rd	Bachman Dr	Off	17	3683	24
12TH ST	DALLAS	S Bishop Ave	S Beckley Ave	Off	7	1679	22
CEDAR SPRINGS RD	DALLAS	N Pearl St	Dickason Ave	Off	16	3810	22
SKILLMAN ST	DALLAS	Eastridge Dr	Abrams Rd	Off	8	1949	22
US0077	DENTON	Maple St	Pauline St	On	17	4165	22

Corridor Name	City	Begin of Corridor	End of Corridor	On/Off System	Total Crashes	Corridor Length [Feet]	Ratio = Crashes / Length [Miles]
HEMPHILL ST	FORT WORTH	Lilac St	W Maddox Ave	Off	10	2462	21
ROSEDALE ST	FORT WORTH	College Ave	Crawford St	Off	14	3488	21
TAYLOR ST	FORT WORTH	Texas St	W Weatherford St	Off	11	2820	21
FOREST LN	DALLAS	Shepherd Rd	Audelia Rd	Off	35	9899	19
OAK LAWN AVE	DALLAS	Fairmount St	Lemmon Ave	Off	13	3662	19
PARK LN	DALLAS	Greenville Ave	Larmanda St	Off	19	5247	19
BRUTON RD	DALLAS	Asper St and N St Augustine Dr	Nantucket Village Dr	Off	13	3901	18
ROSS AVE	DALLAS	N Griffin St	Routh St	Off	14	4051	18
S MALCOLM X BLVD	DALLAS	Peabody Ave	Casey St	Off	9	2639	18
SH0180	FORT WORTH	35 W	Collard St	On	44	13246	18
ESPERANZA RD	DALLAS	kit Ln	Midpark Rd	Off	7	2187	17
JACKSON ST	DALLAS	S Griffin St	S Hardwood St	Off	9	2803	17
HARRY HINES BLVD	DALLAS	Butler St	Medical District Dr	Off	6	1933	16
INWOOD RD	DALLAS	Redfield St	Cedar Springs Rd	Off	12	4052	16
MAIN ST	DALLAS	S Market St	between N 2nd Ave and N Exposition Ave	Off	29	9608	16
MAPLE AVE	DALLAS	Inwood Rd	Wycliff Ave	Off	19	6424	16
MIDPARK RD	DALLAS	Maham Rd	Goldmark Dr	Off	5	1686	16
SHADY BROOK LN	DALLAS	Southwestern Blvd	Melody Ln	Off	10	3308	16
WESTMORELAND DR	DALLAS	W Wheatland Rd	W Camp Wisdom Rd	On	17	5627	16
JEFFERSON BLVD	DALLAS	S Van Buren Ave	E Davis St	Off	22	7936	15
SPRING VALLEY RD	RICHARDSON	Manam Rd	S Weatherred Dr	Off	8	2833	15
GASTON AVE	DALLAS	N Malcolm X Blvd	Glendale St	Off	27	10311	14
N HALL ST	DALLAS	Knight St	McKinney Ave	Off	13	4832	14
YOUNG ST	DALLAS	S Ervay St	S Good Latimer Expy W	Off	10	3699	14

Corridor Name	City	Begin of Corridor	End of Corridor	On/Off System	Total Crashes	Corridor Length [Feet]	Ratio = Crashes / Length [Miles]
LEMMON AVE	DALLAS	Herschel Ave	Throckmorton St	Off	5	2069	13
SL0012 2nd location	DALLAS	Corrigan Dr	Between Wadworth Dr and unnamed street	On	32	13342	13
SL0354 HARRY HINES BLVD	DALLAS	W Northwest Highway	Myrtle Springs Ave	On	8	3577	12
WELCH ST	DENTON	Maple St	E Oak St	Off	6	2718	12
SL0012 BUCKNER BLVD	DALLAS	Chenault St	Beck Ave	On	11	5235	11
CALHOUN ST	FORT WORTH	E 15th	E Weatherford St	Off	8	3995	11
S JOSEY LN	CARROLTON	Valwood Pkwy	Pearl St	Off	12	6506	10
IH0030	DALLAS	N Jim Miller Rd	Campbell Dr	On	12	6508	10
LIVE OAK ST	DALLAS	N Hardwood St	N Munger Blvd	Off	20	11320	9
W HICKORY ST	DALLAS	Jagoe St	Us Hwy 77	Off	9	5077	9
ARAPAHO RD	RICHARDSON	Us 75	N Grove Rd	On	5	2792	9
FM157	ARLINGTON	Fannin Dr	E Division St	On	45	35376	7
25TH ST	FORT WORTH	Loving Ave	N Main St	On	7	5199	7
ROSS AVE	DALLAS	Mccoy St	Summit Ave	Off	9	7397	6

Table 5.18 summarizes the pedalcyclist high-incidence corridors identified in the analysis. Corridors are listed by the city and street that the corridor is on. The research team aimed to create the corridors as long as possible, however with the search radius for crashes within 1 mile, there were no additional crashes within that distance of the crash clusters verified in the KDE analysis. As Table 5.18 shows the resulting corridor lengths range from 1 ft. to 41,392 ft. The corridors were ranked from the highest to the lowest crash/length ratio, which is the number of crashes divided by the corridor length.

Table 5.18 Pedalcyclist High-Risk Corridors.

Corridor Name	City	Begin of Corridor	End of Corridor	On/Off System	Total Crashes	Corridor Length [Feet]	Ratio = Crashes / Length [Miles]
EAGLE DR	DENTON	Ave A	Ave A	Off	3	1	10899
GREEN OAKS BLVD	ARLINGTON	Greenbelt Rd	Park Highland Way	Off	5	9	2863

Corridor Name	City	Begin of Corridor	End of Corridor	On/Off System	Total Crashes	Corridor Length [Feet]	Ratio = Crashes / Length [Miles]
MILNER RD	IRVING	E Grauwyler Rd	E Grauwyler Rd	Off	2	6	1817
BIG RIVER DR	THE COLONY	Goldhawk Dr	Goldhawk Dr	Off	2	10	1065
ESTACADO DR	DALLAS	Estacado Dr	Estacado Dr	Off	2	70	150
THROCKMORTON ST	FORT WORTH	W 5th St	W 4th St	Off	3	259	61
LEMMON AVE	DALLAS	N Central Expy	N Central Expy	On	3	414	38
GRIFFIN ST	DALLAS	Commerce St	Elm St	Off	4	555	38
MILITARY PKWY	MESQUITE	N Masters Dr	N Masters Dr	Off	2	299	35
LAKE HIGHLANDS DR	DALLAS	Biscayne Blvd	Peninsula Dr	Off	2	407	26
CROZIER ST	DALLAS	Pine St	Exline St	Off	2	423	25
PRAIRIE ST	DENTON	US Hwy 77	S Bell Ave	On	3	706	22
US0077	DENTON	E Mulberry St	Ferguson St	On	12	3112	20
WILBARGER ST	FORT WORTH	Dowdell St	Before Martin Luther King Fwy	Off	4	1089	19
SPRING VALLEY RD	RICHARD-SON	S Sherman St	Business Pkwy	Off	3	908	17
KNOX ST	DALLAS	Katy Trail	N Central Expy	Off	4	1612	13
LAMAR ST	DALLAS	Main St	N Houston St	Off	6	2593	12
HOLY HILL DR	DALLAS	Greenville Ave	Pineland Dr	Off	6	2661	12
BLAIR OAKS DR	THE COLONY	Before Arbor Glen Rd	S Colony Blvd	Off	6	2580	12
HALL ST	DALLAS	Turtle Creek Blvd	Carlisle St	Off	2	928	11
MUNGER BLVD	DALLAS	Gaston Ave	Santa Fe Trail	Off	7	3757	10
ROSS AVE	DALLAS	N Fitzhugh Ave	Hubert St	Off	6	3596	9
US0377	DENTON	Lindsey St	E Collins St	On	4	2462	9
14TH ST	PLANO	Jupiter Rd	Ridgecrest Dr	Off	5	3264	8
7TH ST	FORT WORTH	Curry St	N Henderson St	Off	9	6442	7
MILLER AVE	FORT WORTH	Baylor St	Forbes St	Off	5	3785	7
JUPITER RD	ALLEN	White Oak St	Roaming Rd Dr	Off	4	3465	6
CARROLL AVE	DALLAS	Ash Ln	Ross Ave	Off	8	7420	6

Corridor Name	City	Begin of Corridor	End of Corridor	On/Off System	Total Crashes	Corridor Length [Feet]	Ratio = Crashes / Length [Miles]
OAK ST	DENTON	Jagoe St	N Cedar St	Off	6	4987	6
WALNUT HILL	IRVING	Texas 161 Frontage Rd	Las Brisas Rd	Off	6	5582	6
FM0157	ARLINGTON	E 2nd St	Brown Blvd	On	14	15739	5
MEANDERING WAY	DALLAS	W Belt Line Rd	Campbell Rd	Off	10	10076	5
MAIN ST	DALLAS	N Ervay St	S Washington Ave	Off	8	8127	5
CEDAR SPRINGS RD	DALLAS	Cedar Plaza Ln	Throckmorton St	Off	6	6470	5
US0380	DENTON	N Bonnie Brae St	Redwood Pl	On	15	15240	5
GREENVILLE AVE	ALLEN	W Ridgemont Dr	Pebblebrook Dr	Off	8	11489	4
ARKANSAS LN	ARLINGTON	Richmond Dr	S Watson Rd	Off	9	11332	4
SH0180	ARLINGTON	N Bowie Rd	N East St	On	11	14407	4
FM0157	ARLINGTON	Wimbledon Dr	Washington Dr	On	29	41392	4
MALCOLM X BLVD	DALLAS	Farragut St	After Louise Ave	Off	10	13300	4
CENTERVILLE RD	GARLAND	San Marcus Ave	Columbia Blvd	On	15	21789	4
OLD ORCHARD LN	LEWISVILLE	W Corporate Dr	College Pkwy	Off	7	9668	4
HASKELL AVE	DALLAS	Elm St	N Central Expy	On	5	9536	3
SL0288	DENTON	Colorado Blvd	Oriole Ln	On	8	12454	3
CAMPBELL RD	RICHARD-SON	Before Lauder Ln	N Central Expy	Off	10	16499	3

Step 2. Determine Risk Safety Factors and Crash Groups

Risk safety factors and crash type groups are determined for each high-risk corridor following the guidelines described in Chapter 3. PBCAT crash groups are assigned following the process described in Appendix E. Additional risk-safety information about the high-risk corridor is obtained from the KDE+ analysis (Bíl, 2019).

Step 3. Select Cost-Effective Safety Countermeasures

Once the crash groups are determined, countermeasures are recommended using the tables in Appendix F. These countermeasures can be narrowed down for specific local conditions by conducting a field visit. As an alternative, in this case study Google Earth™ was used to verify the applicability of the countermeasures recommended for a sample of the identified high-incidence crash corridors.

Table 5.19 and 5.20 show a toolbox with potential countermeasures for the top two corridors high-risk pedestrian corridors based on the number of crash incidences. The applicability of these countermeasures is preliminarily checked using Google Earth™. Appendix G includes countermeasures recommended for all high-risk corridors listed in Step 2.

Pedestrian Corridor: Dallas N Washington Ave

Dallas N Washington Ave corridor includes 6 crashes that occurred at an intersection, and 2 midblock crashes. All 6 intersection crashes occurred in a crosswalk between 1/2014 and 8/2016. Verification of this location using Google Earth™ showed that before 1/2017 the intersection had only one 'ladder' crosswalk and three 'standard' crosswalks, which were then repainted to four 'ladder' crosswalks. Since then, there were no other pedestrian-related crashes in the location. Marked crosswalks is a countermeasure recommended by FHWA for the PBCAT crash groups identified at this location.

Table 5.19 Potential Countermeasures for High-Risk Incident Pedestrian Corridors: Dallas N Washington Ave.

Corridor Name	City	PBCAT Crash Groups	Crashes (%)	Toolbox with Potential Countermeasures
N WASHINGTON AVE	DALLAS	790 Crossing Roadway - Vehicle Turning	7 (87.5%)	Marked crosswalks is a countermeasure recommended by FHWA for the PBCAT crash groups identified at this location.
N WASHINGTON AVE	DALLAS	750 Crossing Roadway - Vehicle Not Turning	1 (12.5%)	Marked crosswalks is a countermeasure recommended by FHWA for the PBCAT crash groups identified at this location.

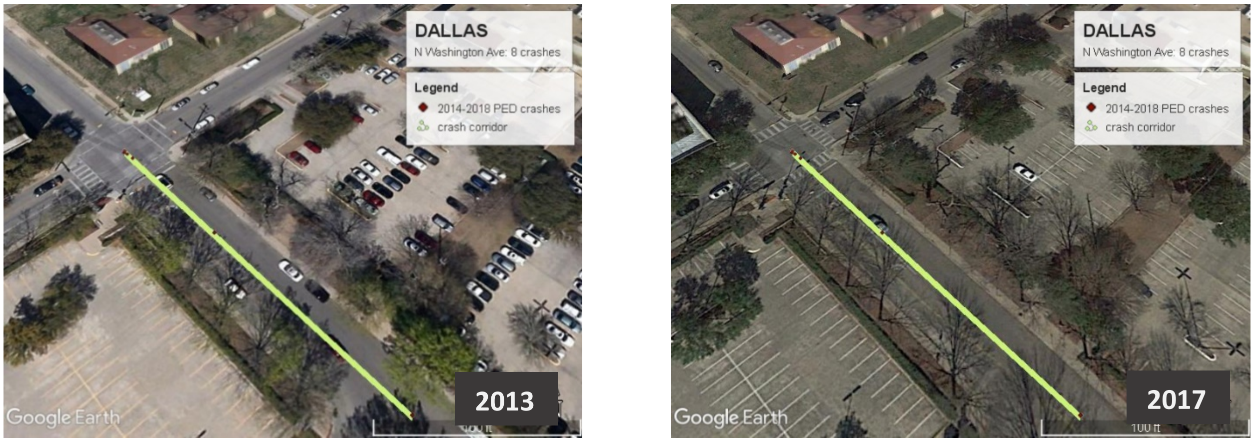


Figure 5.8 Dallas N Washington Ave, 2013 and 2017

Original photos: ©2013, 2017 Google Earth™

Note: No crashes reported after crosswalks were repainted in 2017.

Pedestrian Corridor: Dallas McKinney Ave

Dallas McKinney Ave corridor includes a total of 8 crashes and 4 of them occurred in a crosswalk at the intersection with Lemmon Ave during 2014-2017. Verification of this location using Google Earth™ showed that no improvements were made between 2014 and 2018, then in 2019 one crosswalk was repainted with ornaments and another one with a 'ladder'. Marked crosswalks is a countermeasure recommended by FHWA for the PBCAT crash groups identified at this location.

Table 5.20 Potential Countermeasures for High-Risk Pedestrian Corridors: Dallas McKinney Ave.

