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Effective Design and Operation of Pedestrian Crossings

Noshin S. Ahmad, Raul Pineda-Mendez, Fahad Alqahtani, Mario Romero, Jose Thomaz, Andrew P. Tarko

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16. Abstract

Pedestrians are vulnerable road users since they are prone to more severe injuries in any vehicular collision. While innovative solutions promise improved pedestrian safety, a careful analysis of local conditions is required before selecting proper corrective measures. This research study had two focuses: (1) methodology to identify roads and areas in Indiana where the frequency and severity of pedestrian collisions are heightened above the acceptable level, and (2) selecting effective countermeasures to mitigate or eliminate safety-critical conditions. Two general methods of identifying specific pedestrian safety concerns were proposed: (1) area-wide analysis, and (2) road-focused analysis. A suitable tool, Safety Needs Analysis Program (SNAP), is currently under development by the research team and is likely the future method to implement an area-wide type of analysis. The following models have been developed to facilitate the road-focused analysis: (1) pedestrian crossing activity level to fill the gap in pedestrian traffic data, and (2) crash probability and severity models to estimate the risk of pedestrian crashes around urban intersections in Indiana. The pedestrian safety model was effectively utilized in screening and identifying high-risk urban intersection segments for safety audits and improvements. In addition, detailed guidance was provided for many potential pedestrian safety countermeasures with specific behavioral and road conditions that justify these countermeasures. Furthermore, a procedure was presented to predict the economic feasibility of the countermeasures based on crash reduction factors. The findings of this study should help expand the existing RoadHAT tool used by the Indiana Department of Transportation (INDOT) to emphasize and strengthen pedestrian safety considerations in the current tool.

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EXECUTIVE SUMMARY

Introduction

Pedestrians are vulnerable road users who suffer much more severe injuries in collisions than passengers of vehicles. According to the Indiana ARIES data, the annual number of pedestrians involved in crashes had not significantly reduced in recent years, while the number of pedestrians killed increased considerably. Although the multiplicity of pedestrian-protecting solutions is encouraging, improving safety at troublesome pedestrian crossings necessitates a careful analysis of local conditions before effective countermeasures can be selected.

This research study focuses on a methodology that helps identify roads and areas in Indiana where the frequency and severity of pedestrian-vehicle collisions are heightened above the acceptable level and select effective countermeasures to mitigate or eliminate addressed safety-critical conditions. Two general methods of identifying specific pedestrian safety concerns were proposed: (1) areawide analysis and (2) road-focused analysis. The emphasis of this study is on the road-focused approach.

Findings

Probabilistic regression models were developed to estimate pedestrian activity and safety on segments around urban intersections. A multinomial logit model was used to assess the effects on a seven-level categorical pedestrian AADT using a small sample of urban intersection segments across Indiana. Results from this analysis were later used to predict the pedestrian crossing activity at other sites based on available land use, vehicle traffic, and roadway data. While pedestrian count data is scarce and its collection prohibitively expensive, the developed pedestrian activity model links land use and other spatial features with pedestrian crossing activities and has an unprecedented ability to provide a sound estimate of pedestrian presence at any urban intersection in Indiana. The analysis focuses on intersections located in communities with more than 2,500 residents.

A sequential binary logit framework was used to estimate the crash probabilities at four severity levels: (1) property damage only, (2) non-incapacitating, (3) incapacitating, and (4) fatal. The analysis confirmed the strong effect of speed limits on pedestrian safety combined with other local conditions. The knowledge of the pedestrian activity level allowed the research team to separate the pedestrian exposure factor from other safety factors and develop intuitive crash probability and severity models that include estimated effects of pedestrian traffic, vehicle traffic, built environment, speed limits, and traffic control. Since the available data contains observations from 2020, COVID-19 effects were estimated. This is helpful to avoid biases in future safety analyses that include the pandemic effect. In addition, a more practical and accurate estimation of crash probability was achieved by combining probability estimates with observed crash counts using the specialized EB method.

EB method is widely used in current safety management practice to adjust crash counts. An Empirical Bayes (EB) method based on the beta distribution is proposed to improve the crash probability estimates with past crash occurrence and resulting injury severity. The research report describes and tests its application to crash probabilities.

The pedestrian safety model provides a basis to identify high-risk urban intersection segments that are eligible for safety audits and improvements. The screening criterion includes the crash cost calculated with the crash risk and severity models. The safety estimate is further improved by combining it with the crash occurrence and its severity with the Empirical Bayes (EB) method adjusted to the probabilistic safety representation. A screening criterion alternative to the crash cost is the crash probability obtained for intersection segments.

Implementation

Two sets of models were developed to facilitate the road-focused analysis: (1) pedestrian Crossing Activity Level models to fill the gap in pedestrian traffic exposure data and (2) crash probability and injury severity models to estimate the risk of pedestrian crashes around urban intersections in Indiana. The resulting equations serve as the primary tool for road-focused screening. The developed models and procedures can be implemented in an existing tool, RoadHAT 4D, via an additional module specialized in analyzing pedestrian safety. A suitable tool for areawide analysis, SNAP, is under development by the research team in a separate project.

The results of this study provide a groundwork for improving pedestrian safety on road segments in close vicinity to urban intersections in Indiana where the majority of road crossing takes place. Multiple potential pedestrian safety countermeasures with specific behavioral and road conditions that justify these countermeasures are provided in this report. A computational procedure to predict the economic effects of the proposed countermeasures based on associated crash reduction factors was also facilitated.

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1. INTRODUCTION

1.1 Background

Pedestrians are vulnerable road users, and vehicles colliding with pedestrians inflict on pedestrians much more severe injuries than on vehicles' occupants. According to the "Indiana Traffic Safety Facts" yearly publication, from 2012 to 2019, yearly pedestrian involvement in crashes has remained within a range from 1,688 to 1,914. Although pedestrian involvement in crashes has remained relatively stable from 2012 to 2019 (Figure 1.1), the number of pedestrian fatalities has seen a steady increase until 2018, followed by a substantial drop in 2019. At its peak, in 2018, 117 pedestrian fatalities in 1,650 pedestrian collisions correspond to about 1 pedestrian fatality for every 14 pedestrian crashes (Indiana University Public Policy Institute, 2019).

According to NHTSA's yearly "Pedestrian Traffic Safety Facts" publications, the pedestrian fatality rate per 100,000 population for Indiana almost doubled, from 0.9 in 2012 to 1.7 in 2018 (Indiana University Public Policy Institute, 2019). This value, in 2018, ranked 30th in the United States, in order from lowest to highest (NHTSA, 2019). NHTSA also shows that, on a national level, if broken down by age categories, this pedestrian fatality rate by 100,000 population is highest for elderly pedestrians in the 55 to 64 age group. Future autonomous vehicles may improve these statistics only to a limited extent due to the difficulties in detecting pedestrians by vehicle sensors and pedestrians' sudden and unexpected movements to which driverless vehicles (as much as human drivers) have problems responding timely.

The persistently high rate of pedestrian deaths can be attributed to a variety of factors. The most significant factor is the vulnerability of unprotected pedestrians to a direct impact. The contributing factors are reduced visibility at night, insufficient road illumination, illegal road crossing, drivers failing to yield, excessive vehicle speed, driver/pedestrian distraction, driver/pedestrian intoxication, and others. Inadequate pedestrian infrastructure, such as the absence of mid-block crossings or long distances to cross, increase the probability of conflicts and collisions. The analysis of available crash data and risk factors can provide insights for practitioners who aim to reduce the number and severity of pedestrian crashes.

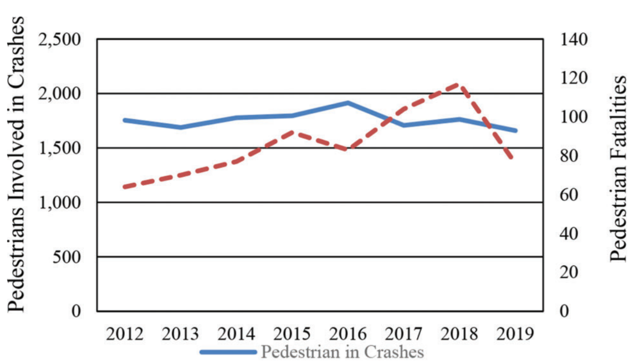

Figure 1.1 Pedestrians in crashes and pedestrian fatalities in Indiana (Indiana University Public Policy Institute, 2019).

The multiplicity of pedestrian-protecting solutions is encouraging, but, at the same time, a careful analysis of local conditions is required to improve safety at troublesome crosswalks by selecting adequate countermeasures. This report presents the results of a research study and possible solutions that adopt a proactive approach to improving pedestrian safety at high-risk locations based on learning about behavioral and environmental conditions that contributed to pedestrian crash occurrence elsewhere. This strategy includes two major components: (1) identifying locations with the built environment and other features that produce high pedestrian exposure and (2) performing safety audits to detect risky behaviors of road users and road features connected with the high risk. This strategy contributes to and may supplement a systemic approach of applying inexpensive and adequate countermeasures at many locations in Indiana's road network.

1.2 Purpose and Content of the Report

The report is meant to provide a defendable basis for pedestrian safety management and its procedures in Indiana. The findings of this study should help expand the existing RoadHAT tool used by the Indiana Department of Transportation (INDOT) to emphasize and strengthen pedestrian safety considerations in the current tool. Furthermore, the report will help use another tool being developed for the Indiana Criminal Justice Institute (ICJI) to identify areas with an excessive number of crashes of user-defined certain types of crashes (pedestrians) under certain conditions. Among the mentioned two approaches, the road-focused approach requires more advanced analysis. Therefore, the report describes the conducted research and its results that provide a practical procedure for roads screening, safety auditing of high-risk roads, and selecting specific countermeasures prompted by the observed conditions during the auditing. In addition, the guidelines include a complete set of equations and tables to calculate the pedestrian level of activity, probability of crash and its severity, an extensive collection of countermeasures with conditions that justify these countermeasures, and the benefit-cost analysis. All these components of safety management follow the established Indiana safety management concepts for other types of collisions to utilize the existing tools to the maximum extent.

1.3 Organization of the Report

The report consists of three introductory chapters (Chapters 1, 2, and 3) two chapters providing technical details of statistical analysis of pedestrian exposure and safety (Chapters 4 and 5), four chapters describing the four steps of the road-focused pedestrian safety management (Chapters 6, 7, 8, and 9; screening, audit, countermeasures, and B-C analysis), and a closure chapter (Chapter 10). In addition, the four appendices provide an example screening applied to Indiana urban intersections (Appendix A) and valuable supplemental material in the analysis: example screening results, locations of Indiana cities' centers (Appendix B), crash reduction factors (Appendix C), and a list of pedestrian crash factors (Appendix D).