Corridor Name	City	PBCAT Crash Groups	Crashes (%)	Toolbox with Potential Countermeasures
MCKINNEY AVE	DALLAS	790 Crossing Roadway - Vehicle Turning	6 (75.0%)	Marked crosswalks is a countermeasure recommended by FHWA for the PBCAT crash groups identified at this location.
MCKINNEY AVE	DALLAS	750 Crossing Roadway - Vehicle Not Turning	1 (12.5%)	Marked crosswalks is a countermeasure recommended by FHWA for the PBCAT crash groups identified at this location.
MCKINNEY AVE	DALLAS	600 Pedestrian in Roadway – Circumstances Unknown	1 (12.5%)	Miscellaneous

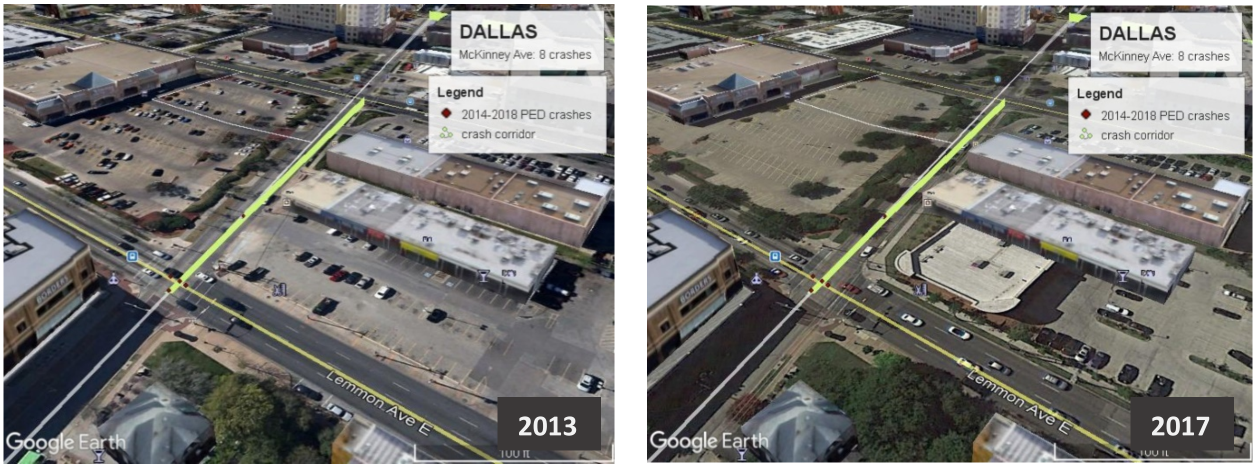


Figure 5.9 Dallas McKinney Ave., 2013 and 2017
Original photos: ©2013, 2017 Google Earth™

Pedalcyclist Corridor: Denton Eagle Dr

Denton Eagle Dr corridor includes a total of three crashes that occurred between 2017 and 2018 within the same intersection. Verification of this location using Google Earth™ showed that an unprotected bike lane was implemented on Eagle Dr in early 2017, and soon after that the pedalcyclist crashes occurred. According to the PBCAT crash types, two crashes occurred when pedalcyclist were crossing the intersection in the bike lane during a green light but were hit by motorists who were turning from Eagle Dr. to Ave A. Potential countermeasures from the toolbox could include colored pavement material guidance, turning restrictions, or optimized signal timing.

Table 5.21 Potential Countermeasures for High-Risk Incident Pedalcyclist Corridors: Denton Eagle Dr.

Corridor Name	City	PBCAT Crash Group	Crashes (%)	Toolbox with Potential Countermeasures
EAGLE DR	DENTON	150 Motorist Failed to Yield - Signalized Intersection	1 (33.3%)	• Curb radius reduction • Optimizing signal timing for bicyclists • Sign improvements for bicyclists
EAGLE DR	DENTON	215 Motorist Right Turn / Merge	1 (33.3%)	• Curb radius reduction • Merge and weave redesign • Sign improvements for bicyclists
EAGLE DR	DENTON	210 Motorist Left Turn / Merge	1 (33.3%)	• Curb radius reduction • Merge and weave redesign • Optimizing signal timing for bicyclists • Sign improvements for bicyclists

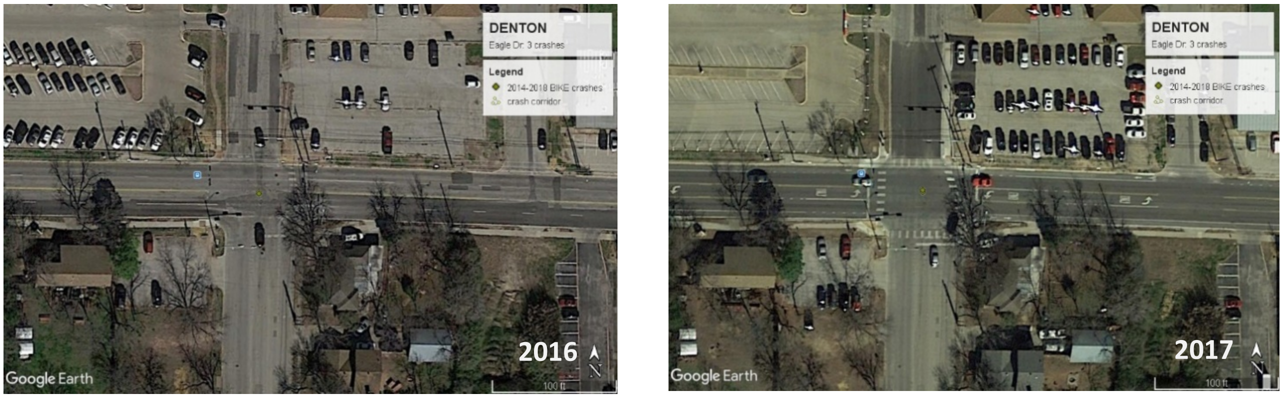


Figure 5.10 Denton Eagle Dr., 2016 and 2017
Original photos: ©2016, 2017 Google Earth™

Pedalcyclist Corridor: Arlington Green Oaks Blvd

Arlington Green Oaks Blvd corridor includes a total of five crashes that occurred between 2015 and 2018 within the same intersection. Verification of this location using Google Earth™ showed that there have not been any engineering improvements done at this intersection. All five crashes occurred at the same leg of the intersection and four of them under the same scenario – pedalcyclist entered a crosswalk during without a walk signal (after previously riding on the sidewalk along Green Oaks Blvd) and was hit by a motorist coming from Green Belt Rd., which is also reflected in the assigned PBCAT crash group '158 Bicyclist Failed to Yield - Signalized Intersection'. Potential countermeasures from the toolbox could include implementing bike lane and intersection improvements, improving signage, and encouraging pedalcyclists not to cross the roadway unless the walk signal is on.

Table 5.22 Potential Countermeasures for High-Risk Pedalcyclist Corridors: Arlington Green Oaks Blvd.

Corridor Name	City	PBCAT Crash Group	Crashes (%)	Toolbox with Potential Countermeasures
GREEN OAKS BLVD	ARLINGTON	158 Bicyclist Failed to Yield - Signalized Intersection	4 (80%)	• Colored pavement material guidance • Intersection markings • Lane narrowing • Optimizing signal timing for bicyclists • Sign improvements
GREEN OAKS BLVD	ARLINGTON	190 Crossing Paths - Other Circumstances	1 (20%)	• Miscellaneous

Figure 5.11 Arlington Green Oaks Blvd., 2018
Original photo: ©2018 Google Earth™

Step 4. Implement Countermeasures and Monitor for Safety Effectiveness

Countermeasures identified in Step 3 for the high-risk corridors should be followed by "Roadway Safety audits" to confirm the appropriate improvements in each location before implementation.

Recommendations for the implementation of the countermeasures are provided in section 5.4 emphasis should be given to combine engineering, educational, enforcement, and policy countermeasures to be more effective. Report cards summarize the location, crash information and recommended countermeasures. A total of 106 report cards are included in Appendix H.

CHAPTER 6. PILOT ON-LINE CRASH DATA ANALYSIS AND VISUALIZATION APPLICATION

This Chapter provides an overview of the Crash Data Analysis and Visualization Application (CDAVA) tool that was developed to visually present the results of this project. The web-based application was developed in-house by Texas A&M AgriLife and University of Texas at El Paso (UTEP) researchers using the modern web development method with an emphasis on ease-of-use and security (Figure 6.1). All data used by CDAVA is stored securely in a MySQL database at UTEP. A representational state transfer (REST) application programming interface (API) was designed to securely access the data. The "Express" based REST API implements access control for all calls from any client. Only users with correct credentials are allowed to access any data. An 'Angular' based web client/interface was designed to consume the data from the REST API and present the results. The architecture of the web application (database, REST API, and the web interface) ensures future extendibility to other platforms (e.g., mobile apps). Also, it enables the team to enable new features quickly.

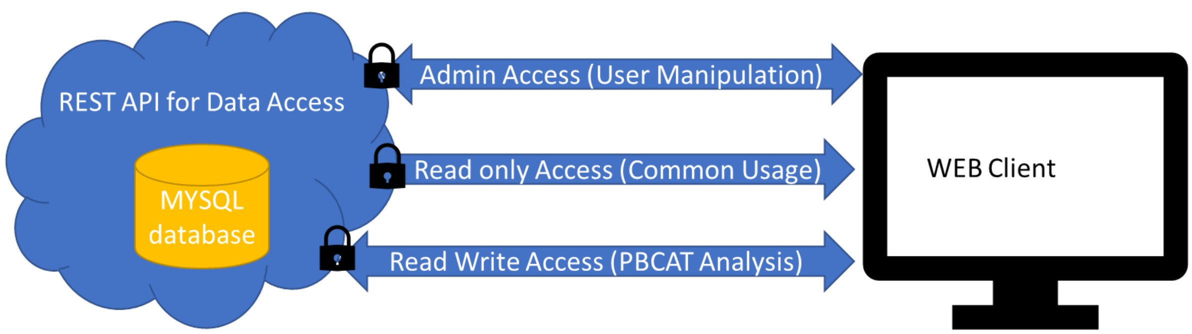


Figure 6.1 Schematic of the Software Design.

The three critical components of the application developed for this project are the database, the REST API for data access, and the Web (browser) Client to display results.

6.1 Overview of the Database and REST API

The database was designed in MySQLv8. The entity-relationship diagram, describing the tables and connections, is shown in Figure 6.2. The relations were developed to ensure data integrity and compatibility with the TXDOT crash reports, PBCAT outputs, and results of the analysis in the project.

A REST API was developed on the MYSQL database to control access. The API allows access to all data and metadata necessary for gainfully using the data. Selected endpoints for the API are listed in Table 6.1. The API was developed in "Express." Express is a web framework for Node.js. API allows three levels of access based on the user credentials token (JWT token): a) "R" or read-only access, b) “RW” or read and write access, and c) “ADMIN” or administrative access. All calls to the API endpoints (except /auth/login) require a JWT token obtained from the login endpoint.

ADMIN access is used to perform admin functions. Configured admin functions include adding and removing users, updating users (including roles), and changing passwords for users.

R access is the normal access level for most users. R level allows reading all data and changing the user password.

RW access is used for updating the database. Besides the ability to access data as with R access level, the RW level allows modification of any data. Note that changes to users (editing, deleting, or adding users) are not allowed under this access level. Only ADMIN access allows changes to users.

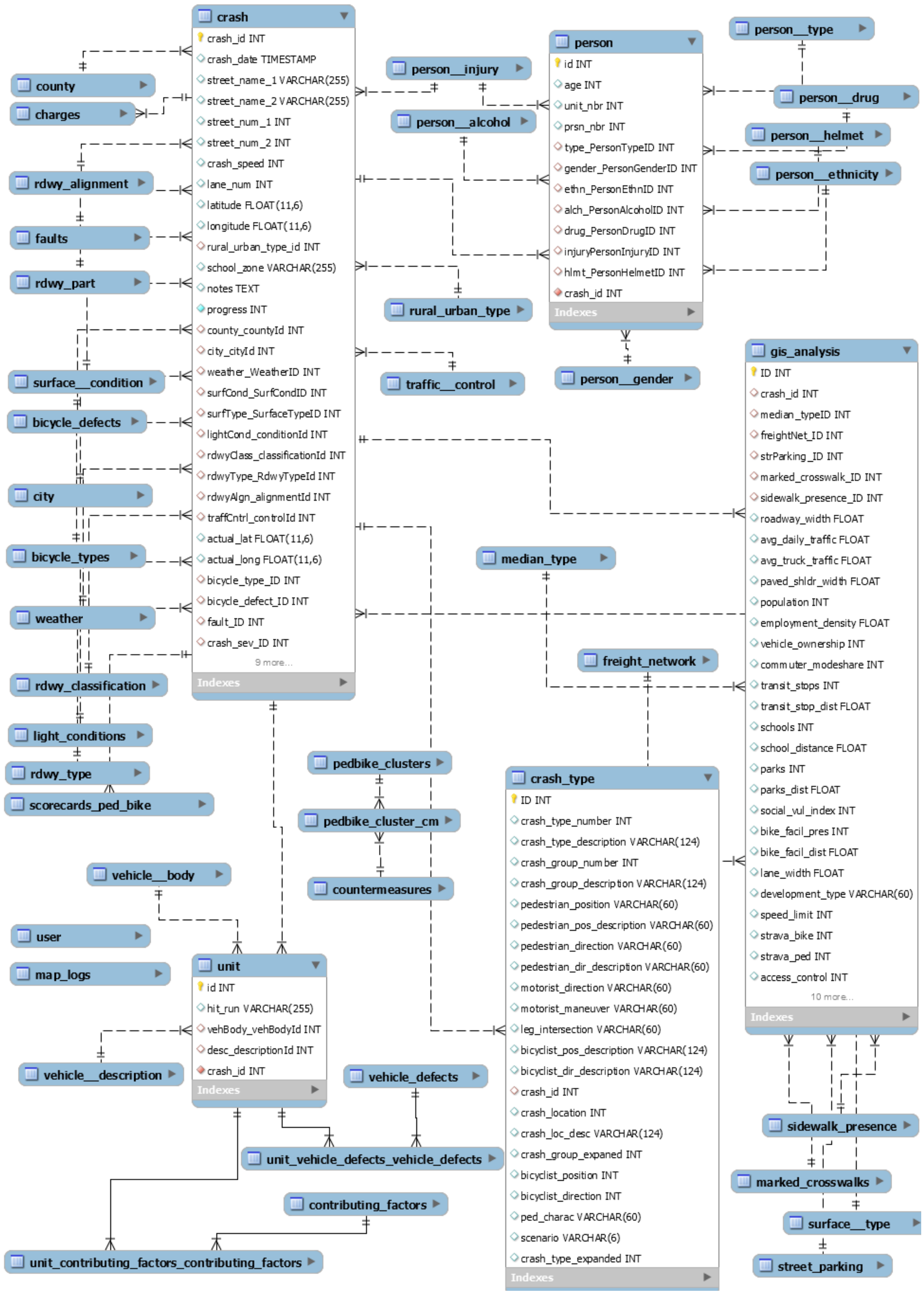


Figure 6.2 Entity Relations Diagram for the Database.