The following documents provide additional background information.

- *Pedestrian and Bicyclist Road Safety Audit Guide and Prompt List* (Goughnour et al., 2020).
- Step-by-Step Guide–National Pedestrian Safety Campaign (FHWA, 2008).
- Pedestrian and Bicycle Information: pedbikesafe.org.
- *Systemic Pedestrian Safety Analysis* (Thomas et al., 2018).
- Guidelines for roadway safety improvements, JTRP, INDOT, and Purdue, 2019.

2. LOCATIONS AND PERIODS WITH PEDESTRIAN SAFETY CONCERNS

Pedestrian crashes in Indiana are linked with a variety of environmental and behavioral factors. This chapter illustrates where and when pedestrian-vehicle crashes occurred, who was involved in these incidents, and other factors based on crash records from 2013 to 2018 in Indiana and sociodemographic data (U.S. Census Bureau and NHTSA). The information given in this chapter provides a data-based ground reference for the recommendations made in the guidelines, especially for conducting road safety audits. In addition, the data analysis below portrays situations where changes might lead to fewer and less severe crashes.

2.1 Spatial Distribution of Pedestrian-Vehicle Crashes

Typically, urban areas cluster a higher number of pedestrian-vehicle crashes compared to rural areas. Areas with high population density experience high travel intensity (by vehicle and foot) and high exposure of pedestrians to crash. Figure 2.1 shows that the concentration of the reported collisions strongly coincides with the densely populated urban areas. Focusing pedestrian safety improvement efforts on such sites may lead to a broad safety improvement in the system. This strategy should be supplemented with an attempt to identify isolated concentrations of pedestrian crashes outside of the focus areas to maintain the fairness of the safety management system.

2.2 Temporal Distribution of Pedestrian-Vehicle Crashes

Comparing the daily trend of crashes on urban roads versus rural roads reveals similarities (Figure 2.2). Although people tend to walk more frequently in the morning and afternoon in urban areas (school and work-related trips), more accidents occur in the afternoon (except one morning hour on rural roads). Furthermore, the risk-elevated afternoon periods are much longer since they also include after-work activities. This pattern may be related to the following facts.

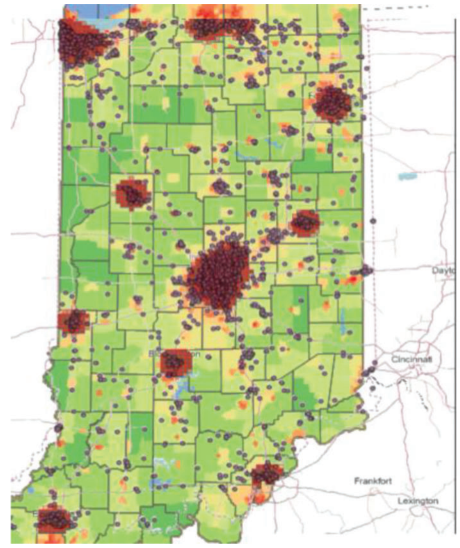

Figure 2.1 A combination of the 2010 population map and crashes from 2016 to 2018 in Indiana.

- Drivers' and pedestrians' afternoon alertness is lower than in the morning.
- Morning and afternoon activities are different.
- Intoxication prevails in the late afternoons and at night.

Field safety audits should include the periods with the risk of elevated pedestrian crashes. The Indiana ARIES data indicate (Figure 2.2 compares urban to rural areas) the following periods tend to experience such risk.

- Morning short periods at 7 am.
- Prolonged periods between 2 pm and 7 pm.
- Friday and Saturday between 4 pm and midnight.
- Saturday and Sunday between 12 am to 3 am.

2.3 Contributing Safety Factors

Crash reports include narratives that describe the driver's or pedestrian's actions before the collision. This information can provide a general classification of the primary contributing factors (Figure 2.3 and Figure 2.4). Crash records accessed via the Automated Reporting Information Exchange System (ARIES) portal indicated that drivers were found responsible for 54% of pedestrian crashes in rural areas and for 61% in urban areas. Pedestrians were found at fault in 34% of pedestrian-involved crashes in rural areas and in 38% of pedestrian crashes in urban areas. Other factors attributed to the roads, vehicles, and other conditions were mentioned in only 5% of pedestrian crashes. A secondary factor is usually reported when the police officer believes that another factor also increased the crash risk, although to a lower degree.

Given the prevailing responsibility of road users in crash occurrence, a road safety audit should focus on the behavior of drivers and pedestrians, with additional attention given to the local conditions that may contribute to the observed behaviors and errors. Table 2.1

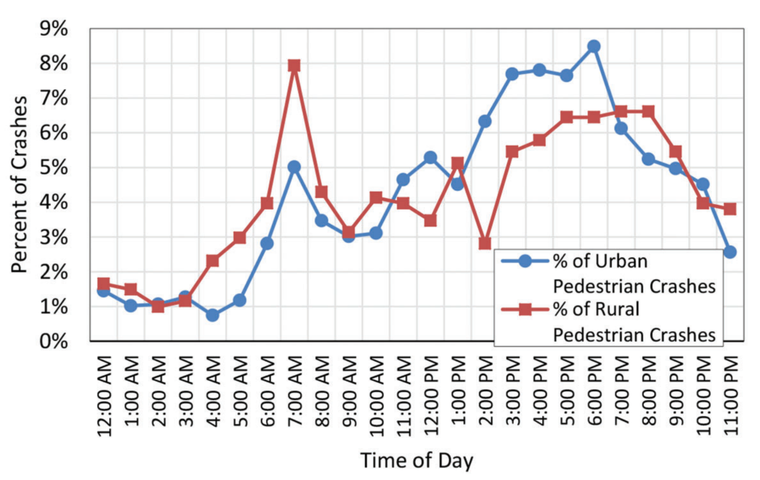

Figure 2.2 Distribution of crashes by time of day and road environment.

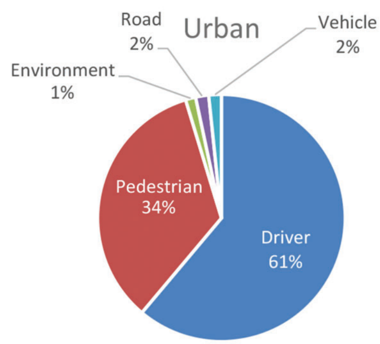

Figure 2.3 Primary safety factors on urban roads.

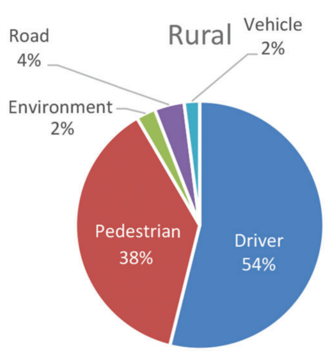

Figure 2.4 Primary safety factors on rural roads.

lists the top five primary factors documented by police officers who reported the crashes. Failure to yield was declared as the primary cause of a pedestrian collision in 24% of collisions. Interactions between drivers and pedestrians (hesitation, lack of attention, enforcing own right of way, evasive behavior to avoid a collision, high speed, among others.) observed by auditors may reveal to what extent these interactions may lead to crashes and what additional conditions are associated with the occurrence of these dangerous driver-pedestrian interactions.

TABLE 2.1
Distribution of Crashes by Primary Safety Factors (2016–2018 Indiana Crashes)

Primary Factor	Percentage of Crashes (%)
Driver–failure to yield right of way	24
Pedestrian–pedestrian action	20
Driver–other	13
Driver–unsafe backing	9
Pedestrian–crossing not at an intersection	5
Other factors (see Appendix D)	29

3. APPROACHES TO PEDESTRIAN SAFETY MANAGEMENT

There are two general approaches to safety management, including pedestrian safety: (1) areawide and (2) road-focused.

3.1 Areawide Approach

The areawide approach is preferred if pedestrian safety problems are caused by behavioral factors such as disregard of road rules by pedestrians or drivers or frequent poor weather that reduces pedestrians' visibility and the braking abilities of drivers. These safety factors require countermeasures applied in a larger part of the road network (areawide speed regulation, increased enforcement in the region, improving the safety of walking to school).

An area-wide screening will be addressed in the near future with a tool similar to the SNIP and being developed to address the needs of the Indiana Criminal Institute (ICJI) in the 2021 project: *Indiana Safety Belts Survey and CODES Project*. The tool is called the Safety Needs Analysis Program (SNAP). It is being designed to identify areas with an excessive density of a user-defined category of crashes, including pedestrian crashes. Example aggregation levels for area-wide analysis include counties, townships, ZIP codes, TAZs, or user-defined grids.

In addition, the crash category defined by the end-user may include police-reported contributing factors, including behavioral issues and external adverse conditions. Thus, targeted area-wide screening from the point of view an envisioned countermeasure by incorporating in the screening step contributing factors to be addressed by the countermeasure such as police enforcement, school-age walking children, suburban areas with narrow shoulders, etc.

The Center for Road Safety has been developing the mentioned software tool to screen areas based on the distribution of multiple-year crashes with user-defined criteria. The results will include aggregated safety indices, including crash counts, costs, density-based indicators, and geographical areas such as counties and townships. Some of the features expected in the tool are the following.

- A self-contained program running in computers with the Microsoft Windows operating System. The application reads original ARIES Data extracts.
- Ability to query most fields available in the ARIES database, including crash and person and vehicle characteristics as selected by the user. One of the available selection options is pedestrian crashes.
- Extracted crashes displayed on maps based on geo-coordinates in the police database.
- User selects specific areas for analysis such as counties, townships, cities, Traffic Analysis Zones (used by transportation planners).
- Heat maps are displayed in a grid or by geographic units (counties, townships, etc.). They can reflect frequencies, crash density, proportions, and rates by population, total VMT, others (depending on the available data). See Figure 3.1 for a visual.
- Results displayed in tabular or graphical formats.
- Exporting numerical results (tables) to text files and graphics (graphs) to jpg files.

3.2 Road-Focused Approach

In a general case, the assessment of safety, identification of the probable causes, and adequate countermeasures are supported by analyzing crashes at a

Figure 3.1 Safety heat maps.

studied road. Such an approach is particularly beneficial if a cluster of crashes is large. Thus, it provides sufficient information about the contributing factors specific to the investigated location. However, pedestrian crashes are strongly dispersed across roads, and the number of collisions at a single location unlikely exceeds one. Yet, the overall loss caused by pedestrian crashes is high due to highly probable severe outcomes and the potential presence of pedestrians on any road, particularly in urban areas.

For the above reason, these guidelines provide a safety analysis method that relies more on the estimated risk of pedestrian crashes and less on observed pedestrian crashes. From this point of view, the applied approach is proactive and identifies sites for potential safety improvements based on a high probability of crash and detected risk factors for pedestrians. It may select roads for a safety audit, identify safety countermeasures, and justify their application even if no collision has occurred yet within several recent years. The initial analysis of the spatial concentration of pedestrian crashes indicated urban intersections as the most frequent locations. Therefore, the presented procedure focuses on urban intersections. The recommended approach for pedestrian safety improvement is described in general terms below.

Step 1. Road Screening aims to identify road locations with the higher-than-expected risk of pedestrian crashes. Typically, the volume of pedestrians crossing a road is unknown, but this is a vital safety factor (risk exposure). To fill this gap, pedestrian exposure is estimated based on the land use around the analyzed road location (Chapter 4). This exposure is expressed with the Crossing Activity Level (CAL). Finally, the CAL and other safety factors are used to calculate the expected crash risk at multiple injury severity levels for each road (Chapter 5).

Roads with an estimated high probability of crash, for example, roads with a pedestrian crash risk higher than 15% for 3 years, are selected for safety audits to provide a more in-depth analysis of local conditions.

Step 2. Road Safety Audit (RSA) is to be conducted at the identified high-risk locations (in Step 1) to point out behavioral and road conditions contributing to the pedestrian crash risk (Chapter 7) and the corresponding adequate countermeasures (Chapter 8). Example contributing factors include poor lighting condition, inadequate sight distance, longer crossing distance, driver/pedestrian inattention, speeding, and drivers' non-compliance with pedestrians' right of way.

Step 3. Selection and Implementation of Countermeasures (Chapter 8) involves selecting the most promising countermeasures and their combination by performing a benefit-cost analysis. For example, multiple countermeasures may be grouped into a single improvement to enhance the effectiveness of the pedestrian treatments by tackling several contributing factors simultaneously.

Step 4. Evaluation of the Program Effectiveness is meant to re-evaluate the program and its components after several years when new pedestrian crash data are available. Unlike in the case of vehicle-vehicle crashes, the lack of pedestrian crash clustering does not allow analyzing specific countermeasure site by site. Instead, groups of sites with similar improvements could be evaluated. Alternatively, the entire project may also be evaluated via special study similar to the one presented in this report.

4. ESTIMATING PEDESTRIAN ACTIVITY

Pedestrian traffic information is an essential input in the safety analysis. Such information allows controlling for exposure, which is particularly useful when studying crash frequency. Unfortunately, the historical pedestrian traffic information is not available. Thus, a model for pedestrian crossing activity, which is a proxy for pedestrian volume, is introduced and tested in this chapter.

4.1 Data Description

Pedestrian activity, vehicular traffic, road, and intersection features, land use, and socioeconomic data were acquired and consolidated for analysis. Some of the data are road specific such as functional classification of roads, while others are unique for the intersection, such as land use in the vicinity of the intersection. A total of 46,360 intersection road segments (corresponding to 22,506 intersections) in 182 cities across Indiana are represented in the data. The analysis is focused on urban intersection segments in communities with more than 2,500 residents, which is the threshold that distinguishes a town from a city (U.S. Census Bureau, 2019).

4.1.1 Pedestrian Activity Data

Pedestrian counts at intersections that are considered within the scope of research were essential to account for the level of exposure to conduct pedestrian safety analysis. However, the manual collection of location-specific pedestrian counts is prohibitively expensive and time-consuming, while historical data are unavailable. Thus, a model had to be built based on pedestrian counts at sample intersections obtained from an INDOT-authorized source, i.e., *StreetLight Data, Inc.* A model based on a small sample of intersection segments was later used to estimate pedestrian traffic at other intersections in Indiana.

StreetLight Data, Inc. has been collecting pedestrian traffic data in Indiana and other states since 2018 via GPS technology available on mobile phones. Due to their high cost, average daily pedestrian counts data were obtained for only 514 roads (see Figure 4.1). A random selection of road segments was utilized across the study area to form the initial sample. In addition, Esri ArcGIS tools were employed in organizing and processing the data.

The data supplied by the company was obtained in Average Daily Traffic in different seasons (i.e., fall, winter, spring, and summer) and day types (i.e., weekday and weekend) during the period between 2018 and 2020. In addition, all pedestrian crossings made within 75 ft from the curb line of the intersecting road were assigned to the road. Therefore, the selected observation was a stretch of a roadway at an intersection at a specific year, season, and day type. Also, the length of each road was considered 75 ft from the curb line on both sides of the road (see Figure 4.2). This pedestrian crossing area was established to identify the distance from an intersection in which a pedestrian crossing or crash will be assigned to a road or not.

4.1.2 Vehicle Traffic and Roadway Attributes

Annual average daily traffic (AADT) was derived from Federal Highway Administration's Highway Performance Monitoring System (HPMS). AADTs were further adjusted using adjustment factors published by the Indiana Department of Transportation (INDOT) to estimate the average daily volume of vehicle traffic. The average daily traffic was adjusted based on the year, season, and day type. In addition, relevant information characterizing the road functional class and presence of signalization was supplied to this study from the Center for Road Safety (CRS) at Purdue University. Summary statistics of the data obtained for the traffic data is shown in Table 4.1.

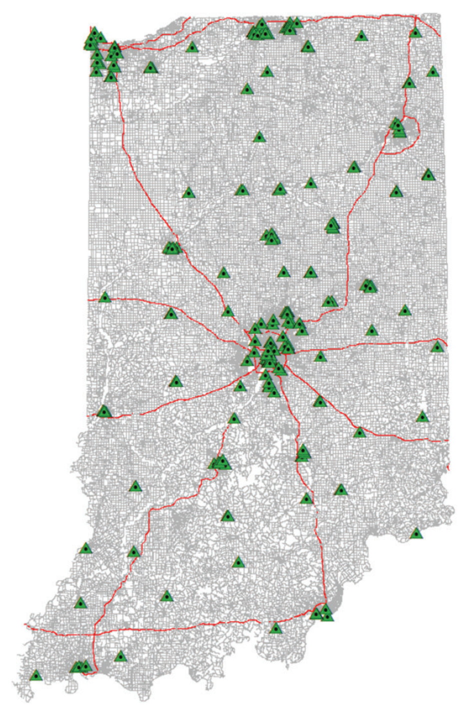

Figure 4.1 Geographical distribution of intersections with available pedestrian crossing activity data.

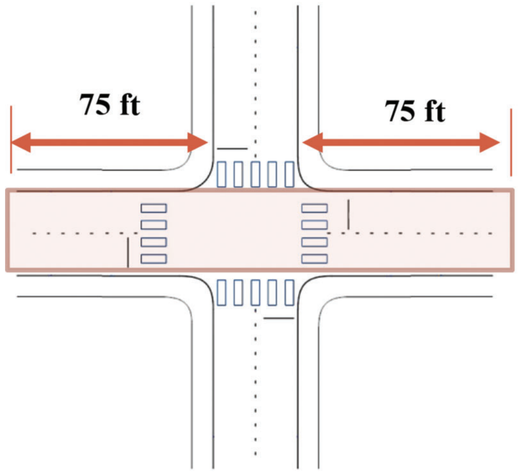

Figure 4.2 Definition of intersection segment and pedestrian crossing area.

4.1.3 Sociodemographic Information and Built Environment Characteristics

Land use data were extracted from the U.S. Census Bureau, IndianaMAP, and United States Environmental Protection Agency (EPA). The socioeconomic and land use data were collected in the vicinity of each intersection using multiple buffer zones of different sizes. The size of the buffers ranges from 0.1 miles to 8 miles in the area of intersections. A summary statistic of the data obtained for the socioeconomic and land use data is demonstrated in Table 4.2.

- The data from U.S. Census Bureau was used to define the population at each traffic analysis zone (TAZ) in the years between 2018 and 2020. Since an intersection might fall between or at an edge of the traffic analysis zone, a weighted sum was used to estimate the population in the vicinity of each intersection.
- IndianaMAP provided shapefiles that identify the locations of critical facilities in Indiana. The number of facilities in the vicinity of each intersection was extracted by populating the number of the facilities around each intersection based on the distance (up to 8 miles). The data includes the locations of schools, colleges, hospitals, recreational facilities, and census data. The information is updated as available and posted (most data updated in 2011 and 2012).
- EPA provides a summary of characteristics of census block groups (CBG) in all states. Block groups are confined within census areas and generally include between 600 and 3,000 people, with an optimum size of 1,500 people. The land area of block groups varies based on population density. Variables included in this study are the number of households in CBG that own zero, one or two automobiles, percent of the working-age population, and the number of employees. Most of the variables were extracted using weighted sum such as counts variables (i.e., number of employees), while some required weighted average such as the percentage of households owning a car.

4.2 Sample Characteristics

A total of 514 intersection segments were used to develop a pedestrian activity model. The summary statistics of the sample are presented in Table 4.3. In the model, 66% of roads are classified as arterials, 19% collectors, and 15% locals. The average vehicle AADT in the sample is 15,760 veh/day, with some roads up to 104,780 veh/day. In addition, 35% of roads are in signalized intersections. On average, the selected sites are within 1.3 miles away from the center of the city.

To improve the model's prediction power, an aggregation of the observed pedestrian daily traffic was used. Seven Crossing Activity Levels (CALs) were defined based on the Pedestrian AADT values, as shown in Table 6.1. Figure 4.3 presents the distribution of sample intersection segments by CAL. The figure describes a bell-shaped trend among sites. Most sites fall under medium levels 3 and 4, corresponding to pedestrian AADT values from 250 to 999.