Note: Crash, Person, Unit, Crash_Type, and GIS_Analyis are the key tables that map data generated/collected by the project.

Table 6.1 Selected REST API Endpoints.

PATH	*METHOD*	*ACCESS*	*PURPOSE*
/auth/login	POST	ALL	login and establish credentials
/auth/logout	GET	ALL	Remove credentials
/auth/change-password	POST	R, RW	Change password for a user with key
/auth/change-password-admin	POST	ADMIN	Change password for any user
/user/getUsers	GET	ADMIN	Get all users
/user/:id([0-9]+)	GET	ADMIN	Get information about a user
/user/newUser	POST	ADMIN	Create a new user
/user/editUser/:id([0-9]+)	PATCH	ADMIN	Edit user
/user/deleteUser/:id([0-9]+)	DELETE	ADMIN	Delete user
/api/crash/:id([0-9]+)	GET	R, RW	Retrieve information about a crash
/api/crash/:id([0-9]+)	PUT	RW	Edit information of a crash
/api/createPerson	PUT	RW	Create a new person involved in the crash
/api/createUnit	PUT	RW	Create a new unit involved in the crash
/api/createCharges	PUT	RW	Create new charges involved in the crash
/api/new_lat_long	PUT	RW	Update latitude and longitude of the crash
/api/person/:id([0-9]+)	DELETE	RW	Remove a person involved in the crash
/api/unit/:id([0-9]+)	DELETE	RW	Remove a unit involved in the crash
/api/charges/:id([0-9]+)	DELETE	RW	Remove a change involved in the crash
/api/all_crash	GET	R, RW	Retrieve all crash information
/api/selectPanel	GET	R, RW	Retrieve selected information about all crashes
/api/city	GET	R, RW	Retrieve all cities
/api/contributing_factors	GET	R, RW	Retrieve contributing factors information
/api/county	GET	R, RW	Retrieve all counties
/api/light_conditions	GET	R, RW	Retrieve light conditions information
/api/person__alcohol	GET	R, RW	Retrieve person alcohol information
/api/person__ethnicity	GET	R, RW	Retrieve person ethnicity information
/api/person__helmet	GET	R, RW	Retrieve person helmet information
/api/person__injury	GET	R, RW	Retrieve person injury information
/api/person___type	GET	R, RW	Retrieve person type information
/api/person__drug	GET	R, RW	Retrieve person drug information
/api/person__gender	GET	R, RW	Retrieve person gender information
/api/rdwy_alignment	GET	R, RW	Retrieve rdwy alignment information
/api/rdwy_classification	GET	R, RW	Retrieve rdwy classification information
/api/rdwy_type	GET	R, RW	Retrieve rdwy type information
/api/surface__condition	GET	R, RW	Retrieve surface condition information
/api/surface___type	GET	R, RW	Retrieve surface type information
/api/traffic__control	GET	R, RW	Retrieve traffic control information

PATH	METHOD	ACCESS	PURPOSE
/api/vehicle__body	GET	R, RW	Retrieve vehicle body information
/api/vehicle__description	GET	R, RW	Retrieve vehicle description information
/api/vehicle_defects	GET	R, RW	Retrieve vehicle defects information
/api/weather	GET	R, RW	Retrieve all weather information
/api/rural_urban_type	GET	R, RW	Retrieve rural urban-type information
/api/mapQuery	POST	R, RW	Retrieve information based on filters
/api/clusterMap	GET	R, RW	Retrieve information about clusters for map display
/api/corridorsPedBike	GET	R, RW	Retrieve information about high crash corridors
/api/getScorecardCrashes	POST	R, RW	Get the report card for a high crash corridor
/api/scorecardHelper	POST	R, RW	Retrieve report card information about all crashes
/api/getDistinct	POST	R, RW	Retrieve distinct options in the DB for any column
/api/topTenFilters	GET	R, RW	Retrieve information about the top 10 used filters for a user

6.2 Overview of the Interface

After navigating to the web URL (https://myctis.utep.edu/pbcat/), a user is presented with a login page, as shown in Figure 6.3. Username and password should be provided by the administrator to authorized users.

After providing the correct credentials, users may log in to fetch data. As discussed earlier, the user has either R, RW, or ADMIN access. This chapter only outlines read access (R) use case.

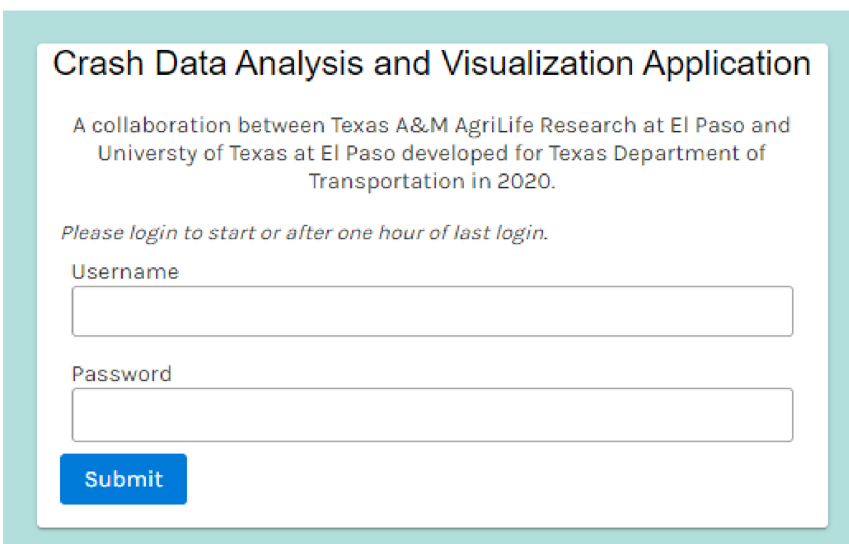


Figure 6.3 Login Form.

After logging in, a map of all the crashes analyzed in this project is displayed (Figure 6.4). Based on the desired crash selection, a user may filter crashes using the "Filter Crashes" button, show/hide the crashes displayed on the map using the "Show Crashes" or "Hide Crashes" buttons, display a table with all crashes using the "Crash Table" button, show or hide high incidence crash corridors on the map using the "Show Corridors" or "Hide Corridors" buttons, and display a table of corridors identified with the "Corridors Table" button. Logout () and change password () buttons are also available.

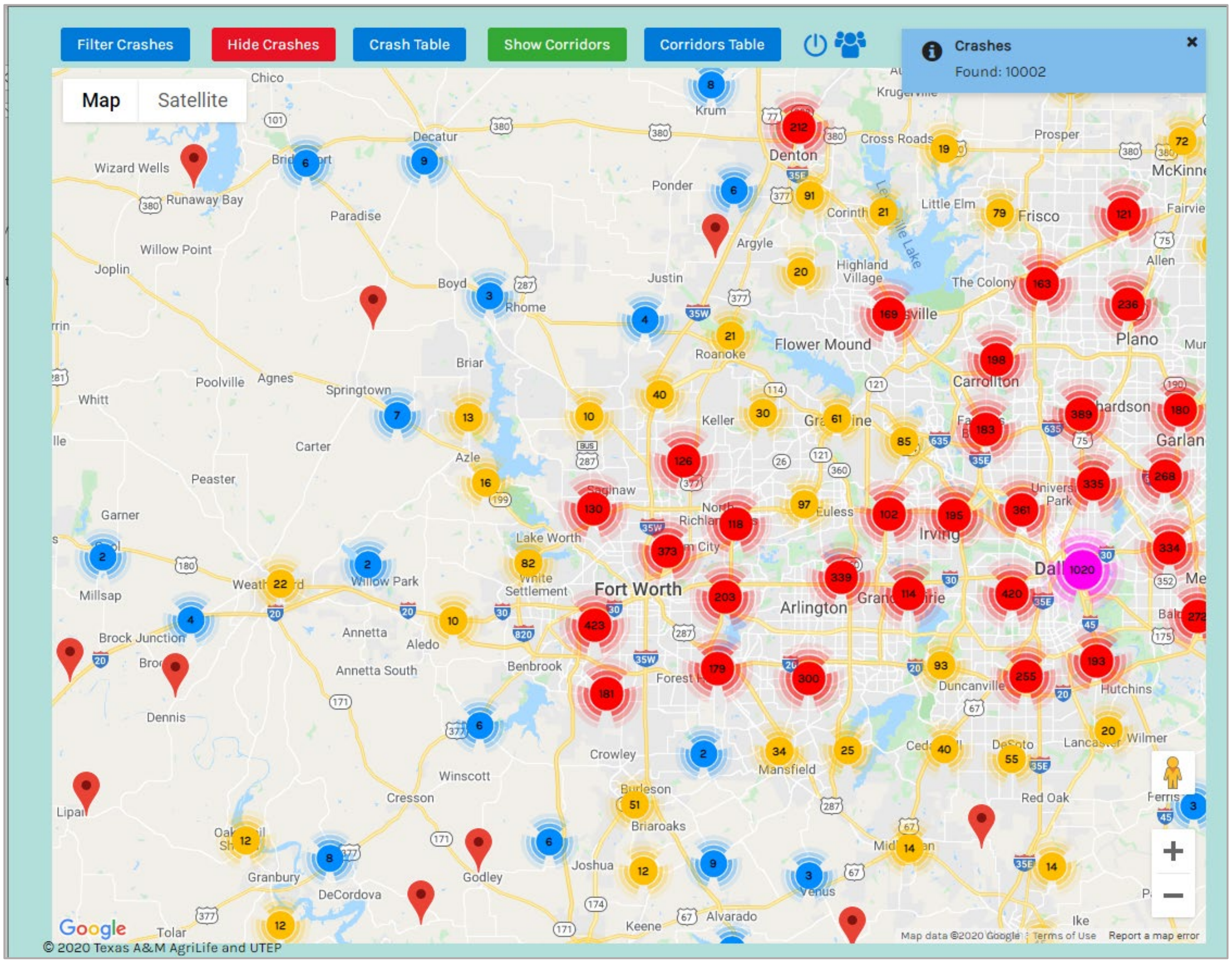


Figure 6.4 The Main Page for the On-line Application.

Note: The main buttons are on the top. All the displays on the map are also clickable to get more information about a crash.

Clicking the "Filter Crashes" button brings up a filter dialog (Figure 6.5) that may be used to query crashes based on all available features of the crash. The application dynamically puts frequently used filters on the top for ease-of-use. Depending on the usage, filters inside the "Frequently used" tab may change. The filters in the "Frequently used" filters will change after a user has used the application frequently and applied at least ten different filters.

The filters are also organized in categories (e.g., roadway, person, unit, etc.) for a more systematic search. As filters are selected, the crashes displayed on the map and the table (not shown in Figure 6.5) also change.

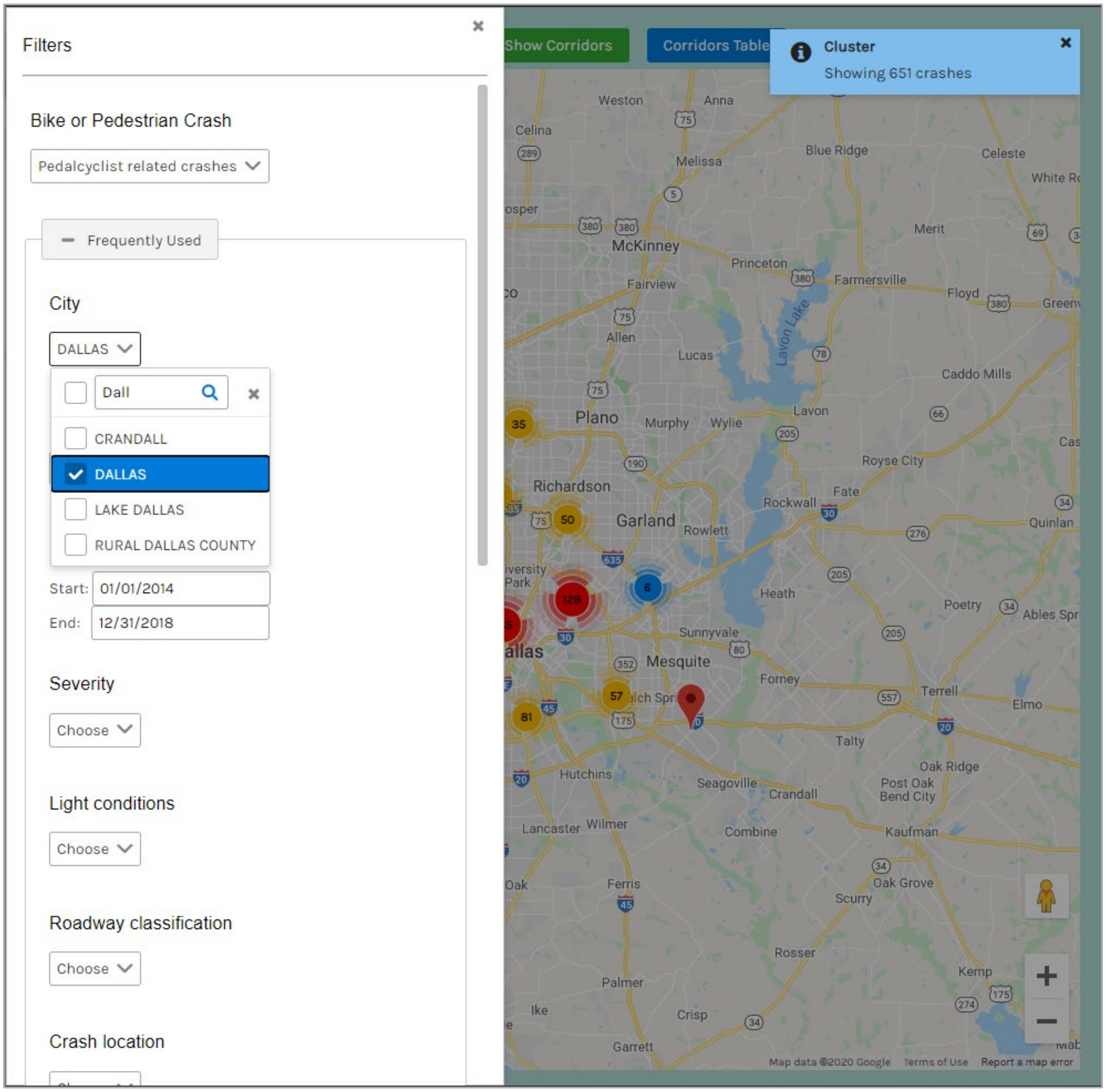


Figure 6.5 Filter Crash Dialog.
Note: Filtering crashes dynamically changes the crashes displayed on the map and the table (not shown). All features analyzed in this project are available for systematic filtering; however, the top filter category is dynamically created based on usage.

Figure 6.6 shows the crash table; as discussed above, the table is dynamically linked to the filter selection. Also, the table allows further search/filtering, and clicking on a row will bring up details of the crash.