TABLE 4.1
Pedestrian and Vehicle ADTs (2018–2020)

ADT	Season	Day Type	Mean	Std. Dev	Minimum	Maximum
Pedestrian ADT	Fall	Weekday	1,043	2,019.0	1	27,550
Pedestrian ADT	Fall	Weekend	843	1,667.8	1	25,652
Pedestrian ADT	Spring	Weekday	847	1,374.3	1	24,393
Pedestrian ADT	Spring	Weekend	627	991.3	1	12,937
Pedestrian ADT	Summer	Weekday	846	1,264.2	1	19,488
Pedestrian ADT	Summer	Weekend	701	1,274.2	1	18,098
Pedestrian ADT	Winter	Weekday	888	1,556.8	1	19,125
Pedestrian ADT	Winter	Weekend	681	1,190.7	1	15,104
Vehicle ADT	Fall	Weekday	5,726	7,960.0	1	101,740
Vehicle ADT	Fall	Weekend	4,504	6,260.2	1	79,604
Vehicle ADT	Spring	Weekday	5,810	8,078.0	1	102,623
Vehicle ADT	Spring	Weekend	4,307	5,985.5	1	76,828
Vehicle ADT	Summer	Weekday	5,705	7,931.2	1	100,915
Vehicle ADT	Summer	Weekend	4,479	6,225.8	1	79,350
Vehicle ADT	Winter	Weekday	5,760	8,007.3	1	102,198
Vehicle ADT	Winter	Weekend	4,358	6,056.7	1	77,170

TABLE 4.2
Land Use Summary Statistics for 22,451 Intersections (Continuous and Discrete Variables)

Variable	Buffer (miles)	Mean	Std. Dev	Minimum	Maximum
Employed population	0.1	33	31.1	0	422
	0.2	131	116.5	0	1,363
	0.4	508	419.3	0	3,032
	0.6	1,102	863.3	1	5,895
	1	2,819	2,068.8	15	10,821
	2	9,313	6,650.6	80	26,745
	3	17,822	13,225.3	223	50,160
	4	27,651	21,610.8	432	82,474
	5	38,446	31,829.9	727	123,321
	6	50,087	43,929.5	1,098	168,883
	8	74,891	72,494.5	2,197	267,303
Number of colleges	0.2	0.00	0.0	0	1
	0.4	0.01	0.1	0	1
	0.6	0.02	0.1	0	1
	0.8	0.03	0.2	0	1
	1	0.04	0.2	0	2
	2	0.15	0.4	0	3
Number of employees	0.1	16.75	47.1	0	607
	0.2	66.18	186.2	0	2,398
	0.4	256.95	722.8	0	9,309
	0.6	557.02	1,566.9	0	20,181
	1	1,425.00	4,008.5	0	51,628
Number of hospitals	0.1	0.01	0.1	0	2
	0.2	0.03	0.2	0	5
	0.4	0.09	0.4	0	6
	0.6	0.18	0.5	0	6
	0.8	0.30	0.7	0	6
	1	0.42	0.8	0	7
	2	1.14	1.4	0	8
Number of recreational facilities	0.6	3.27	2.6	0	16
	1	7.72	5.0	0	30
	2	21.61	13.5	0	68
	3	37.23	25.1	0	111
	4	53.63	38.6	0	165
Number of schools	0.1	0.06	0.2	0	3
	0.2	0.20	0.5	0	5
	0.4	0.70	0.9	0	7
	0.6	1.43	1.4	0	7
	0.8	2.29	1.8	0	9
	1	3.24	2.2	0	12
	2	8.96	5.7	0	27
	3	15.51	11.1	0	46
The % of households with at least one vehicle	0.1	82.11	10.4	0	100
	0.2	82.07	10.3	0	100
	0.4	82.10	9.8	15.61	96.68
	0.6	82.15	9.5	24.99	96.56
	1	82.23	9.2	39.545	95.92
	2	82.58	8.6	48.93	95.30
	3	82.99	8.1	54.10	94.83
	4	83.36	7.6	58.33	94.63
Population	0.1	80	74.1	0	1,383
	0.2	316	275.8	0	3,953
	0.4	1,227	987.8	2	9,253
	0.6	2,659	2,044.0	3	15,698
	1	6,805	4,946.3	37	29,756
	2	22,427	16,039.5	188	63,562
	3	42,659	31,731.7	511	123,835
	4	65,682	51,360.4	1,027	192,409
	5	90,514	74,801.8	1,886	276,203
	6	116,856	102,112.8	2,775	385,817
	8	172,101	165,137.5	5,361	608,666

TABLE 4.3
Characteristics of Pedestrian Crossing Activity Sample (N = 514)

Variable	Mean	Std. Dev	Minimum	Maximum
Population within 1 mile (10,000 inhabitants)	0.88	0.57	0.01	2.68
Major arterial (1-FC = 3, 0-else)	0.34	0.47	0.00	1.00
Minor arterial (1-FC = 4, 0-else)	0.33	0.47	0.00	1.00
Major collector (1-FC = 5, 0-else)	0.17	0.37	0.00	1.00
Minor collector (1-FC = 6, 0-else)	0.02	0.14	0.00	1.00
Local road (1-FC = 7, 0-else)	0.15	0.35	0.00	1.00
AADT (1,000 veh/day)	15.76	12.46	0.04	104.78
State-administered road (1-yes, 0-else)	0.39	0.49	0.00	1.00
Signalized intersection (1-yes, 0-else)	0.35	0.48	0.00	1.00
Number of big colleges within 2 miles	0.35	0.55	0.00	2.00
Number of medium colleges within 0.8 miles	0.04	0.19	0.00	1.00
Number of small colleges within 0.4 miles	0.01	0.09	0.00	1.00
National walkability index	11.13	2.81	3.33	17.13
Number of recreational facilities within 0.6 miles	4.07	2.60	0.00	11.00
Number of schools within 0.8 miles	1.72	1.35	0.00	6.00
Percent of households within 1 mile with at least one vehicle	0.79	0.11	0.52	0.95
Distance to city center (mi)	1.31	1.07	0.01	6.39
Employed population within 0.6 miles (1,000)	4.26	8.89	0.04	51.63
Number of households	665.56	615.48	2.00	5,166.00
Downtown Indianapolis	0.012	0.11	0.00	1.00

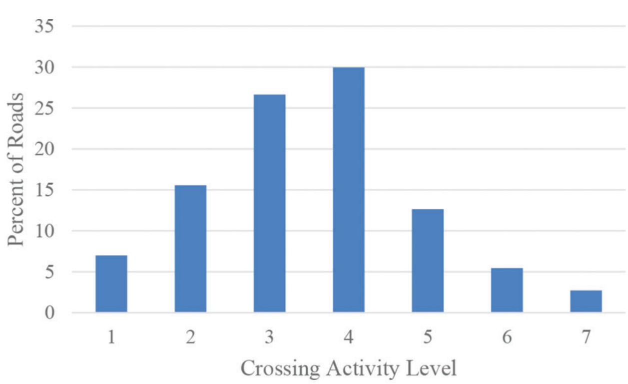

Figure 4.3 Distribution of roads by crossing activity level.

4.3 Statistical Analysis Approach

A Multinomial Logit (MNL) model is used to estimate pedestrian activity. The response value is the probability of a site belonging to each CAL. The CAL with the highest probability will be the predicted value of the pedestrian activity. The formal expression of the MNL model is presented below.

$$P_n(i) = \frac{\exp(\beta_i X_{in})}{\sum_{i=1}^{7} \exp(\beta_i X_{in})} \qquad \text{(Eq. 4.1)}$$

where:

- $P_n(i)$ is the probability of site n having CAL level $i = 1, \ldots, 7$.
- β_i is a vector of estimable parameters for the discrete outcome.
- X_{in} is a vector of observable characteristics (built environment, socio-economic, vehicle traffic, etc.) that determine discrete outcomes for observation n.

4.4 Estimated Effects on Pedestrian Activity

Table 4.4 presents the estimated effects on pedestrian crossing activity. Four road-related variables were found associated with CAL. Their estimated effects are intuitive. A brief summary follows.

- A large surrounding population increases pedestrian activity.
- Major collector roads tend to have higher pedestrian activity.
- Higher vehicle AADTs are associated with higher pedestrian activity.
- Except for CAL = 7, the distance to the city center is inversely associated with pedestrian activity.
- Large surrounding employment is linked with high pedestrian activity.

Figure 4.4 illustrates the resulting model's accuracy. In terms of exact pedestrian CAL matches, the model successfully classifies 39.5% of roads. However, if we consider the neighboring CALs, the model's accuracy improves to 83.5%. The previous is common when dealing with discrete features, such as CAL, derived from continuous variables, such as pedestrian AADT.

TABLE 4.4
Estimated Effects on Average Daily Pedestrian Crossing Activity

Parameter	Level	Estimate	Std. Error	Chi-Square	Pr > ChiSq
Intercept	2	0.6162	0.5005	1.52	0.2183
Intercept	3	0.4952	0.4810	1.06	0.3032
Intercept	4	-0.5237	0.5032	1.08	0.2979
Intercept	5	-2.0394	0.5919	11.87	0.0006
Intercept	6	-6.0044	1.0176	34.81	<.0001
Intercept	7	-17.3393	3.7083	21.86	<.0001
Population (10,000 inhabitants)	2	0.5613	0.5114	1.20	0.2724
Population (10,000 inhabitants)	3	0.8589	0.4881	3.10	0.0784
Population (10,000 inhabitants)	4	1.3186	0.4942	7.12	0.0076
Population (10,000 inhabitants)	5	1.2567	0.5331	5.56	0.0184
Population (10,000 inhabitants)	6	2.7180	0.6253	18.89	<.0001
Population (10,000 inhabitants)	7	5.7403	1.2265	21.90	<.0001
Major collector	2	0.9456	0.7534	1.58	0.2095
Major collector	3	0.7931	0.7422	1.14	0.2852
Major collector	4	1.6446	0.7386	4.96	0.0260
Major collector	5	2.0045	0.7780	6.64	0.0100
Major collector	6	2.9501	0.8657	11.61	0.0007
Major collector	7	5.1091	1.4976	11.64	0.0006
AADT (1,000 veh/day)	2	0.0149	0.0256	0.34	0.5594
AADT (1,000 veh/day)	3	0.0406	0.0239	2.88	0.0898
AADT (1,000 veh/day)	4	0.0891	0.0242	13.62	0.0002
AADT (1,000 veh/day)	5	0.1162	0.0256	20.56	<.0001
AADT (1,000 veh/day)	6	0.1257	0.0295	18.13	<.0001
AADT (1,000 veh/day)	7	0.1322	0.0327	16.31	<.0001
Distance to city center (mi)	2	-0.5160	0.1600	10.40	0.0013
Distance to city center (mi)	3	-0.6144	0.1555	15.61	<.0001
Distance to city center (mi)	4	-0.8551	0.1728	24.48	<.0001
Distance to city center (mi)	5	-0.8095	0.2031	15.88	<.0001
Distance to city center (mi)	6	-0.4939	0.2519	3.84	0.0499
Distance to city center (mi)	7	0.2160	0.5474	0.16	0.6931
Total employment (EPA data)	2	0.3727	0.2190	2.90	0.0889
Total employment (EPA data)	3	0.5484	0.2098	6.83	0.0089
Total employment (EPA data)	4	0.6094	0.2098	8.44	0.0037
Total employment (EPA data)	5	0.6246	0.2102	8.83	0.0030
Total employment (EPA data)	6	0.6818	0.2103	10.51	0.0012
Total employment (EPA data)	7	0.8231	0.2151	14.65	0.0001

Observed CAL	Predicted CAL						
	1	2	3	4	5	6	7
1	11	3	16	6	0	0	0
2	3	3	53	21	0	0	0
3	2	5	77	53	0	0	0
4	0	2	54	91	2	5	0
5	0	1	13	46	4	1	0
6	0	0	3	15	0	6	4
7	0	0	0	1	0	2	11

Figure 4.4 Observed vs. predicted crossing activity levels.