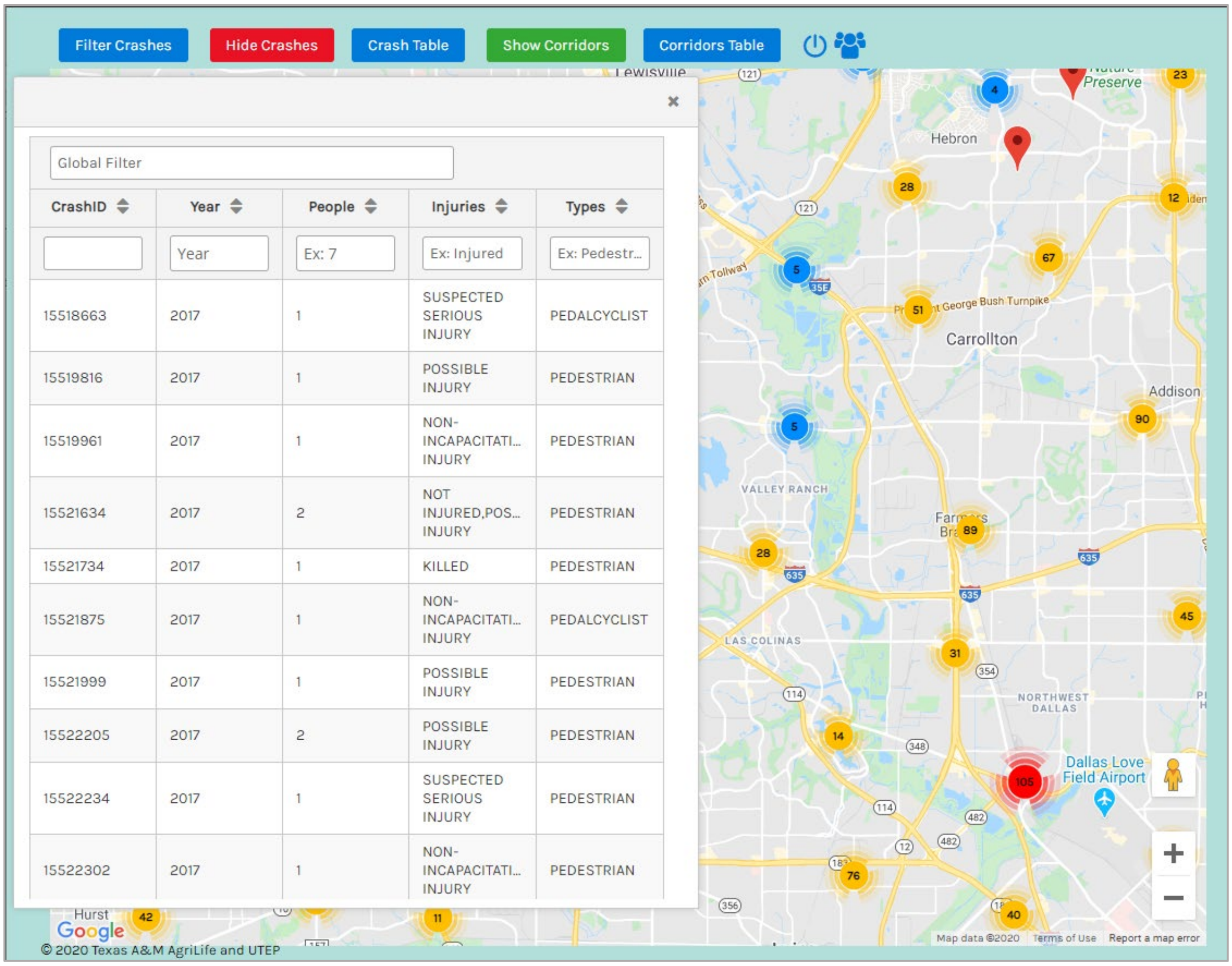


Figure 6.6 Table of Filtered Crashes.

Note: Clicking on a row in the table (similar to clicking on a crash on the map) will bring up details about the crash and the table presents more quick-filtering options.

Figures 6.7 and 6.8 show the details of a single crash that may be obtained by clicking on the map or table row. Crash information is organized in sections, with essential information displayed in the first section. Note for RW access level users, the interface will allow correcting the crash information from this screen.

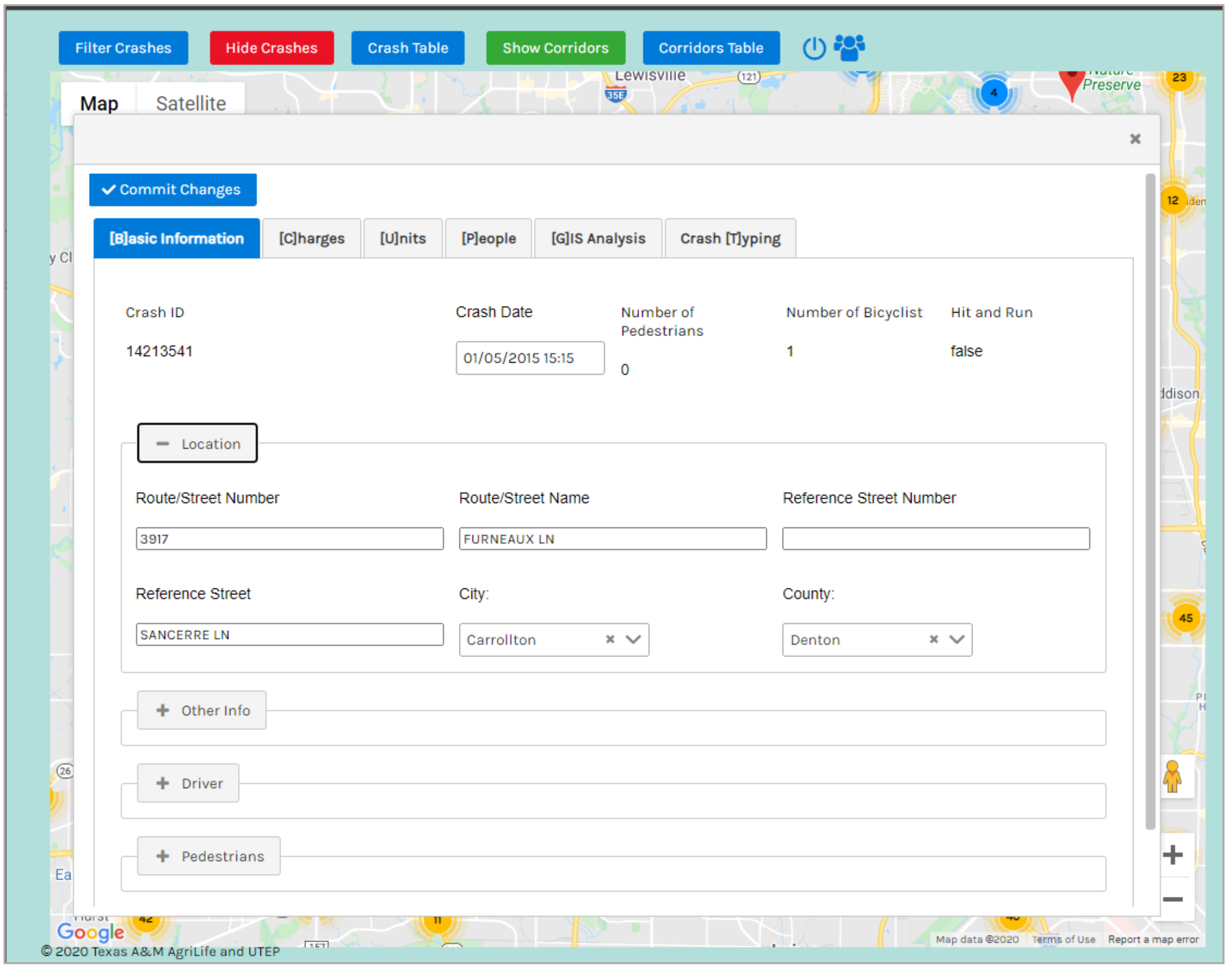


Figure 6.7 Crash Detail Dialog Showing Information about a Crash in Categories.
Note: This dialog pops up when a crash is clicked on the map or the table. The "Basic Information" tab, shown in the figure, displays essential information about the crash.

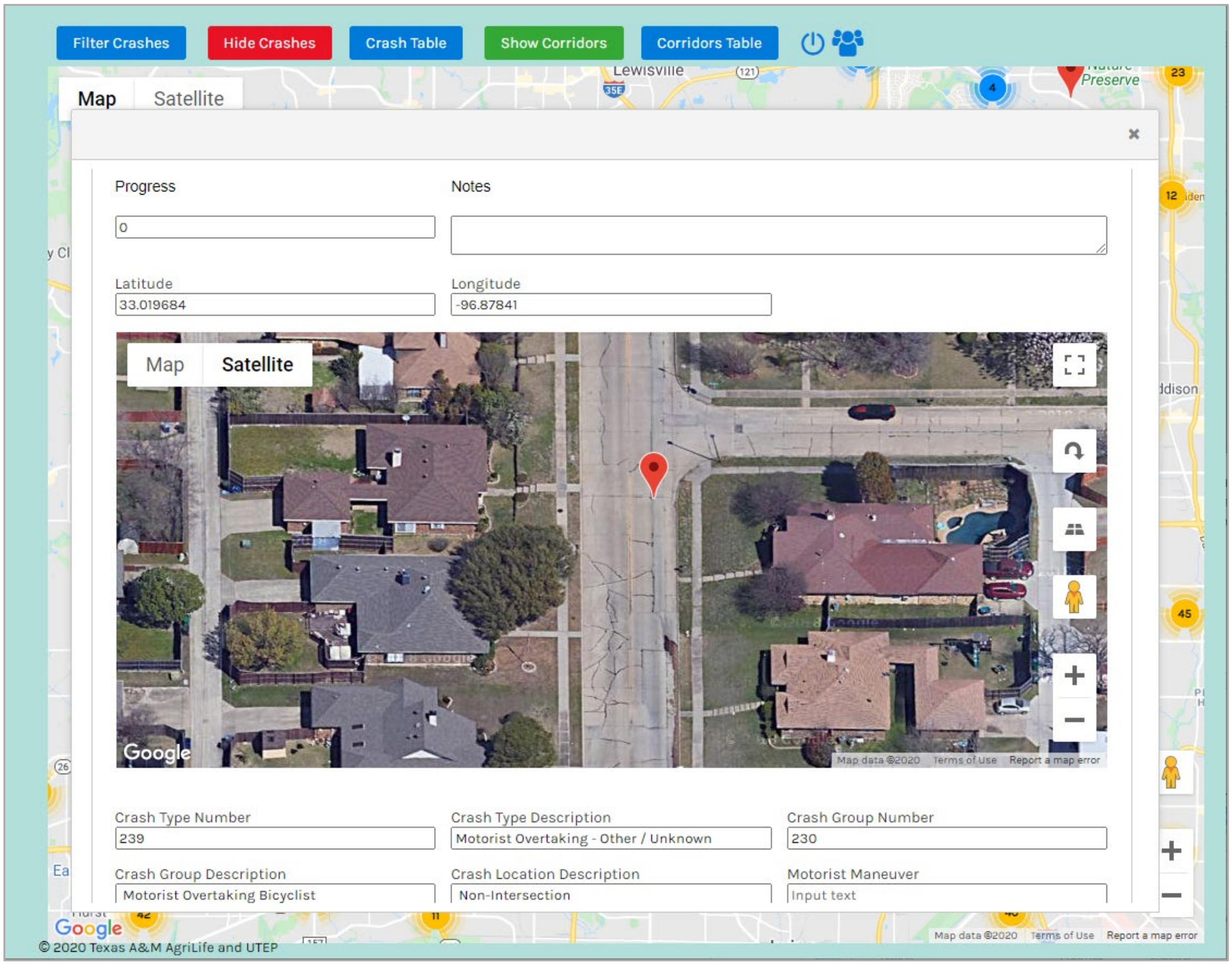


Figure 6.8 "Crash Typing" Tab in the Crash Detail Dialog.
Note: This tab contains information that was obtained from PBCAT software.

High incidence crash corridors are also displayed on the map or the table (Figure 6.9).

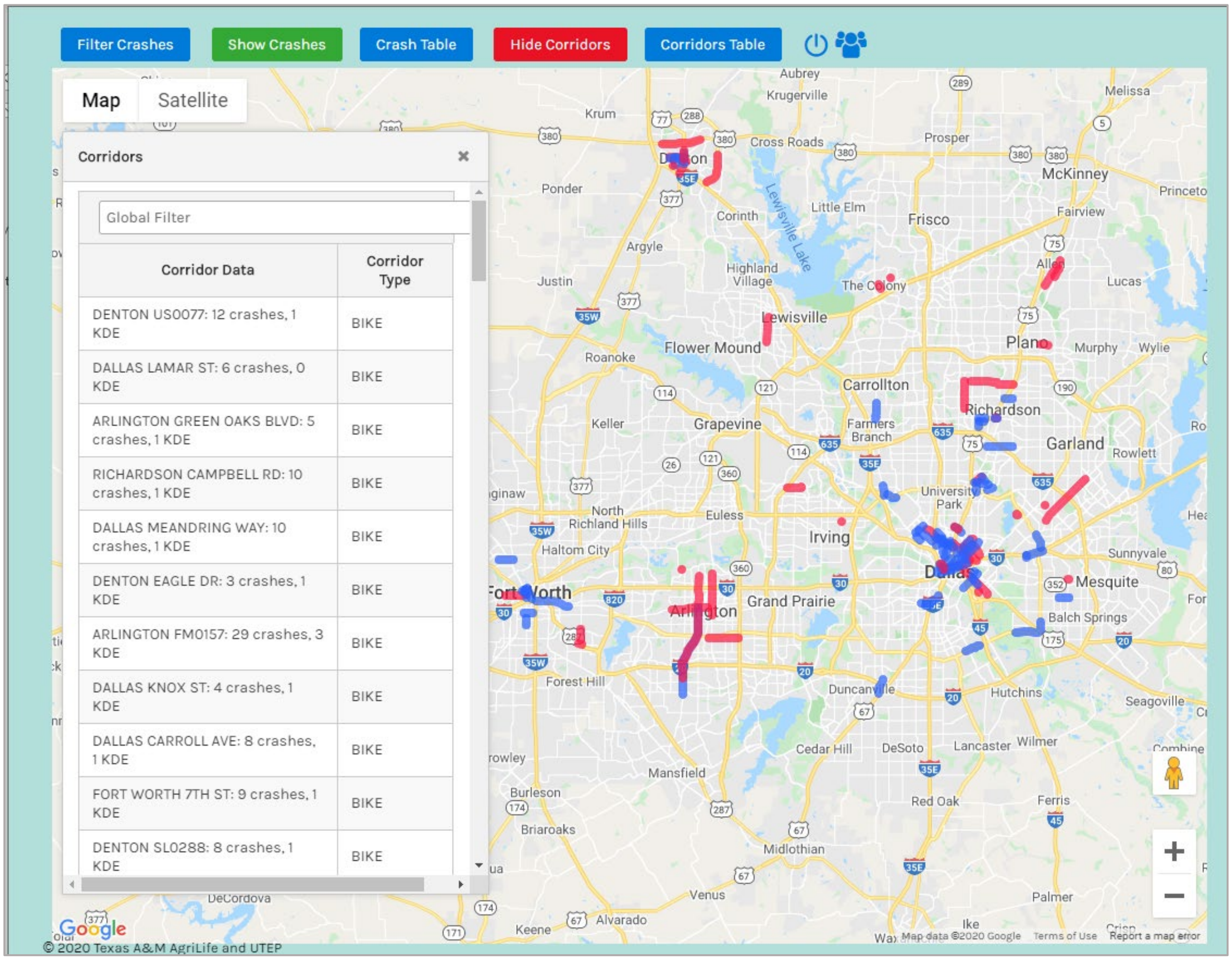


Figure 6.9 High-incidence Crash Corridors Table and Location.