5. ESTIMATING PEDESTRIAN SAFETY

5.1 Pedestrian Crash Data

In addition to the data described in Section 4.1, pedestrian-vehicle crashes from 2013 to 2020 were obtained from the Automated Reporting Information Exchange System (ARIES), a database of police-reported crashes occurring on Indiana's roads. Crashes occurring at the selected intersections were included in the sample. Crashes were further assigned to the corresponding road segment where the collision occurred. The assignment was based on the direction of travel of the pedestrian who was involved in the crash. In some cases, narratives and police diagrams were used to examine further and investigate the direction of travel, primary and secondary factors, and type of crash.

5.2 Sample Characteristics

A total of 2,456 pedestrian-vehicle crashes were used to study pedestrian safety. Figure 5.1 presents the distribution of crashes into five severity levels, namely Property Damage Only (PDO), non-incapacitating injury, incapacitating injury, fatal, and other. In our analysis, PDO and "other" are combined. These crashes were assigned to 1,985 intersection segments. In addition, due to a large number of sites without crashes, a random sample of 19,850 (1:10 ratio) intersection segments without crashes were used to describe non-crash conditions.

The summary statistics of the sample are presented in Table 5.1. The average vehicle AADT is 5,600. Of the sample, 76% of observations have an intermediate CAL (CAL = 3 or 4), while 22% have low pedestrian activity. Furthermore, 61% of observations are in arterials, 23% on collectors, and 16% on local roads. A handful of crashes occurred on interchange ramps. Lastly, to account for abnormal conditions derived from the COVID-19 pandemic, an annual indicator was used.

5.3 Statistical Analysis Approach

A Sequential Binary Logit (SBL) framework is used to analyze the crash probability and injury severity. It consists of four consecutive models. Each model estimates the likelihood of a more severe safety outcome conditioned on the previous event occurrence (see Figure 6.2). The SBL model is shown in Equation 5.1.

$$P_n(j|i) = \frac{\exp\left(\beta_{j|i} X_n\right)}{1 + \exp\left(\beta_{j|i} X_n\right)} \qquad \text{(Eq. 5.1)}$$

where:

- $P_n(j/i)$ probability of observation n having discrete outcome j, conditioned on the occurrence of event i.
- i is the preceding event.
- j is the analyzed severe event.
- $\beta_{j|i}$ is a vector of estimable parameters for the discrete outcome.
- X_n is a vector of observable characteristics (covariates) that determine discrete outcomes for observation n.

Unconditioned probabilities for each injury severity level, which are often preferred in practice, can be estimated as in Equation 5.2. A complete list of equations derived for the current analysis is presented in Section 6.3.

$$P_n(j) = P_n(i) \times P_n(j|i) \qquad \text{(Eq. 5.2)}$$

Additionally, a random covariate component is introduced to account for multiple observations (8 years) on the same roads. This random intercept helps capture local characteristics reducing the bias of the estimates (Washington et al., 2020). Nevertheless, fixed effects models have a practical advantage since they do not require the simulation of random variables for their implementation.

5.4 Estimated Effects on Pedestrian Safety

5.4.1 Pedestrian Crash Occurrence

The effects on crash probability are shown in Table 5.2. Several factors were found associated with the crash occurrence. To illustrate the magnitude of the effects on crash probability, average marginal effects (AMEs) were calculated. AMEs are shown in Figure 5.2. A summary of the estimated results follows.

- The crash probability increases with vehicle AADT. This finding is intuitive as vehicle AADT is an exposure measure.
- The crash probability increases with pedestrian activity. The previous is derived from the four significant CALs that include pedestrian AADTs as low as 500. For instance, high pedestrian activity (CAL) is linked with a 1.7% increase in crash probability. CALs lower than 4 were grouped as they did not refer from the baseline (CAL = 1).
- In terms of built environment characteristics, the surrounding population, the number of recreational facilities, and the number of schools tend to increase the probability of crash. In contrast, the number of nearby colleges and a higher proportion of vehicle owners tend to reduce it.
- Signalized intersections increase the crash probability by 1.1% on average.

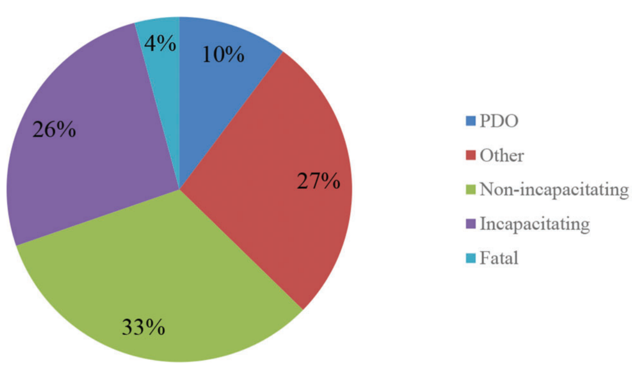

Figure 5.1 Distribution of pedestrian-vehicle crashes by injury severity level (2013–2020).

TABLE 5.1
Characteristics of Pedestrian Safety Sample (N = 174,680)

Variable	Mean	Std. Dev	Minimum	Maximum
AADT (1,000 veh/day)	5.60	7.71	0.00	91.45
Pedestrian CAL = 1	0.11	0.31	0.00	1.00
Pedestrian CAL = 2	0.11	0.31	0.00	1.00
Pedestrian CAL = 3	0.49	0.50	0.00	1.00
Pedestrian CAL = 4	0.27	0.45	0.00	1.00
Pedestrian CAL = 5	0.01	0.09	0.00	1.00
Pedestrian CAL = 6	0.01	0.07	0.00	1.00
Pedestrian CAL = 7	0.01	0.08	0.00	1.00
Number of recreational facilities within 0.6 miles	3.31	2.56	0.00	16.00
Number of schools within 0.8 miles	2.32	1.80	0.00	9.00
Number of big colleges within 2 miles	0.15	0.40	0.00	3.00
Number of medium colleges within 0.8 miles	0.03	0.18	0.00	1.00
Number of small colleges within 0.4 miles	0.01	0.09	0.00	1.00
Population within 1 mile (10,000 inhabitants)	0.70	0.50	0.00	2.97
Percent of households within 1 mile with at least one vehicle	0.82	0.09	0.40	0.96
Signalized intersection (1-yes, 0-else)	0.06	0.24	0.00	1.00
Interchange ramp (1-FC=1 or 2, 0-else)	0.00	0.07	0.00	1.00
Major arterial (1-FC=3, 0-else)	0.22	0.41	0.00	1.00
Minor arterial (1-FC=4, 0-else)	0.39	0.49	0.00	1.00
Major collector (1-FC=5, 0-else)	0.22	0.42	0.00	1.00
Minor collector (1-FC=6, 0-else)	0.01	0.10	0.00	1.00
Local road (1-FC=7, 0-else)	0.16	0.36	0.00	1.00
COVID-19	0.13	0.33	0.00	1.00

TABLE 5.2
Estimated Effects on Pedestrian-Vehicle Crash Probability

	Fixed Effects		Random Effects	
Parameter	**Estimate**	**Std. Error**	**Estimate**	**Std. Error**
Intercept	-7.269	0.260	-8.145	0.359
Log AADT	0.210	0.014	0.206	0.017
Crossing Level Activity (CLA) = 4	0.437	0.052	0.490	0.070
CLA = 5	0.514	0.157	0.493	0.237
CLA = 6	0.584	0.170	0.659	0.281
CLA= 7	1.334	0.130	1.569	0.233
Recreational facilities within 0.6 miles	0.050	0.009	0.055	0.012
K-12 schools within 0.8 miles	0.023	0.013	0.033	0.019
Big colleges within 2 miles	-0.092	0.050	-0.120	0.070
Medium colleges within 0.8 miles	-0.226	0.141	-0.246	0.180
Population within 1 mile (10,000s)	0.752	0.051	0.797	0.074
Proportion of households with at least one vehicle within 1 mile	-1.031	0.257	-1.310	0.361
Signalized intersection	0.855	0.061	0.989	0.093
Major arterial road	0.568	0.100	0.536	0.122
Minor arterial road	0.325	0.097	0.243	0.116
Collector road	-0.199	0.105	-0.306	0.127
COVID-19	-0.401	0.073	-0.425	0.075
Covariance parameter–intercept	–	–	2.918	0.207
AIC (smaller is better)	22,586		22,079	
BIC (smaller is better)	22,757		22,223	

- Major and minor arterials increase the probability of crash by 0.8% and 0.4%, respectively. Collectors reduce the crash probability by 0.3% on average.
- COVID-19 was found to reduce crash probabilities by 0.5%. The previous may be related to low pedestrian and vehicle traffic exposure.

5.4.2 Severity of Pedestrian-Involved Crash

Tables 5.3, 5.4, and 5.5 present the estimated effects on the conditional probabilities of injury (incapacitating and non-incapacitating) and severity of injury (incapacitating or fatal). Among the significant predictor

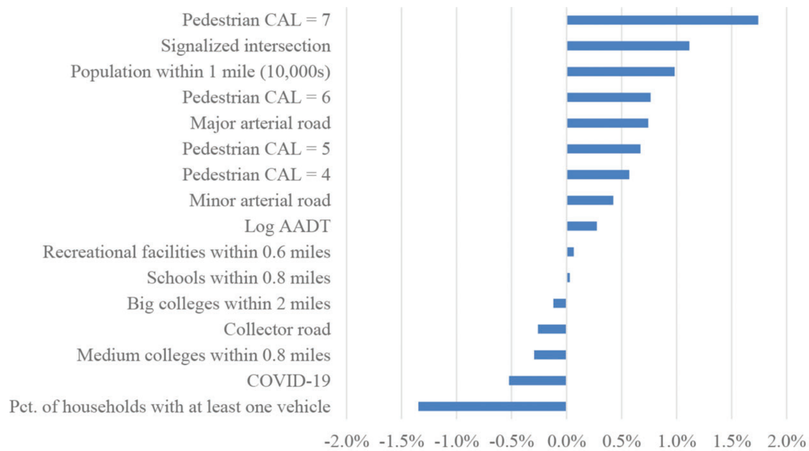

Figure 5.2 Average marginal effects on probability of crash.

TABLE 5.3
Estimated Effects on Probability of Injury Conditioned on Crash Occurrence

Variable Name	Estimate	Std. Error	Chi-Square	p-value
Intercept	1.1445	0.3981	2.87	0.0040
Recreational facilities within 0.6 miles	-0.0442	0.0165	-2.68	0.0073
Schools within 0.8 miles	0.0506	0.0261	1.94	0.0525
Big colleges within 2 miles	-0.1959	0.0959	-2.04	0.0410
Small colleges within 0.4 miles	-0.7592	0.4340	-1.75	0.0803
Proportion of households with at least one vehicle within 1 mile	-0.8259	0.4550	-1.81	0.0695
Posted speed limit = 35, 40, or 45 mph	0.1820	0.0959	1.90	0.0576
Posted speed limit K ≥ 50 mph	0.6983	0.4717	1.48	0.1388
Missing speed limit information	-0.0340	0.1370	-0.25	0.8043
COVID-19	0.6023	0.1637	3.68	0.0002

TABLE 5.4
Estimated Effects on Probability of Severe Outcome Conditioned on Injury Occurrence

Variable Name	Estimate	Std. Error	Chi-Square	p-value
Intercept	-0.7036	0.6333	1.23	0.2665
Pedestrian CAL = 5	-0.6467	0.3890	2.76	0.0964
Pedestrian CAL = 6	-0.8570	0.4728	3.29	0.0699
Pedestrian CAL = 7	-0.7193	0.3547	4.11	0.0426
Recreational facilities within 0.6 miles	0.0713	0.0208	11.70	0.0006
Small colleges within 0.4 miles	1.4083	0.8029	3.08	0.0794
Population within 1 mile (10,000s)	-0.7116	0.1198	35.27	<.0001
Proportion of households with at least one vehicle within 1 mile	0.9842	0.6709	2.15	0.1424
Speed limit = 30 mph	0.2621	0.1658	2.50	0.1138
Speed limit = 35 mph	0.4215	0.1741	5.86	0.0155
Speed limit = 40 mph	0.5333	0.2288	5.43	0.0197
Speed limit ≥ 45 mph	0.7246	0.2903	6.23	0.0126
Missing speed limit information	-0.1306	0.2153	0.37	0.5441
COVID-19	1.2300	0.1985	38.41	<.0001

variables, there are built environment and roadway characteristics. Figures 5.3, 5.4, and 5.5 show the average marginal effects on each severity level. A summary of the estimated effects follows.

- Probability of injury given crash occurrence.
  - The probability of injury conditioned on pedestrian crash increases when the target road is surrounded by schools.

TABLE 5.5
Estimated Effects on Probability of Fatality Conditioned on Severe Outcome Occurrence

Variable Name	Estimate	Std. Error	Chi-Square	p-value
Intercept	-2.6408	0.7087	13.88	0.0002
Log AADT	0.1328	0.0770	2.98	0.0845
Signalized intersection	-1.0768	0.3300	10.65	0.0011
Missing signal information	-0.8722	0.2541	11.78	0.0006
Posted speed limit = 35, 40, or 45 mph	0.6495	0.2453	7.01	0.0081
Posted speed limit ≥ 50 mph	1.4627	0.6268	5.44	0.0196
Missing speed limit information	-0.1632	0.5064	0.10	0.7472

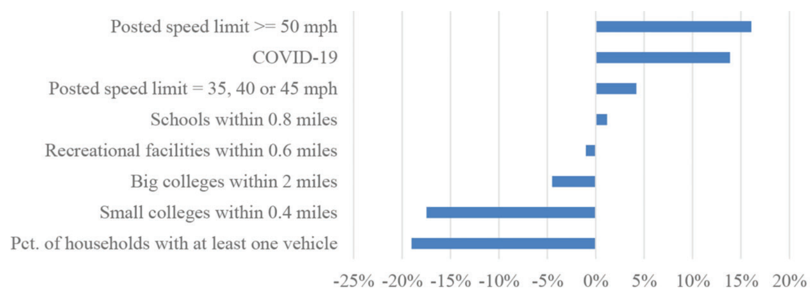

Figure 5.3 Marginal effects on injury probability given crash.

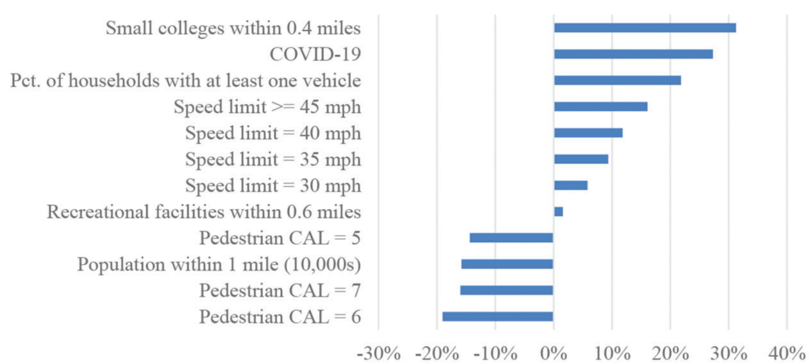

Figure 5.4 Marginal effects on severe outcome probability given injury.

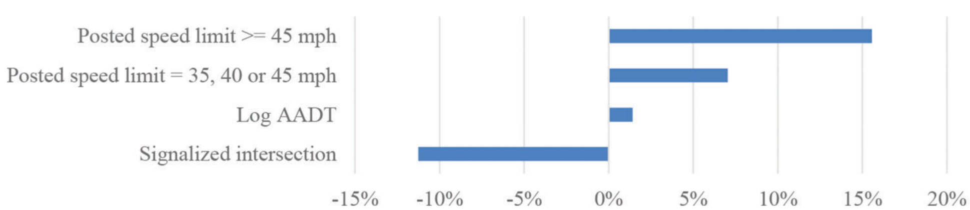

Figure 5.5 Marginal effects on fatality probability given severe outcome.

- ○ The probability of injury conditioned on pedestrian crash decreases nearby colleges and areas with high rates of vehicle ownership.
- ○ High-speed limits tend to increase the probability of injuries. For example, compared to low-speed limit roads (30 mph or less posted speed), intermediate posted speed limits (35–45 mph) increase the probability of injury by 4%, while posted speeds of 50 mph or higher increase it by 16% on average.
- ○ Lastly, COVID-19 was found to increase the probability of injuries by 14% on average. Higher operating speeds could explain the previous effect.

- Probability of severe outcome (non-incapacitating injury or fatality) given injury occurrence is as follows.

  - ○ High pedestrian activity sites tend to be linked with a lower probability of a severe crash outcome.

On average, sites with a pedestrian AADT of 1,000 or more have a 16% lower chance of severe outcomes. The previous may be linked with pedestrians being more visible and therefore providing more braking time for the driver to avoid the fatal outcome. CALs lower than 5 were grouped as they did not refer from the baseline (CAL = 1).

  - Built environment factors were linked to the probability of a severe outcome. For example, large population densities tend to reduce the risk of severe outcomes. In contrast, more nearby recreational facilities, small colleges, and household vehicle owners tend to increase it.
  - Speed limits intuitively affect the probability of a severe outcome. For example, roads with a speed limit of 30 mph have a 6% higher likelihood of a severe outcome. This trend continues until roads with a posted speed of 45 mph or higher experience a 22% higher probability of severe outcomes.
  - COVID-19 was found to affect the probability of severe outcomes significantly. A 27% increase in such probability is expected during 2020. The previous is critical to avoid any bias to future analysis due to abnormal traffic conditions due to the pandemic.

- Probability of fatality given severe crash occurrence is as follows.
- Signalized intersections tend to reduce the probability of a deadly outcome by 11% on average.

  - The vehicle AADT was found to marginally affect the probability of fatal conditioned on severe outcome occurrence. While statistically significant, its practical effect is low: 1% increase in the probability of fatal for every 1,000 veh/day increase in AADT on average.
  - Speed limits are linked to the probability of fatal crashes. Compared to low-speed limit roads (30 mph or less), roads with intermediate speed limits (35–40 mph) have a 7% increase in the probability of fatal pedestrian crashes. Furthermore, high-speed roads (speed limit $>$ 40 mph) experience a 15% average increase in the probability of a deadly crash.

6. ROAD-FOCUSED SCREENING

As proposed in Chapter 3, Indiana's road network can be screened for pedestrian safety issues in two ways: (1) area-wide screening and (2) road-focused screening. This report proposes the road-focused screening in the vicinity of urban intersections. This focus is justified with a substantial overrepresentation of a relatively small portion of the network in the number of pedestrian crashes; 30% of pedestrian crashes occur in the direct vicinity of urban intersections. As opposed to long road segments, a small area allows stationary observers to concentrate their attention on safety-relevant behavior of pedestrians and drivers such as hesitation, confusion, speeding, violation of the traffic priority, rapid maneuvers to avoid a crash, etc.

To perform a road-focused network screening, it is necessary to specify a road element to be analyzed. Many pedestrians are hit within 75 ft from a curb line. Thus, an analyzed intersection road segment is around 170-ft-long (including 20 ft for the intersection average width) and crossed in the middle by another road segment. A four-leg intersection includes two intersection segments of full length. A three-leg intersection includes a full-length segment and a half-length segment that ends at the intersection.

The screening process of intersection segments has the following three computation steps.

1. Calculating the pedestrian traffic (pedestrian exposure to risk) with the pedestrian Crossing Activity Level (CAL) model.
2. Calculating the probability of crash at multiple severity levels. The aforementioned sequential probabilistic approach produces the crash probability at four severity levels: PDO, non-incapacitating injury, incapacitating injury, and fatality.
3. Calculating the comprehensive cost of crash for a user-defined analysis period; typically, 3 years. The average unit crash costs calculated from recent state records are used in the comprehensive cost calculation.

6.1 Pedestrian Crossing Activity Level (CAL)

Pedestrian and vehicle traffic volumes are essential inputs to safety analysis. A high number of crashes is expected at a location with high vehicle volume. On the other hand, the relationship between pedestrian volume and pedestrian safety is not that straightforward. A large pedestrian volume with a constant presence of pedestrians may be associated with fewer pedestrian-vehicle crashes than lower pedestrian volume. This somewhat surprising effect is produced by pedestrian grouping when crossing the road. Large groups of pedestrians are more visible, and they command drivers' attention. The previous hypothesis follows the results presented in Chapter 5, where high pedestrian activity was linked to a higher probability of crash and a lower proportion of severe outcomes.

While vehicle traffic counts are typically available, especially for state-administered roads, pedestrian volume counts are scarce. Pedestrian crossing volumes may be observed at specific intersections upon request from transportation engineers. Still, an effort of pedestrian data collection for the entire road network is prohibitively resource-demanding. For roads lacking pedestrian volume information, the proposed screening procedure includes a Crossing Activity Level model that produces the most likely Crossing Activity Level (CAL) based on the surrounding land use and other information available for the road network. This model was built based on a sample of 514 roads with *Street Light* pedestrian volume data of sufficient quality. The pedestrian AADT thresholds, which define the individual CALs are provided in Table 6.1.

The probability of each CAL is calculated using Equations 6.1 through 6.8. Thus, the CAL with the highest estimated probability would be the expected CAL for a given road.