Note: Corridor locations marked on the map in red. Clicking on the corridor table or map will bring up information about the corridor.

Clicking on the corridor shown on the map or the table row will bring up more summary information about the crashes on the corridor (Figure 6.10). Note that the table also allows some filtering based on the corridor-type (not shown).

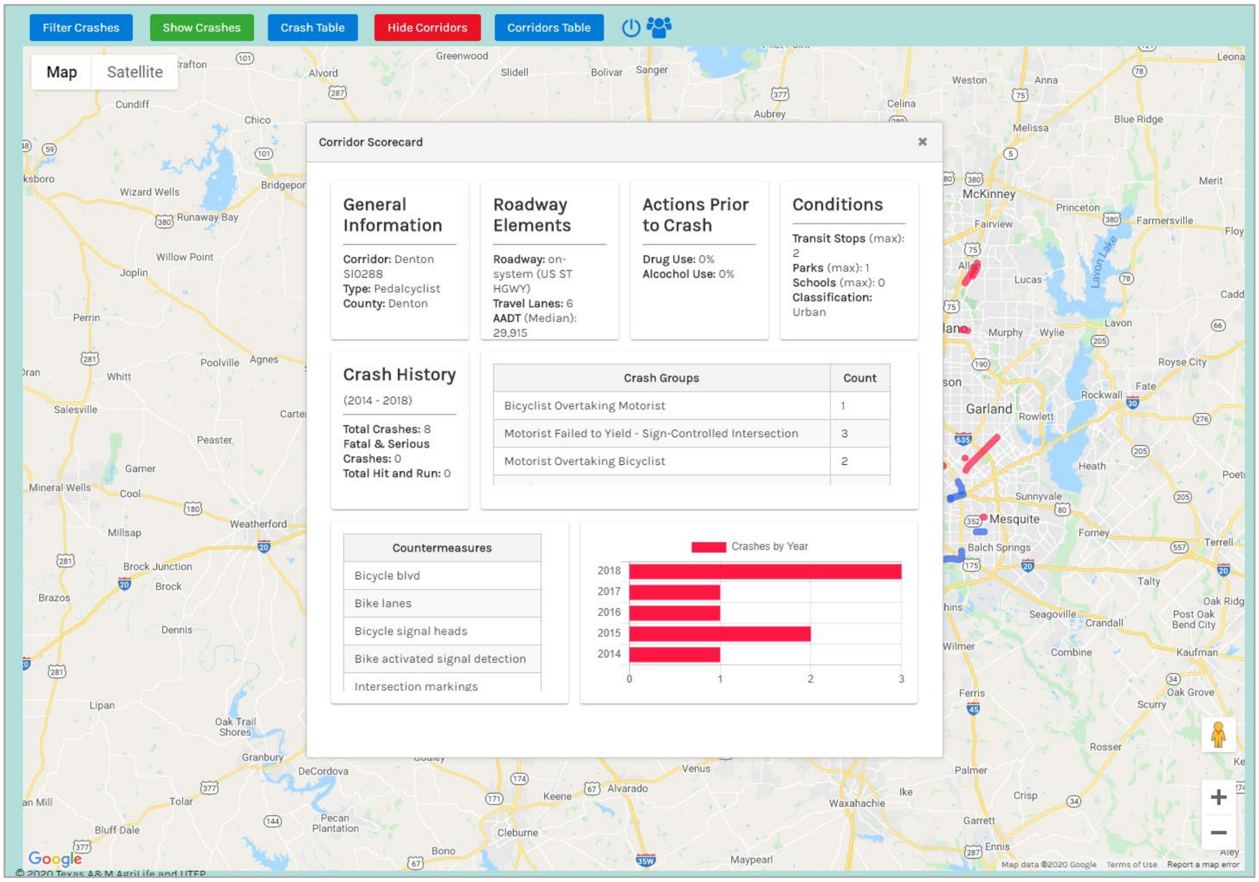


Figure 6.10 Summary Details of the Corridor Available when a High-Incidence Corridor is Clicked.

If the Crash ID (TXDOT Crash Id) of a crash is known then information about the crash may be obtained directly by typing the id with the URL, e.g., */crash?id=14446555*; replace the number with the Crash ID and prepend the base URL (Figure 6.11).

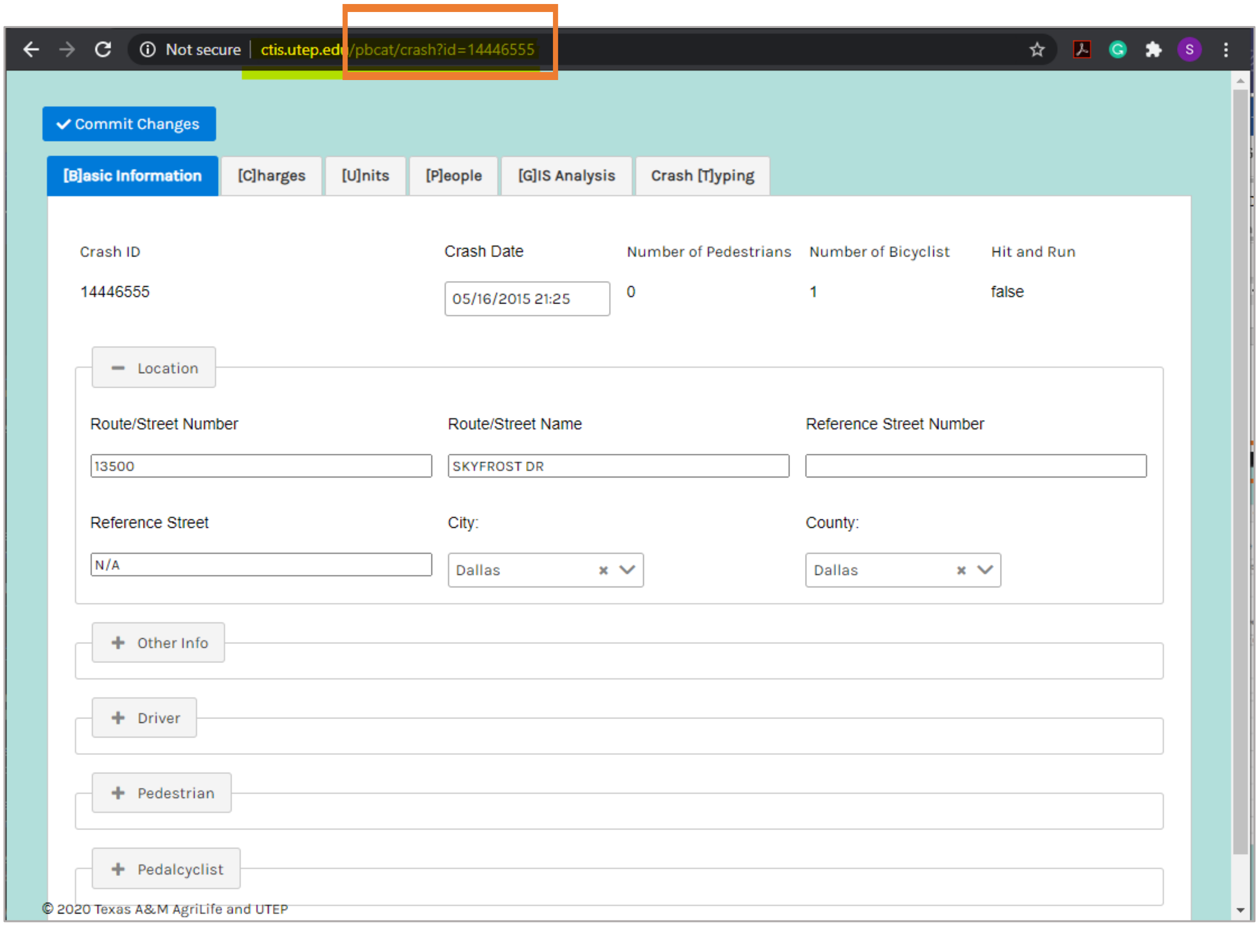


Figure 6.11 Direct Access to Crash Information Using URL.

Note: A pattern such as https://myctis.utep.edu/pbcat/crash?*id=14446555* will retrieve information about the crash identified by the Crash ID 14446555.

6.3 Display High-incidence Crash Corridors

As shown in Figure 6.12, High-Incidence Crash Corridors identified by the project are displayed on the map. The blue line indicates a high-incidence pedestrian crash corridor while a red-line indicate a high-incidence pedalcyclist crash corridor. The corridors are also displayed on the table and clicking on a corridor on the map or table will bring more information about the corridor

(Figure 6.10). By filtering for pedestrian corridor (or pedalcyclist corridor), crashes in a corridor may be analyzed (Figure 6.12).

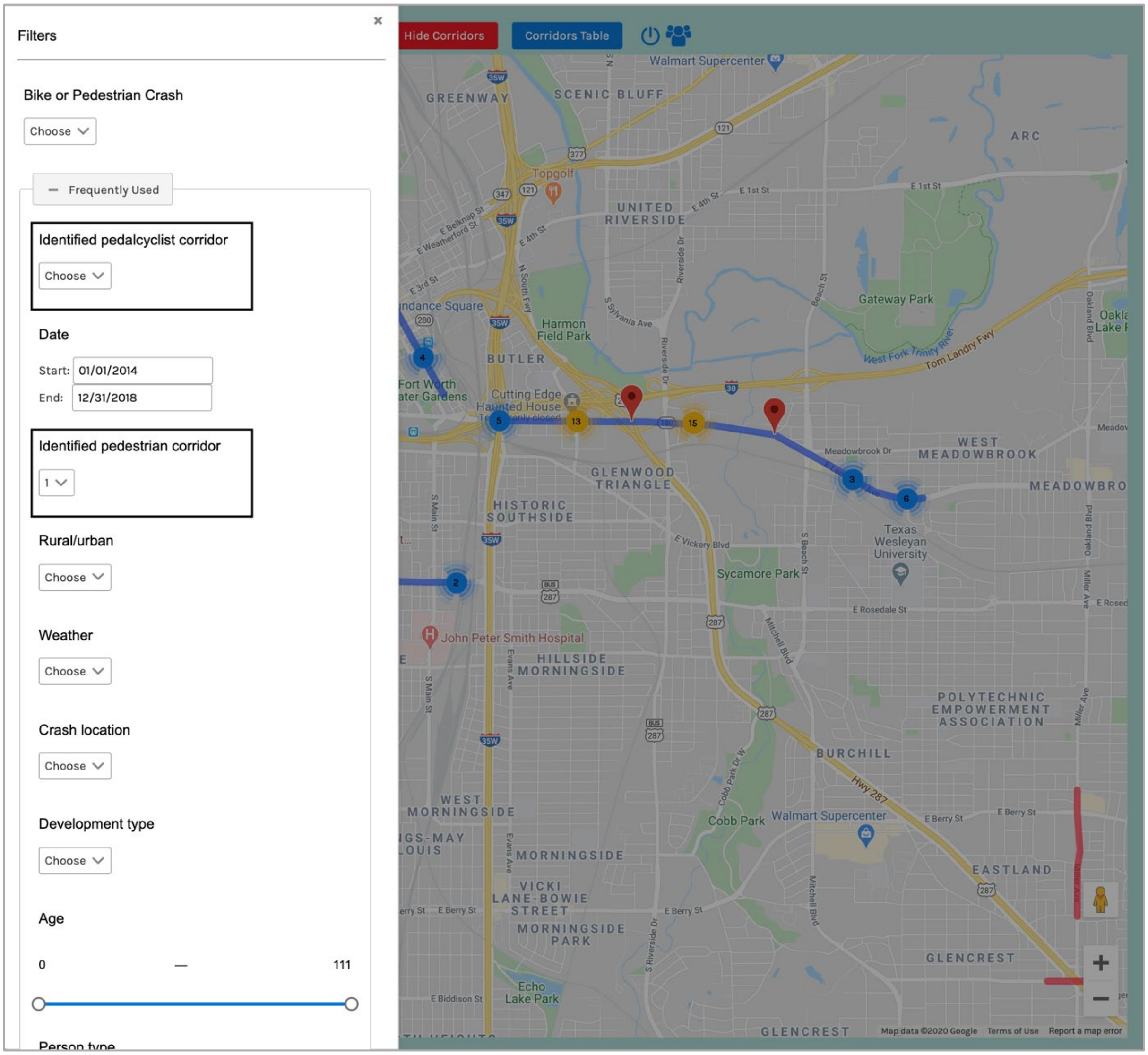


Figure 6.12 Filtering for High-Incidence Corridors.

Note: Both "Show Crashes" and "Show Corridors" buttons were enabled. The "Identified Pedestrian Corridor" and the "Identified Pedalcyclist Corridor" filters are in the "Crash Report" group.

6.4 Display Potential Safety Countermeasures

Countermeasures were identified for all high-incidence corridors. They are listed on the 'report card' generated by the web interface (Figure 6.10 and Figure 6.13).

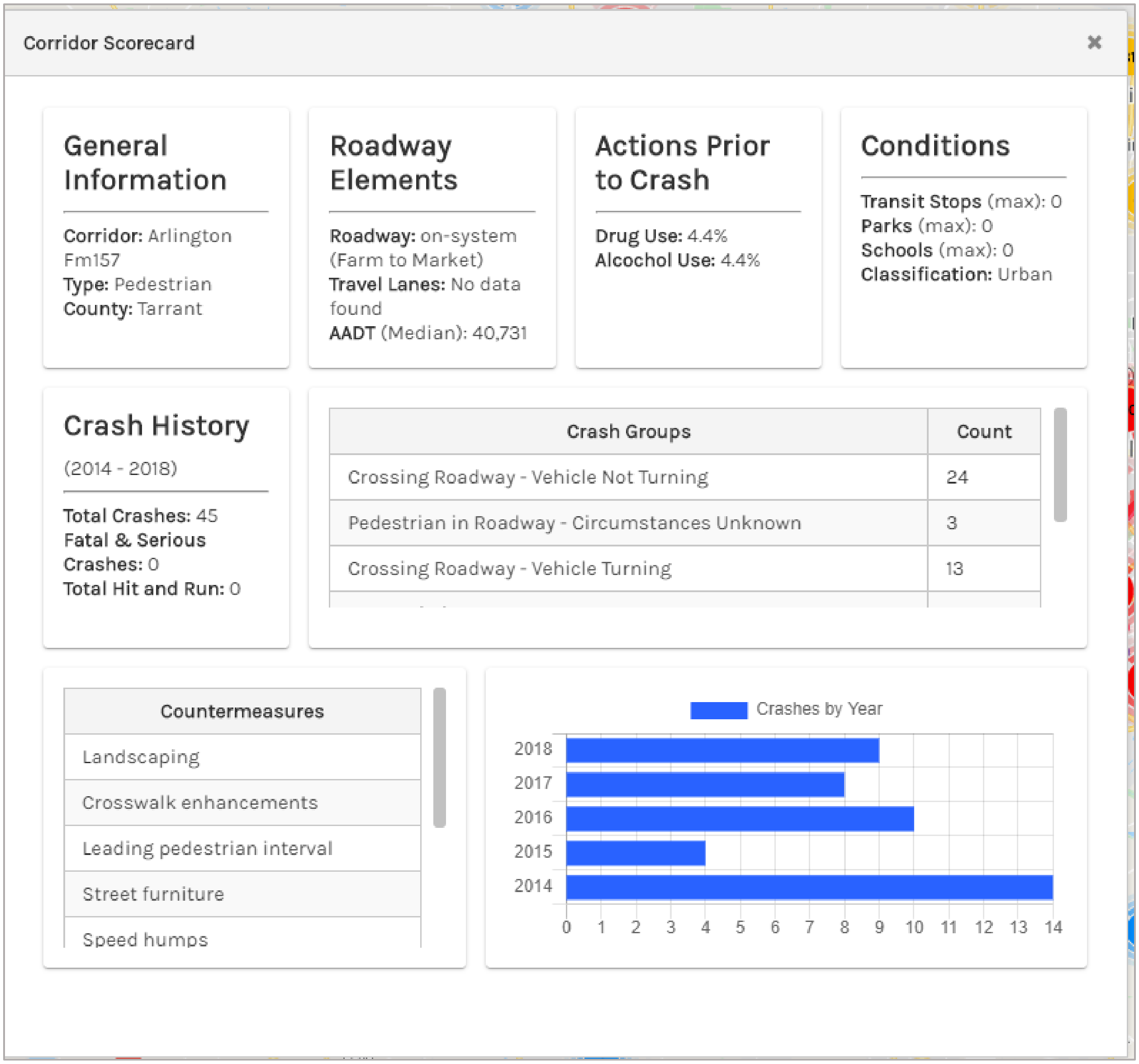


Figure 6.13 Report Card for High-Incidence Corridors.
Note: Countermeasures are listed on the report card along with other information about the corridor.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This Chapter summarizes key findings as a result of the research study and provides recommendations for implementation and further enhancements. The major contribution of this research study are the identified pedestrian and bicycle safety needs in North Central Texas, that are visually presented in a pilot version of an on-line application, which includes a Crash Database & Query Builder, an interactive map of high-incidence crash corridors that were identified, information about the crashes and corridors and related potential countermeasures. These can be used by Districts and municipalities during planning of safety enhancements in pedestrian and bicycle networks. Identified high-incidence corridors can further investigated during road safety audits where the most appropriate countermeasures can be selected.

7.1 Pedestrian and Bicyclist Safety and Crash Data

1. Data-based performance management is emphasized in the latest transportation bills, MAP-21, and FAST Act. DOTs are required to set targets for five safety performance measures and report to the FHWA on an annual basis. A safety performance measure that directly applies to pedestrians and bicyclists is the ‘number of combined non-motorized fatalities and non-motorized serious injuries reported as a 5-year moving average.

2. Pedestrian and bicyclist crashes can be described by crash factors (person, vehicle, prior action), environmental factors (roadway, conditions), and exposure factors (counts, mode-share, etc.). A pedestrian and bicycle crash database was created based on data from the CRIS Automated Crash Data Public Extract, narratives and diagrams in the CR-3 crash report forms, Roadway Inventory Annual Data, Strava Metro, U.S. Census Bureau: American Community Survey (ACS) and Longitudinal Employer-Household Dynamics (LEHD) and asset inventories provided by the North Central Texas Council of Governments (NCTCOG). Some data fields were directly populated from the available datasets, some needed manual review and input to PBCAT, and others were spatially analyzed in ArcGIS prior to importing to the database. In cases where relevant crash data was not available in the CRIS Automated Crash Data Public Extract, recommendations for future improvements were discussed in accordance with the NHTSA Model Minimum Uniform Crash Criteria (MMUCC) voluntary guidelines for crash data collection.

3. PBCAT crash types were assigned to a total of 10,002 crashes, following the crash typing methodology of the Pedestrian and Bicycle Crash Analysis Tool version 2.0. Majority of PBCAT crash typing questions were answered based on the information included in the *“Narrative and Diagram”* section of the CR-3 crash report form, complemented by information captured in the *“Identification and location”* section and the *“Vehicle, driver, and persons”* section. It was found that 0.6% of crashes that were identified as pedestrian-related in CRIS actually did not have any pedestrian present (42 out of 7,084 crashes). In

the case of crashes that were identified as pedalcyclist-related in CRIS, only 0.4% actually did not have any pedalcyclist involved based on the description in narrative and diagram (11 out of 2,948 crashes).

4. The most common crash types observed in the North Texas dataset were similar to those reported in PBCAT crash studies in Arizona, Michigan, and Wisconsin (Arizona DOT, 2017; Michigan OHSP, 2016; WisDOT, 2006) amount of pedalcyclist crashes (500 out of 2,958) and lesser amount on pedestrian crashes (157 out of 7,046) were categorized in PBCAT with crash types that included "unknown" or "other". For example, in some cases the CR-3 crash report's narrative stated that witnesses found a pedestrian in the roadway but did not know how the pedestrian got there or what were the actions that lead to the crash. In other cases, the report narrative did not explain any actions that contributed to the crash. In some cases, the actions described in the narrative did not align with actions in PBCAT and therefore were classified as "other." Table 7.1 shows the crash types for pedestrian and pedalcyclist which had to be coded into these categories for either not fitting in with the actions provided by PBCAT or due to missing information.

Table 7.1 Pedestrian and Pedalcyclist Crash Types with "Unknown" or "Other – Unknown"

Pedestrian (157 crashes)	Pedalcyclist (500 crashes)
• Backing Vehicle – Other / Unknown • Driveway Crossing – Other / Unknown • Intersection – Other / Unknown • Motorist Turn / Merge – Other / Unknown • Non-intersection – Other/Unknown • Off Roadway – Other / Unknown • Other – Unknown Location • Walking Along Roadway – Direction / Position Unknown	• Bicyclist Failed to Clear – Unknown • Bicyclist Lost Control – Other / Unknown • Bicyclist Overtaking – Other / Unknown • Bicyclist Ride Out – Midblock – Unknown • Crossing Paths – Intersection – Other / Unknown • Crossing Paths – Midblock – Other / Unknown • Head-On – Unknown • Motorist Drive Out – Midblock – Unknown • Motorist Lost Control – Other / Unknown • Motorist Overtaking – Other / Unknown • Motorist Turn / Merge – Other / Unknown • Parallel Paths – Other / Unknown • Signalized Intersection – Other / Unknown • Sign-Controlled Intersection – Other / Unknown • Unknown Approach Paths

Key findings from the descriptive trend analysis include:

1. The highest number of pedestrian crashes occurred in year 2015 but by 2018 pedestrian crashes have declined by 12 percent. The highest number of pedalcyclist crashes occurred in year 2017 and by 2018 also pedalcyclist crashes have declined by 11 percent.

2. During the five-year period, approximately 31% of pedestrian crashes resulted in fatal or serious injuries. Approximately 15% of all crashes that involved a pedalcyclist resulted in fatal or serious injuries.

3. The month with the highest number of pedestrian crashes was October and for pedalcyclists the month with the most crashes was September. Overall, pedestrian crashes were highest during months of September through January, while pedalcyclist crashes were highest from March through October.

4. Pedestrian crashes occurred most frequently on Fridays and were lowest on Sundays. Pedalcyclist crashes were higher during workdays and lowest on weekends.

5. Almost 95% of all pedestrian crashes and 92% of K/A crashes occurred in only four counties: Dallas, Tarrant, Denton, and Collin, while only 88% of the region's population resides in these counties. Majority of pedalcyclist crashes (95% of all crashes and 92% of K/A crashes) occurred in only four counties: Dallas, Tarrant, Denton, and Collin.

6. While many fatal and serious pedestrian crashes occurred during daylight (36%), more than a half (60%) occurred in dark (lighted and not lighted) conditions. The majority of fatal and serious pedalcyclist crashes occurred during daylight (59%). The crash frequency of fatal and serious pedalcyclist crashes was similar in dark but lighted conditions (19%) and in not lighted (16%).

7. More than 93% of crashes with passenger vehicles, SUV/van/truck, or freight trucks resulted in injuries (K/A/B/C). About one third of crashes with passenger vehicles (31%) and SUV/van/truck (31%) resulted in fatal or serious injuries, while half of crashes (52%) between pedestrians and freight trucks resulted in fatalities and serious injuries. While majority of crashes between pedalcyclists and motorized vehicles resulted in injuries (B/C), about 13% of crashes with passenger vehicles were fatal or serious (15% for SUV/van/truck and 19% for freight trucks).

8. In rural areas, majority of fatal and serious crashes occurred on-system roadways. In urban areas, majority of pedestrian crashes that resulted in injuries (B/C) were off-system, however fatal and serious injury crashes were almost as high on-system (954) as off-system (1,132).

9. In rural areas, all fatal and serious pedalcyclist crashes occurred on-system roadways. In urban areas, majority of pedalcyclist crashes that resulted in injuries (B/C) were off-system, however fatal and serious injury crashes off-system (293) were more than double of those on-system (128).

10. Off-system roadways with speed limit at or below 30 mph had the lowest pedestrian fatality and serious injury rate of 21%. The fatality rate appears to be rising with posted speed, with the highest fatality rate of 63% on on-system roadways with speed limits over 50 mph. Similar to the pedestrian statistics, pedalcyclist statistics show that off-system roadways with speed limit at or below 30 mph had the lowest fatality and serious injury rate of 12%. Also, the pedalcyclist fatality rate appears to be rising with posted speed, with the highest fatality rate of 45% on on-system roadways with speed limits over 50 mph.

11. A majority of pedestrian crashes occurred on roadways with 2 to 4 lanes (72%) and 28% of all crashes occurred on roadways with more than 4 lanes. Roadways with 2 to 4 lanes experienced the highest proportion of pedalcyclist crashes (80%) and 20% of all crashes occurred on roadways with more than 4 lanes.

12. Majority of fatal and serious injury pedestrian crashes (40%) occurred at non-intersection locations, while most of fatal and serious injury pedalcyclist crashes occurred at non-intersection locations as well as directly at intersections.

13. From 425 crashes where either driver or pedestrian was impaired, 389 of them (92%) resulted in fatal or serious injuries. From 24 crashes where either driver or pedalcyclist was impaired, 16 of them (67%) resulted in fatal or serious injuries. The crash database indicated unknown impairment.

14. During the five-year period, a total of 1,609 pedestrian crashes (23%) were identified as a hit and run. During the five-year period, a total of 471 pedalcyclist crashes (16%) were identified as a hit and run.

15. *Crossing roadway (with vehicles not turning or turning)* lead to the highest number of fatal and serious crashes, as well as unusual circumstances, such as *Disabled-Vehicle* related crashes. *Crossing expressway* resulted in fatal and serious injuries in 70% of crashes. For pedalcyclists, *Motorist overtaking bicyclist* led to the highest number of fatal and serious crashes.

A multinomial logit (MNL) model, looking into significant factors that may contribute to fatal or serious severity of a crash, was developed based on data from 7,047 pedestrian crashes and 2,958 pedalcyclist crashes. The key findings from the multinomial logit (MNL) model include:

1. Thirteen factors were considered significant for the Pedestrian MNL model and these include roadway conditions (Posted Speed, presence of Traffic Control), conditions (Driver Age, Pedestrian Age, Light Condition, and presence of a Freight Truck), and actions (Motorist Maneuver, PBCAT Crash Group, Drug Positive, Alcohol Positive, Pedestrian Position and PBCAT Intersection).

2. Six factors were considered significant for the Pedalcyclist MNL model and these include: roadway conditions (Posted Speed), conditions (Light Condition), and actions (Driver Age, Pedalcyclist Age, PBCAT Crash Group, and Bicyclist Direction).

7.2 Guidelines for Safety Countermeasures

The guidelines should assist state, regional, and local organizations to develop of strategic plans at the management network level following four steps:

Step 1. Identify high-risk crash locations

Step 2. Determine risk safety factors and crash types

Step 3. Select cost-effective safety countermeasures.

Step 4. Implement countermeasures and monitor for safety effectiveness

- A combination approach is recommended to identify risk-high incident crash locations. This approach combines historical crash pattern analyses with predictive risk safety models.
- "Roadway Safety audits" should be conducted to confirm the appropriate countermeasures each location before implementation. Emphasis should be given to combine engineering, educational, enforcement, and expert knowledge is required to finally select cost-effective countermeasures.
- Report cards are recommended to summarize information collected about each corridor and corresponding countermeasures. The report cards in Appendix H contain an overview about where the crashes occurred, when they occurred, the roadway elements and conditions, as well as the PBCAT crash groups indicating the unsafe actions that lead to those crashes.

7.3 Pilot On-line Application

The pilot on-line application visually presents the results of the research as it displays location of individual crashes, identified high-incidence corridors, and potential countermeasures. It also allows users to query crash data using multiple filters.

7.4 Potential Application in Existing State and Local Efforts

There are a number of potential applications of the results from this research. The procedure developed for PBCAT analysis can lead to recommendations on what fields could be included in future versions of the crash report form CR-3, and the lessons learned in the development of the crash database, methodology applied to identify high-incidence crash corridors and recommend cost-effective countermeasures can be leveraged in existing state and local efforts.

1. **PBCAT Analysis:** A procedure to automatically populate PBCAT database fields from CRIS Automated Crash Data Public Extract files was developed in an effort to reduce the data entry time. In cases where roadway-related data was not available in CRIS data fields, the TxDOT Roadway Inventory Annual Data (TxDOT, 2017) was queried. That way, majority of PBCAT crash typing questions were answered based on the information included in the "Narrative and Diagram" section of the CR-3 crash report form, complemented by information captured in the "Identification and location" section and the "Vehicle, driver, and persons" section. It took approximately 5 minutes to review the narrative and diagram in each CR-3 crash report form and to answer PBCAT questions related to the crash location, bicyclist/pedestrian position, direction, and approach paths. The time varied based on the complexity of the crash or due to missing or contradicting information that usually required a more thorough review. The procedure developed during this project could be leveraged in analysis of future crash data in the North Texas region, as well as in crash analysis in other counties/districts in Texas.