TABLE 6.1
Pedestrian AADT Thresholds of Crossing Activity Levels

Crossing Activity Level (CAL)	Pedestrian AADT	
	Lower Bound	Upper Bound
1	0	100
2	100	249
3	250	499
4	500	999
5	1,000	1,999
6	2,000	3,999
7	4,000	∞

$$\Pr(CAL1) = 1/(1+Z) \quad \text{(Eq. 6.1)}$$

$$\Pr(CAL2) = \exp(0.6162 + 0.5613 * Pop + 0.9456 * Coll + 0.0149 * AADT - 0.5160 * Dist + 0.3727 * Emp)/(1+Z) \quad \text{(Eq. 6.2)}$$

$$\Pr(CAL3) = \exp(0.4952 + 0.8589 * Pop + 0.7931 * Coll + 0.0406 * AADT - 0.6144 * Dist + 0.5484 * Emp)/(1+Z) \quad \text{(Eq. 6.3)}$$

$$\Pr(CAL4) = \exp(-0.5237 + 1.3186 * Pop + 1.6446 * Coll + 0.0891 * AADT - 0.8551 * Dist + 0.6094 * Emp)/(1+Z) \quad \text{(Eq. 6.4)}$$

$$\Pr(CAL5) = \exp(-2.0394 + 1.2567 * Pop + 2.0045 * Coll + 0.1162 * AADT - 0.8095 * Dist + 0.6246 * Emp)/(1+Z) \quad \text{(Eq. 6.5)}$$

$$\Pr(CAL6) = \exp(-6.0044 + 2.718 * Pop + 2.9501 * Coll + 0.1257 * AADT - 0.4939 * Dist + 0.6818 * Emp)/(1+Z) \quad \text{(Eq. 6.6)}$$

$$\Pr(CAL7) = \exp(-17.3393 + 5.7403 * Pop + 5.1091 * Coll + 0.1322 * AADT + 0.216 * Dist + 0.8231 * Emp)/(1+Z) \quad \text{(Eq. 6.7)}$$

$$\begin{aligned} Z = {} & \exp(0.6162 + 0.5613 * Pop + 0.9456 * Coll + 0.0149 * AADT - 0.5160 * Dist + 0.3727 * Emp) \\ & + \exp(0.4952 + 0.8589 * Pop + 0.7931 * Coll + 0.0406 * AADT - 0.6144 * Dist + 0.5484 * Emp) \\ & + \exp(-0.5237 + 1.3186 * Pop + 1.6446 * Coll + 0.0891 * AADT - 0.8551 * Dist + 0.6094 * Emp) \\ & + \exp(-2.0394 + 1.2567 * Pop + 2.0045 * Coll + 0.1162 * AADT - 0.8095 * Dist + 0.6246 * Emp) \\ & + \exp(-6.0044 + 2.718 * Pop + 2.9501 * Coll + 0.1257 * AADT - 0.4939 * Dist + 0.6818 * Emp) \\ & + \exp(-17.3393 + 5.7403 * Pop + 5.1091 * Coll + 0.1322 * AADT + 0.216 * Dist + 0.8231 * Emp) \end{aligned} \quad \text{(Eq. 6.8)}$$

where:

- *Pop* = Population within one mile from the intersection in 10,000 inhabitants.
- *Coll* = Major collector road indicator (1 if yes; 0 otherwise).
- *AADT* = Intersection AADT in (1,000 veh/day).
- *Dist* = Intersection distance to the city center (miles).
- *Emp* = Number of employed people within one mile from the intersection in 1,000s.

The ability to predict CAL at any intersecting road is essential for road network screening and other elements of safety analysis. The estimated CAL is among the crash frequency or crash risk variables. To determine the most likely pedestrian CAL, the developed pedestrian CAL model utilizes commonly available data such as a road functional class, land use, socio-economic data, and

TABLE 6.2
Data Required for Pedestrian Crossing Activity Estimation

Variable Name	Description	Source
Pop	Population within one mile from the intersection	U.S. Census Bureau
Coll	Road functional class is major collector	INDOT
AADT	Total intersection AADT	INDOT
Dist	Distance to the city center	Appendix B
Emp	Total employment within 1 mile	Environmental Protection Agency (EPA)–Smart Location Database

AADT. The estimated CAL is two-directional pedestrian traffic crossing an analyzed intersection segment. The CAL for an intersection segment that ends at a three-leg intersection must be adjusted by reducing the obtained CAL by one level. This is equivalent to lowering the pedestrian flow crossing the road segment by half. This adjustment account for half of the pedestrian flow on the other side of the main road that does not cross the side street.

The data required to determine the most probable CAL and their sources are shown in Table 6.2.

6.2 Pedestrian Crash Probability

The probability of a pedestrian being hit when crossing an intersection segment at a specific intersection over 1 year is calculated with the equation developed in Chapter 5 and described in this section. A simple scheme of events represents the situation (Figure 6.1). This probability is essential to properly direct the safety audit effort towards locations with a considerable risk of pedestrian crashes.

The pedestrian crash probability is calculated using the following equation.

$$LP = -7.2690 + 0.2102 * \log(AADT) + 0.4366 * CAL4 + 0.5137 * CAL5 + 0.5842 * CAL6 + 1.3338 * CAL7 + 0.0504 * Rec + 0.0228 * Sch - 0.0920 * ColB - 0.2257 * ColM + 0.7517 * Pop - 1.0309 * Own + 0.8545 * Sign + 0.5683 * Art + 0.3251 * mArt - 0.1992 * Coll - 0.4012 * covid \quad \text{(Eq. 6.9)}$$

$$\Pr(Crash) = \exp(LP)/(1 + \exp(LP)) \quad \text{(Eq. 6.10)}$$

where:

- *LP* is a linear combination of significant variables.
- Pr(*Crash*) is the annual probability of crash at the studied road.
- *AADT* is the annual average daily traffic of the intersecting road.
- *CAL4* is a pedestrian crossing activity indicator, 1 if CAL = 4, 0 otherwise.

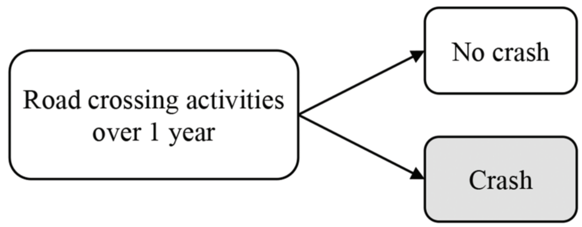

Figure 6.1 Scheme of events in a crash occurrence model.

- *CAL5* is a pedestrian crossing activity indicator, 1 if CAL = 5, 0 otherwise.
- *CAL6* is a pedestrian crossing activity indicator, 1 if CAL = 6, 0 otherwise.
- *CAL7* is a pedestrian crossing activity indicator, 1 if CAL = 7, 0 otherwise.
- *Rec* is the number of recreational facilities within 0.6 miles.
- *Sch* is the number of schools within 0.8 miles.
- *ColB* is the number of large colleges (number of students exceeds 15,000) within 2 miles.
- *ColM* is the number of medium colleges (number of students between 5,000 and 15,000) within 0.8 miles.
- *Pop* is the population within one mile in 10,000 habitants.
- *Own* is the proportion of households with at least one vehicle within one mile.
- *Sign* is a signal indicator, 1 if signalized intersection, 0 otherwise.
- *Art* is a functional class indicator, 1 if major arterial, 0 otherwise.
- *mArt* is a functional class indicator, 1 if minor arterial, 0 otherwise.
- *Coll* is a functional class indicator, 1 if collector, 0 otherwise.
- *Covid* is a COVID-19 indicator, 1 if the crash sample includes 2020 data, 0 otherwise.

A list of the data required to estimate the annual crash probability and their sources are shown in Table 6.3.

6.3 Pedestrian Crash Severity

A sequential binary logit model was used to estimate the probabilities of specific injury outcomes: (crash, injury, severe injury, fatal injury). The general idea of the proposed approach is presented in Figure 6.2. Events are sequentially split at several levels in such a way that the next level (lower level) includes two events

TABLE 6.3
Data Required for Crash Probability Estimation

Variable Name	Description	Source
AADT	Average AADT during the analysis period	INDOT
CAL*n*	Crossing Activity Level (n = 1, …, 7)	Section 6.1 of this document
Rec	Number of recreational facilities	Indiana Maps shapefile (recreational facilities–IDNR)
Sch	Number of schools	Indiana Maps shapefile (schools in Indiana–IDOE)
ColB	Number of large colleges	U.S. Census Bureau
ColM	Number of medium colleges	U.S. Census Bureau
Pop	Population	U.S. Census Bureau
Own	The proportion of households with at least one vehicle	U.S. Census Bureau
Sign	Signalized intersection	INDOT
Art	Major arterial road	INDOT
mArt	Minor arterial road	INDOT
Coll	Collector road	INDOT
Covid	Year = 2020	–

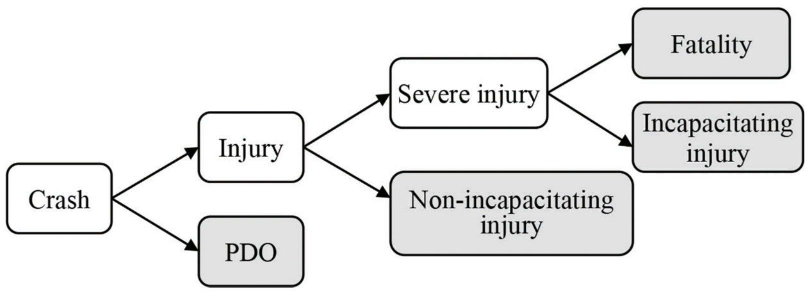

Figure 6.2 Events disaggregation in a four-level sequential binary model with four probability values of crash, injury (non-incapacitating or incapacitating or fatal), severe injury (incapacitating or fatal), and fatal injury (fatality).

obtained by splitting an event at the previous level. Consequently, four models that correspond to the four splits are obtained. These models provide the probabilities of the four events marked in bold font. Probabilities of the other events are calculated from the four directly obtained from the four models. The equations shown in Chapter 5 are used in this chapter to calculate the probability of a crash at any of the four levels of severity (PDO, each of the four levels of injury severity). The injury equation assumes that a crash has occurred, and it provides the probability of injury. The severe injury equation assumes injury occurrence and calculates the probability of severe injury. Finally, the fatality equation assumes severe injury occurrence and estimates the probability of a fatal outcome.