2. **Crash Report Form:** As a part of a background review for this project, notable practices in data commonly collected to analyze crashes that involved a pedestrian or a cyclist were reviewed. Crash reporting practices of eight DOTs, including Colorado, Florida, Georgia, North Carolina, New Mexico, Oregon, Virginia, and Washington were reviewed. A key document is the *National Highway Traffic Safety Administration's (NHTSA) Model Minimum Uniform Crash Criteria (MMUCC)* voluntary guidelines for crash data collection. The MMUCC "identifies a minimum set of motor vehicle crash data elements and their attributes that States should consider collecting and including in their State crash data systems" (NHTSA, 2017a). The fields that could enhance collection of pedestrian and pedalcyclist data on the CR-3 form include non-motorist flag, non-motorist type, non-motorist safety equipment, non-motorist physical condition, pedestrian location, pedestrian action/maneuver, non-motorist contributing factors, and non-motorist facility type. Details about the non-motorist section data elements recommended by NHTSA can be found in the MMUCC.

3. **Regional and City Planning:** The results of this research can also be leveraged in regional and city planning, especially the following products:

    a. **0-6983 Crash Database & Query Builder:** the crash database developed in this project includes not only PBCAT crash types based on CRIS Automated Crash Data Public Extract files (TxDOT, 2019), but also other data collected from various datasets including 2017 Roadway Inventory Annual Data (TxDOT, n.d.), Dallas Area Rapid Transit (DART) data (DART, 2018), the NCTCOG Regional Data

Center (NCTCOG, n.d.-b) Strava Metro (2019), U.S. Census Bureau American Community Survey (US Census Bureau, 2018), U.S. Census Longitudinal Employer-Household Dynamics (U.S Census Bureau, 2015), as well as Pedestrian Fatality Risk (USDOT, 2018b) and the Social Vulnerability Index (CDC, 2016). The online query builder allows users to easily identify locations of crashes by year, TxDOT district, county, city, person type, gender, age, injury severity, alcohol and drug impairment, on/off-system, midblock/intersection, and light conditions. Additionally, an extended set of filters is available in the advanced query section.

b. **Identified High-Risk Incidence Corridors**: based on 2014-2018 crash data, high-incidence corridors were identified. Report cards were prepared for the top 61 pedestrian crash corridors and 45 pedalcyclist crash corridors. They provide information about what city and county the corridor is in, its length, crash history based on 2014-2018 data, roadway elements, impairment, surrounding conditions, identified PBCAT crash groups and related potential countermeasures. This summary is meant for local districts and municipalities to help identify areas that need further safety analysis.

c. **Potential Countermeasures**: the list of countermeasures gathered during this project is based on recommendations from PEDSAFE (FHWA, 2013a), BIKESAFE (FHWA, 2014), Proven Safety Countermeasures (FHWA, 2018c), Urban Bikeway Design Guide (NACTO, 2017) and others (FHWA, 2018b; NCHRP, 2016; TTI, 2015). It is recommended to review the existing countermeasures listed in the Texas Strategic Highway Safety Plan and possibly complement it.

7.5 Recommendations for Future Research

The research team recommends the following topics for consideration in future research:

1. Update crash report form CR-3 to reflect recommendations of National Highway Traffic Safety Administration's (NHTSA) Model Minimum Uniform Crash Criteria (MMUCC) voluntary guidelines regarding information that is collected about crashes that involve pedestrian and bicyclists.

2. Once pedestrian and bicyclist crash reporting is improved, then an automated process can be developed to determine PBCAT crash types without the need to manually review police crash reports. This will be feasible in the future, once police crash reports include fields describing crashes between motorized vehicles and pedestrians or bicyclists (e.g., where crash occurred? pedestrian/bicyclist position? circumstances? approach paths?) rather than capturing this information only in narrative/diagrams.

3. This PBCAT crash typing logic could be added into the web application, so that all pedestrian and bicyclist crash data is in one place.

REFERENCES

AASHTO. (2014). *Highway Safety Manual.* AASHTO.

AASHTO. (n.d.). *Safety Analysis Expected Benefits*. Retrieved from http://www.safetyanalyst.org/benefits.htm

Alabama DOT. (2017). *Alabama Strategic Highway Safety Plan.* AlabamaDOT.

Alluri, P. P., Raihan, A. M., Saha, D. P., Wu, W. P., Huq, A. M., Nafis, S. B., & Gan, A. P. (2017). *Statewide Analysis of Bicycle Crashes.* Florida Department of Transportation.

Arizona DOT. (2017). *ADOT Pedestrian Safety Action Plan.* Kimley-Horn and Associates, Inc.

Aziz, H. M., Abdul, Ukkusuri Satish, V., & Hasan, S. (2013). "Exploring the Determinants of Pedestrian-Vehicle Crash Severity in New York City.". *Accident Analysis and Prevention 50 (January)*, 1298–1309.

Bernard, J. M. (2017). An Application of Decision Tree Models to Examine Motor Vehicle Crash Severity Outcomes. *Journal of the Transportation Research Forum*, https://doi.org/10.5399/osu/jtrf.56.2.4438.

Bike Texas. (2020a). *Sage Passing in Texas*. Retrieved from http://www.biketexas.org/en/advocacy/safe-passing

Bike Texas. (2020b). *Texas in Motion*. Retrieved from https://www.biketexas.org/education/texas-in-motion/

Bíl, M. A. (2019). *KDE+. Computer software. Vers. 2.3.* Retrieved from www.kdeplus.cz/en

BTS. (2018). *Local Area Transportation Characteristics for Households (LATCH Survey)*. Retrieved from https://www.bts.dot.gov/latch

CaDMV, s. o. (2018). *California Driver Handbook*. Retrieved from https://www.dmv.ca.gov/web/eng_pdf/dl600.pdf

CDC. (2016). *Social Vulnerability Index*. Retrieved from https://svi.cdc. gov/data-and-tools-download.html

CDOT. (2017). *Colorado Highway Safety Improvement Program.* Colorado Department of Transportation.

CDOT. (2018). *DR 3447 Data Model*. Retrieved from https://www.codot.gov/about/committees/strac/dr-3447-data-model/dr-3447-data-model/view

Chang, C. (2019). *Vulnerable Road User Safety Enhancements for Transportation Asset Management.* Center for Transportation, Environment, and Community Health Final Report.

Chen, Zhen, & Fan, W. D. (2019). *A Multinomial Logit Model of Pedestrian - Vehicle crash Severity in North Carolina.* Retrieved from https://doi.org/10.1016/j.ijtst.2018.10.001

Cheng, Wen, Gill, G. S., Sakrani, T., Dasu, M., & Jiao, Z. (2017). Predicting Motorcycle Crash Injury Severity Using Weather Data and Alternative Bayesian Multivariate Crash Frequency Models. *Accident Analysis & Prevention*, https://doi.org/10.1016/j.aap.2017.08.032.

Chimba, D. P., Emaasit, D., Cherry, R. C., & Pannell, Z. (2014). *Patterning Demographic and Socioeconomic Characteristics Affecting Pedestrian and Bicycle Crash Frequency.* Transportation Research Board.

City of Chicago. (2020a). *Red Light Camera Enforcement*. Retrieved from https://www.chicago.gov/city/en/depts/cdot/provdrs/automated_enforcement.html

City of Chicago. (2020b). *Childern's Safety Zone Program & Automated Speed Enforcement*. Retrieved from https://www.chicago.gov/city/en/depts/cdot/provdrs/automated_enforcement.html

CMF Clearinghouse. (n.d.). *CRASH MODIFICATION FACTORS CLEARINGHOUSE*. Retrieved from http://www.cmfclearinghouse.org/

Coleman, H., & Mizenko, K. (2018). *Pedestrian and Bicyclist Data Analysis.* Washington, DC: National Highway Traffic Safety Administration.

Cottrell, B. H., & In-Kyu Lim, P. P. (2018). *Systemic Low-Cost Countermeasures for an Unsignalized Intersection Safety Improvement Plan for Virginia.* Virginia Department of Transportation.

Cross, K., & Fisher, G. (1977). *A Study of Bicycle/Motor-Vehicle Accidents: Identification of Problem Types and Countermeasure Approaches.* Washington, DC: NHTSA.

Dadashova, B., Griffin, G., Das, S., Turner, S., & Graham, M. (2018). *Guide for Seasonal Adjustment and Crowdsourced Data Scaling.* TTI, TxDOT, FHWA.

DART. (2018). *Transit Data*. Retrieved from Dallas Area Rapid Transit: https://www.dart.org/transitdata/

Desapriya, E., Subzwari, S., Sasges, D., Basic, A., Alidina, A., Turcotte, K., & Pike, I. (2010). Do Light Truck Vehicles (LTV) Impose Greater Risk of Pedestrian Injury than Passenger Cars? A Meta-Analysis and Systematic Review. http://dx.doi.org/10.1080/15389580903390623.

Drive Kind Ride Kind. (n.d.). Retrieved from http://drivekindridekind.org

Dumbaugh, E., & Rae, R. (2009). Safe Urban Form: Revisiting the Relationship Between Community Design and Traffic Safety. *Journal of the American Planning Association*, 309-329.

Ewing, R., Pendall, R., & Chen, D. (n.d.). *Measuring Sprwal and Its Impact.*

Ewing, R., Schieber, R., & Zegeer, C. (2003). Urban Sprawl as a Risk Factor in Motor Vehicle Occupant and Pedestrian Fatalities. *American Journal of Public Health 93, No. 9*.

Fazzalaro, J. (2003). *Federal Transportation Funds for Bicycle and Pedestrian Facilities*. Retrieved from https://www.cga.ct.gov/PS98/rpt%5Colr%5Chtm/98-R-0010.htm

FDOT. (2018). *Official Florida Driver License Handbook.*

FHWA. (2000). *Accomodating Bicycle and Pedestrian Travel: A Recommended Approach*. Retrieved from https://www.fhwa.dot.gov/environment/bicycle_pedestrian/guidandce/design.cfm

FHWA. (2005). *A Summary of Highway Provisions in SAFETEA-LU*. Retrieved from https://www.fhwa.dot.gov/environment/bicycle_pedestrian/ guidance/design.cfm

FHWA. (2006). *PBCAT-Pedestrian and Bicycle Crash Analysis Tool Version 2.0*. Retrieved from https://www.fhwa.dot.gov/publications/research/safety/pedbike/06090/06090.pdf

FHWA. (2011a). *HSIP Project Identification.* Retrieved from https://safety.fhwa.dot.gov/hsip/resources/fhwasa1102/id.pdf

FHWA. (2011b). *Intersection Safety: A Manual for Local Rural Road Owners.*

FHWA. (2012a). *Moving Ahead for Progress in the 21st Century Act (MAP-21), A Summary of Highway Provisions*. Retrieved from https://www.fhwa.dot.gov/map21/ summaryinfo.cfm

FHWA. (2012b). *2009 Edition with Revisions No. 1 and 2 Incorporated, dated May 2012 (HTML)*. Retrieved from Manual on Uniform Traffic Control Devices : https://mutcd.fhwa.dot.gov/htm/2009r1r2/html_index.htm

FHWA. (2013a). *Pedestrian Safety Guide and Countermeasure Selection*. Retrieved from http://www.pedbikesafe.org/pedsafe/

FHWA. (2013b). *Roadway Departure (RWD) Strategic Plan*. Retrieved from https://safety.fhwa.dot.gov/roadway_dept/docs/rwd_strategic_plan_version2013

FHWA. (2014). *Bicycle Safety Guide and Countermeasure Selection System.* Federal Highway Administration.

FHWA. (2015). *Separated Bike Lane Planning and Design Guide.* Prepared by University of North Carolina HIghway Safety Research Center.

FHWA. (2016a). *Section 148: Older Drivers and Pedestrians Special Rule Final Guidance.* Retrieved from https://www.fhwa.dot.gov/map21/guidance/guideolder.cfm

FHWA. (2016b). *Fixing America's Surface Transportation Act or "FAST Act", A Summary of Highway Provisions*. Retrieved from https://www.fhwa.dot.gov/fastact/summary.cfm

FHWA. (2016c). *Met or Made Significant Progress Determination Fact Sheet.* December 3, 2018: Federal Highway Administration.

FHWA. (2016d). *Reliability of Safety Management Methods.* U.S Department of Transportation.

FHWA. (2016e). *Colorado's Implementation of Level of Service of Safety: Strategies for Using GIS to Advance Highway Safety.* Federal Highway Administration.

FHWA. (2017). *Highway Safety Improvement Program (HSIP)*. Retrieved from https://safety.fhwa.dot.gov/hsip

FHWA. (2018a). *Safety Performance Management (Safety PM), state Safety Performance Targets*. Retrieved from https://safety.fhwa.dot.gov/hsip/spm/state_safety_targets/

FHWA. (2018b). *Guidebook on Identification of High Pedestrian Crash Locations.* FHWA.

FHWA. (2018c). *Making Our Roads Safer: One Countermeasure at a Time.* U.S Department of Transportation.

FHWA. (2018d). *Proven Safety Countermeasures.* U.S Department of Transportation.

FHWA. (2019). *Pedestrian and Bicycle Information Center*. Retrieved from Safety: http://pedbikeinfo.org/factsfigures/facts_safety.cfm

FHWA. (n.d.-a). *Pedestrian and Bicycle GIS Safety Analysis Tools*. Retrieved from https://www.hsisinfo.org/ped-bike-gis.cfm

FHWA. (n.d.-b). *Bicycle Safer Journey*. Retrieved from http://www.pedbikeinfo.org/bicyclesaferjourney

FHWA. (n.d.-b). *USLIMIST2*. Retrieved from <https://safety.fhwa.dot.gov/uslimits/>

FHWA. (n.d.-c). *Pedestrian Safer Joruney*. Retrieved from http://www.pedbikeinfo.org/pedsaferjourney/

FHWA. (n.d.-d). *KABCO Injury Classification Scale and Definitions*. Retrieved from https://safety.fhwa.dot.gov/hsip/spm/conversion_tbl/pdfs/kabco_ctable_by_state.pdf

FHWA. (n.d.-d). *PBCAT Crash Type Images.* Retrieved from <http://www.pedbike info.org/pbcat_us/bike_images.cfm>

Fishman, E., & Schepers, P. (2018). The Safety of Bike Share Systems. *ITF Discussion Papers, International Transport Forum, Paris.*

Fitzpatrick, K., Avelar, R., & Turner, S. (2018). *Guidebook on Identification of High Pedestrian Crash Locations.* Federal Highway Administration.

Flanagan, B. G., Hallisey, E., Heitgerd, J., & Lewis, B. (2011). A Social Vulnerability Index for Disaster Management. *Journal of Homeland Security and Emergency Management.*, Volume 8, Issue 1, Article 3.

FLHSMV. (2018). *Uniform Traffic Crash Report Manual.* HSMV.

Gates, T., Savolainen, P., Avelar, R., Geedipally, S., Lord, D., Ingle, A., & Stapleton, S. (2018). *Safety Performance Functions for Rural Road Segments and Rural Intersections in Michigan.*

GDOT. (2007). *2005-2035 Georgia Statewide Transportation Plan.* Georgia Department of Transportation.

GDOT. (2018). *Georgia Uniform Vehicle Accident Report.* Georgia Department of Transportation.

Gelinne, D., Thomas, L., Lang, K., Zeeger, C., & Goughnour, E. (2017). *How to Develop a Pedestrian and Bicycle Safety Action Plan.* Washington, DC: FHWA.

Greene, & Jones. (1989). *Full Costs and Benefits of Transportation: Contributions to Theory. Accident Facts.* Chicago, IL: SAfety Council.

Haleem, Kirolos, & Gan, A. (2013). Effect of Driver's Age and Side of Impact on Crash Severity Along Urban Freeways: A Mixed Logit Approach. *Journal of Safety Research*, https://doi.org/10.1016/j.jsr.2013.04.002.

Harkey, D., Saplin, L., Lococo, K., Srinivasan, R., Baek, J., Daul, M.,... Tantilo, M. (2014). *Handbook for Designing Roadways for the Aging Population*. Retrieved from FHWA-SA-14-015

Harwood, D., Torbic, D., Gilmore, D., Bokenkroger, C., & Dunn, J. (2008). *Web-Only Document 129: Phase III; Pedestrian SAfety Prediction Methodology.* NCHRP.

Hunter, Stutts, J. C., Pein, W. E., & Cox, C. L. (1996). *Pedestrian and Bicycle Crash Types of the Early 1990's (1996).* Washington, DC: Federal Highway Administration.

Hunter, W. W., Pein, W., & Stutts, J. (1997b). *Bicycle Crash Types: A 1990's Informational Guide.* Washington, DC.: Federal Highway Administration.

Hunter, W. W., Stutts, J., & Pein, W. (1997a). *Pedestrian Crash Types: A 1990's Informational Guide.* Washington, DC.: Federal Highway Administration.

Mansfield, T. J., Peck, D., Morgan, D., McCann, B., & Teicher, P. (2018). *The Effects of Roadway and Built Environment Characteristics on Pedestrian Fatality Risk: A national Assessment at the Neighborhood Scale.* U.S Department of Transportation.

Markowitz, F. (2018). *Lightning for Pedestrian Safety and Walkability*. Retrieved from http://www.pedbikeinfo.org/pdf/Webinar_PBIC_101718.pdf

Michigan OHSP. (2016). *A Summary of a Comprehensive Evaluation of PEdestrian and Bicycle Crashes and Causes in Michigan.* Western Michigan University.

Michigan Technological University. (n.d.). *Roadsoft*. Retrieved from https://www.roadsoft.org/about

Monsere, C., Wang, H., Wang, Y., & Chen, C. (2017). *Risk Factors for Pedestrian and Bicycle Crashes.* Washington, DC.

MTU. (n.d.). *Roadway Asset Managemnet Roadsoft Software suite*. Retrieved from http://www.roadsoft.org/about

NACTO. (2017). *Urban Bikeway Design Guide*. Retrieved from https://nacto.org/publication/urban-bikeway-design-guide/

NCDOT, N. C. (2018). *DMV-349 Crash Report Form.* Divison of Motor Vehicles Traffic Records Branch.

NCHRP. (2004). *Report 500 Volume 10: Guide for Reducing Collisions Involving Pedestrians.*

NCHRP. (2008). *Report 500 Volume 18: A Guide for Reducing Collisions Involving Bicycles.*

NCHRP. (2016). *Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways..*

NCHRP. (2018). *Report 893: Systemic Pedestrian Safety Analysis.*

NCTCOG. (2017). *Pedestrian and Bicycle Traffic Count Program.* Retrieved from https://www.nctcog.org/trans/quality/bikeped/regional-bicycle-and-pedestrian-traffic-monitoring

NCTCOG. (2018a). *Mobility 2045.* North Central Texas Council Government.

NCTCOG. (2018b). *2019-2022 Transportation Improvement Program.* North Central Texas Council of Government.

NCTCOG. (n.d.-a). *Look Out Texans: Bike Walk Drive Safely*. Retrieved from https://www.lookouttexans.org/

NCTCOG. (n.d.-b). *Regional Data Center*. Retrieved from http://data-nctcoggis.opendata.arcgis.com/

Nevada County. (2019). *Local Road Safety Plan.* Retrieved from https://www.mynevadacounty.com/2688/2019-Local-Road-Safety-Plan

NHTSA. (2013). *Identiyfing Countermeasure Strategies to Increase Safety of Older Pedestrians.* Washington, Dc.: Westat.

NHTSA. (2017a). *Guidelines Model Minimum Uniform Crash Criteria*. Retrieved from https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812433

NHTSA. (2017b). *2017 FARS/CRSS Pedestrian Bicyclist Crash Typing Manual. DOT HS 812 564.*

NHTSA. (2019). *Traffic Safety Facts*. Retrieved from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812681

NMDOT. (2018). *New Mexico Uniform Crash Report*. Retrieved from http://nmtrafficrecords.com/resources/new-mexico-uniform-crash-report/

NYC. (2020). *Bike Safety.* Retrieved from https://www1.nyc.gov/html/dot/html/bicyclists/biketips.shtml

NYDMV. (2018). *Driver's Manual*. Retrieved from https://dmv.ny.gov/brochure/mv21.pdf

ODOT. (2018). *Oregon Police Traffic Crash Report*. Retrieved from https://www.oregon.gov/ODOT/Safety/Documents/policecrash46A.pdf

Oregon DMV, O. D. (2018). Retrieved from https://www.oregon.gov/ODOT/Forms/DMV/37.pdf

PBIC. (n.d.). *Are States and Cities Required to Plan for Bicycling and/or Walking?* Retrieved from www.pedbikeinfo.org/data/faq_details.cfm?id=19

Pour-Rouholamin, Mahdi, & Huaguo, Z. (2016). Investigating the Risk Factors Associated with Pedestrian Injury Severity in Illinois. *Journal of Safety Research 57 (June)*, 9-17.

Pulugurtha, S., Duddu, V., & Kotagiri, Y. (2013). Traffic Analysis Zone Level Crash Estimation Models Based on Land Use Characteristics. *Journal of Acciden Analysis and Prevention*, 678-687.

Roy, A., Nelson, T., Fotheringham, A., & Winters, M. (2019). Correcting Bias in Crowdsourced Data to Map Bicycle Ridership of All Bicyclists. *Urban Science*.

Safe State Alliance. (2017). *Consensus Recommendations for Pedestrian Injury Surveillance.* Atlanta, GA.

Salon, Deborah, & McIntyre, A. (2018). *Determinants of Pedestrian and Bicyclist Crash.*

Schneider, R. (2018). Complete Streets Policies and Eliminating Pedestrian Fatalities. *American Journal of Public Health 108, no. 4*, 431-433.

Seattle DOT. (2016). *City of Seattle Bicycle and Pedestrian Safety Analysis.* Retrieved from https://www.seattle.gov/Documents/Departments/SDOT/VisionZero/SDOT_Bike%20and%20Ped%20Safety%20Analysis_Ph2_2420(0).pdf

Snyder, M., & Knoblauch, R. (1971). *Pedestrian Safety: The Identification of Precipitating Factors and Possible Countermeasures.* Washington, DC.

Stamatiadis, N., Kirk, A., Hartman, D., Jasper, J., & Wright, S. (2018). *An Expanded Functional Classification System for Highways and Streets.* NCHRP Research Report 855.

State of Indiana. (2019). *ISP: Driving Safety*. Retrieved from https://www.in.gov/isp/3268.htm

State of Indiana. (n.d.). *Indiana Crash Risk Map*. Retrieved from https://www.in.gov/isp/3147.htm

Strava Metro. (2017). *Comprehensive User Guide Version 5.01*. Retrieved from http://metro.strava.com/wp-content/uploads/2017/04/StravaMetro_5.01_User_Guide.pdf

Strava Metro. (2019). *Strava Metro*. Retrieved from https://metro.strava.com/

Strava Metro. (n.d.). *Bike Counter Correlation*. Retrieved from http://cdn2.hubspot.net/hubfs/1979139/Bike%20Counter%20Correlation.pdf

Tarko, P. A., Inerowicz, M., & Liang, H. (2007). *Safety Conscious Planning in Indiana: Predicting Safety Benefits in Corridor Studies.* FHWA.

Tarko, P. A., Inerowicz, M., & Liang, H. (2008). *Transportation Research Record: Journal of the Transportation Research Board*. http://dx.doi.org/10.3141/2083-03

Thomas, L., Sandt, L., Zegeer, C., Kumfer, W., Lang, K., Lan, B.,... Schneider, R. J. (2018). *Systemic Pedestrian SAfety Analysis.* Washington, DC.: Transportation Research Board.

TRB. (2017). *NCHRP 17-84 (Active): Pedestrian and Bicycle Safety Performance Functions for the Highway Safety Manual*. Retrieved from https://apps.trb.org/cmsfeed/TRBNet ProjectDisplay.asp?ProjectID=4203

Truong, L., & Somenahalli, S. (2011). *Using GIS to Identify Pedestrian-Vehicle Crash Hoy Spots and Unsafe Bus Stops.* University of South Australia.

TTI. (1996). *TCRP Report 19: Guidelines for the Location and Design of Bus Stops.* Texas Transportation Institue.

TTI. (2015). *Developing Methodology for Identifying. Evaluating, and Prioritizing Systemic Improvements.* Austin, Texas: Texas A&M Transportation Insitute.

Turner, S., Sener, I., Martin, M., Das, S., Shipp, E., Hampshire, R., Fitzpatrick, K., Molnar, L., Wijesundera, R. Colety, M., & Robinson, S. (2017). *Synthesis of Methods for Estimating Pedestrian and Bicyclist Exposure to Risk at Areawide Levels and on Specific Transportation Facilities.* Federal Highway Administration.

Turner, S., Sener, I., Martin, M., White, L.D., Das, S., Hampshire, R., Colety, M., Fitzpatrick, K., & Wijesundra, R. (2018). *Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists.* FHWA.

TxDOT. (2015). *Highway Safety Improvement Program Manual.* Texas Department of Transportation.

TxDOT. (2017). *Roadway Inventory Annual Data*. Retrieved from https://www.txdot.gov/inside-txdot/division/transportation-planning/roadway-inventory.html

TxDOT. (2017a). *Texas Strategic Highway Safety Plan 2017-2022.*

TxDOT. (2017b). *Highway Safety Plan FY 2018. Traffic Safety Section, TxDOT Traffic Operations Division.*

TxDOT. (2017c). *Texas Highway Safety Improvement Program 2017 Annual Report.*

TxDOT. (2018). *State of Texas Instructions to Police for Reporting Crashes.* Retrieved from ftp://ftp.dot.state.tx.us/pub/txdot-info/trf/crash_notifications/2018/crash-report-100.pdf

TxDOT. (2019). *Automated Crash Data Extract Files*. Retrieved from https://www.txdot.gov/government/enforcement/data-access.html

TxDOT. (2020a). *Red Light Cameras on State Highways*. Retrieved from https://www.txdot.gov/inside-txdot/division/traffic/safety/laws/red-light.html

TxDOT. (2020b). *Cell Phone Ordinances*. Retrieved from https://www.txdot.gov/inside-txdot/division/traffic/safety/laws/cellphones.html

TxDOT. (2020c). *Click It or Ticket*. Retrieved from https://www.txdot.gov/driver/laws/clickit.html

TxDOT. (n.d.). *Roadway Inventory Annual Data*. Retrieved from https://www.txdot.gov/inside-txdot/division/transportation-planning/roadway-inventory.html

U.S Census Bureau. (2015). *Longitudinal Employer-Household Dynamics Data*. Retrieved from https://lehd.ces. census.gov/data/

U.S Census Bureau. (2017). *American Community Survey Data*. Retrieved from https://www2.census.gov/geo /tiger/TIGER_DP/2017ACS/

University of Alabama. (n.d.). *CARE - The Center for Advanced Public Safety*. Retrieved from http://www.caps.ua.edu/software/care/

US Census Bureau. (2018). *TIGER/Line with Selected Demographic and Economic Data*. Retrieved from https://www.census.gov/geo/maps-data/data/tiger-data.html

USDOT. (2017). *National Household Travel Survey. Popular Person Trops (PT) Statistics*. Retrieved from https://nhts.ornl.gov/person-trips

USDOT. (2018a). *2017 NHTS Data User Guide.*

USDOT. (2018b). *Pedestrian Fatality Risk Map*. Retrieved from https://maps.dot.gov/BTS/PedestrianFatalityModel/

USDOT. (2019). *Safety Data Initiative.* Retrieved from https://www.transportation.gov/content/safety-data-initiative

USDOT. (n.d.). *FARS Pedestrian Traffic Facilities*. Retrieved from https://explore.dot.gov/views/FARSPedestrianTrafficFatalities/Pedestrian

USGS. (n.d.). *National Geospatial Program*. Retrieved from https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map

VDOT. (2017). *Crash Data Analysis Manual Version 1.0.* VDOT Traffic Engineering Division.

VDOT. (2018). *Pedestrian Safety Action Plan.* Retrieved from http://www.virginiadot.org/business/resources/VDOT_PSAP_Report_052118_with_Appendix_A_B_C.pdf

Wahab, Lukuman, & Jiang, H. (2019). A Multinomial Logit Analysis of Factors Associated with Severity of Motorcycle Crashes in Ghana. *Traffic Injury Prevention 20 (5)*, 521-27.

Wang, T., Jun, C., Chen, W., & Xiaofei, Y. (2018). *Understand E-Bicyclist Safety in China: Crash Severity Modeling Using a Generalized Ordered Logit Model. "Advances in Mechanical Engineering"*. http://dx.doi.org/10.1080/15568318.2010.497547

Wier, M. J., Weintraub, J., Humphreys, E., Seto, E., & Bhatia, R. (2009). *An Area-Level Model of Vehicle-Pedestrian Injury Collisions with Implications for Land Use and Transportation Planning.*

WisDOT, W. D. (2006). *Bicycle Crash Analysis for Wisconsin Using a Crash Typing Tool (PBCAT) and Geographic Information System (GIS).* Michael Amsden and Tom Huber.

WSDOT. (2014). *Police Traffic Collision Report Instructions Manual.*

Ye, Fan, & Lord, D. (2014). *Comparing Three Commonly Used Crash Severity Models on Sample size Requirements: Multinomial Logit, Ordered Probit and Mixed Logit Models*. http://dx.doi.org/10.1016/j.amar.2013.03.001

Zong, Fang, Chen, X., Tang, J., Yu, P., & Wu, T. (2019). *Analyzing Traffic Crashs Severity with Combination of Information Entropy and Bayesian Network*. http://dx.doi.org/10.1109/access.2019.2916691