The probability of crash at four severity levels, namely PDO, non-incapacitating, incapacitating, and fatal, can be calculated using the Equations 6.11 through 6.20.

$$LP_{inj} = 1.1445 - 0.0442 * Rec + 0.0506 * Sch - 0.1959 * ColB - 0.7592 * ColS - 0.8259 * Own + 0.182 * SL3545 + 0.6983 * SL50up - 0.034 * MSpeed + +0.6023 * covid \quad \text{(Eq. 6.11)}$$

$$\Pr(Injury|Crash) = \exp(LP_{inj})/(1 + \exp(LP_{inj})) \quad \text{(Eq. 6.12)}$$

$$LP_{sev} = -0.7036 - 0.6467 * CAL5 - 0.857 * CAL6 - 0.7193 * CAL7 + 0.0713 * Rec + 1.4083 * ColS - 0.7116 * Pop + 0.9842 * Own + 0.2621 * SL30 + 0.4215 * SL35 + 0.5333 * SL40 + 0.7246 * SL45up - 0.1306 * MSpeed + 1.2300 * covid \quad \text{(Eq. 6.13)}$$

$$\Pr(Severe|Injury) = \exp(LP_{sev})/(1 + \exp(LP_{sev})) \quad \text{(Eq. 6.14)}$$

$$LP_{fat} = -2.6408 + 0.1328 * \log(AADT) - 1.0768 * Sign - 0.8722 * MSignal + 0.6495 * SL3545 + 1.4627 * SL50up - 0.1632 * MSpeed \quad \text{(Eq. 6.15)}$$

$$\Pr(Fatal|Severe) = \exp(LP_{fat}) / (1 + \exp(LP_{fat})) \quad \text{(Eq. 6.16)}$$

$$\Pr(PDO) = \Pr(Crash) * (1 - \Pr(Injury|Crash)) \quad \text{(Eq. 6.17)}$$

$$\Pr(NoIncap) = \Pr(Crash) * \Pr(Injury|Crash) * (1 - \Pr(Severe|Injury)) \quad \text{(Eq. 6.18)}$$

$$\Pr(Incap) = \Pr(Crash) * \Pr(Injury|Crash) * \Pr(Severe|Injury) * (1 - \Pr(Fatal|Injury)) \quad \text{(Eq. 6.19)}$$

$$\Pr(Fatal) = \Pr(Crash) * \Pr(Injury|Crash) * \Pr(Severe|Injury) * \Pr(Fatal|Injury) \quad \text{(Eq. 6.20)}$$

where:

- LP_{inj}, LP_{sev}, LP_{fat} are linear combinations of significant safety factors for the conditional probabilities of injury, severe outcome (incapacitating injuries and fatalities combined), and fatal, respectively.
- Pr(*Injury*|*Crash*) is the expected probability of injury conditioned on crash occurrence.
- Pr(*Severe*|*Injury*) is the expected probability of incapacitating injury or fatal assuming injury occurrence.
- Pr(*Fatal*|*Severe*) is the expected probability of fatal conditioned on severe outcome occurrence.
- Pr(*PDO*), Pr(*NoIncap*), Pr(*Incap*), Pr(*Fatal*) are the expected annual probabilities of PDO, non-incapacitating, incapacitating, and fatal crashes at a specific road, respectively.
- *CAL5* is a pedestrian crossing activity indicator, 1 if CAL = 5, 0 otherwise.
- *CAL6* is a pedestrian crossing activity indicator, 1 if CAL = 6, 0 otherwise.
- *CAL7* is a pedestrian crossing activity indicator, 1 if CAL = 7, 0 otherwise.
- *AADT* is the annual average daily traffic of the intersecting road.
- *Sign* is a signal indicator, 1 if signalized intersection, 0 otherwise.
- *MSignal* is an instrumental indicator, 1 if missing signal information, 0 otherwise.
- *Rec* is the number of recreational facilities within 0.6 miles.
- *Sch* is the number of schools within 0.8 miles.
- *ColB* is the number of big colleges within 2 miles.
- *ColS* is the number of medium colleges within 0.4 miles.
- *Pop* is the population within one mile in 10,000 inhabitants.
- *Own* is the proportion of households with at least one vehicle within one mile.
- *SL30* is a posted speed limit indicator, 1 if speed limit = 30 mph, 0 otherwise.
- *SL35* is a posted speed limit indicator, 1 if speed limit = 35 mph, 0 otherwise.
- *SL40* is a posted speed limit indicator, 1 if speed limit = 40 mph, 0 otherwise.
- *SL3545* is a posted speed limit indicator, 1 if speed limit = 35 or 40 mph, 0 otherwise.
- *SL45up* is a posted speed limit indicator, 1 if speed limit ≥ 45 mph, 0 otherwise.
- *SL50up* is a posted speed limit indicator, 1 if speed limit ≥ 50 mph, 0 otherwise.
- *MSpeed* is an instrumental indicator, 1 if missing speed limit information, 0 otherwise.
- *Covid* is a COVID-19 indicator, 1 if the sample includes 2020 data, 0 otherwise.

A list of the data required to estimate the annual crash probability at multiple severities and their sources are shown in Table 6.4.

6.4 Empirical Bayes Procedure for Adjusting Crash Probabilities

The estimated crash probabilities derived from the equations presented in Sections 6.2 and 6.3 can be improved using crash records. This adjustment is

TABLE 6.4
Data Required for Crash Severity Estimation

Variable Name	Description	Source
AADT	Average AADT during the analysis period	INDOT
Rec	Number of recreational facilities	Indiana Maps shapefile (recreational facilities–IDNR)
Edu	Number of schools	Indiana Maps shapefile (schools in Indiana–IDOE)
CAL*n*	Crossing Activity Level (*n* = 1, …, 7)	Section 6.1 of this document
ColB	Number of large colleges	U.S. Census Bureau
ColS	Number of small colleges	U.S. Census Bureau
Pop	Population	U.S. Census Bureau
Own	The proportion of households with at least one vehicle	U.S. Census Bureau
Sign	Signalized intersection (1 if yes, 0 if not)	INDOT
Missing	1 if signalization data available, 0 data missing	
SL30, SL35, SL40, SL3545, SL45up, SL50up	Speed limits	INDOT

TABLE 6.5
Comprehensive Crash Costs by Injury Severity Level Using Pedestrian-Vehicle in 2019 U.S. dollars (2013–2020 Indiana crashes)

Crash Severity	Sample Size	Mean	Std. Dev	Minimum	Maximum
PDO	924	23,854	20,767	4,600	155,000
Non-incapacitating	801	367,627	109,511	336,000	1,344,000
Incapacitating	647	1,320,006	362,138	1,219,000	4,454,000
Fatal	104	9,048,774	4,679,868	17,100	22,296,000

known as the Empirical Bayes (EB) method. The EB method consists of three steps described below. These steps apply to any of the levels of events disaggregation in the sequential approach (see Figure 6.2).

Step 1. For a specific road, the following equations should be used to calculate the initial crash probability estimate, μ_0 and its variance, σ^2.

$$\mu_0 = \frac{\exp\left(\sum_{i=0}^{m} b_i x_i\right)}{1+\exp\left(\sum_{i=0}^{m} b_i x_i\right)} \quad \text{(Eq. 6.21)}$$

$$\widehat{\sigma^2} = \frac{\mu_0^2 \sum_{i=0}^{m} (x_i \cdot std\ b_i)^2}{\left[1+exp\left(\sum_{i=0}^{m} b_i x_i\right)\right]^2} \quad \text{(Eq. 6.22)}$$

$$\sigma^2 = \begin{cases} \widehat{\sigma^2},\ if\ \widehat{\sigma^2} < \mu_0(1-\mu_0) \\ \widehat{\sigma^2} - 0.0001,\ otherwise \end{cases} \quad \text{(Eq. 6.23)}$$

where:

- m is the number of significant predictors linked to crash probability.
- b_i are estimated safety effects (see Section 5.4).
- $std(b_i)$ are standard errors of estimated safety effects (see Section 5.4).
- x_i are observed values of predictors.
- b_0 is an intercept with $x_0 = 1$.

Step 2. The next step is to find the beta distribution parameters α and β using the obtained values of crash probability estimate and its variance using the following equations.

$$\alpha = \left(\frac{\mu_0(1-\mu_0)}{\sigma^2} - 1\right)\mu_0 \quad \text{(Eq. 6.24)}$$

$$\beta = \left(\frac{\mu_0(1-\mu_0)}{\sigma^2} - 1\right)(1-\mu_0) \quad \text{(Eq. 6.25)}$$

Step 3. In the last step, the initial crash probability estimate can be further improved based on the crash occurrence data at the location using the following equation.

$$\mu = \begin{cases} \dfrac{\alpha}{\alpha+\beta+1} \text{if crash did not occur} \\ \dfrac{\alpha+1}{\alpha+\beta+1} \text{if crash occured} \end{cases} \quad \text{(Eq. 6.26)}$$

6.5 Screening Results

Infrequent but severe pedestrian crashes on individual intersection segments require modification of the screening criteria. A screening procedure must focus on the risk of crash and its potential severity to fully use the available information. The screening results should also increase the prospect of identifying the most effective countermeasures justified with the B/C analysis. For these reasons, the proposed screening for roads with pedestrian safety issues focuses on locations where both the crash risk and potential outcome severity are high. This can be accomplished by searching for intersection segments with the high crash costs estimated with the full information at hand. This calls for using the EB-based estimates of risk at the levels of crash severity. Thus, the screening utilizes the annual crash probabilities at four severity levels multiplied by the number of years and the Indiana average cost of a pedestrian crash at each severity level. The combined values for each intersection segment represent the expected crash cost. The segments with the highest cost should be selected for safety audits together with the crossing segments to take advantage of the presence of an audit team at the intersection.

Urban intersections are sorted in terms of pedestrian safety performance. To do so, the current procedure uses the cost as described in Equation 6.27.

$$Cost = Y \cdot [\Pr(PDO)C_{PD} + \Pr(Noincap)C_{NI} + \Pr(Incap)C_{IN} + \Pr(Fatal)C_{FT}] \quad \text{(Eq. 6.27)}$$

where:

- *Cost* is the expected cost of pedestrian crashes during Y years.
- *Y* is the number of years in the analysis period.
- C_{pd}, C_{ni}, C_{in}, C_{ft} are the average crash cost for PDO, non-incapacitating, incapacitating, and fatal outcomes (see Table 6.5).
- Pr(*PDO*), Pr(*Noincap*), Pr(*Incap*), Pr(*Fatal*) are the annual probability of crashes at each severity level as defined in Section 6.3.

Using the probability of a crash is an approach alternative to cost-based screening. A high cutoff threshold can be used to identify roads with an increased risk of a pedestrian crash. Table 6.6 shows the distribution of the expected annual pedestrian-crash probability at Indiana urban intersections. One candidate for a crash probability threshold is 0.0739 (7.4%), which is exceeded at 225 locations among 22.5 thousand analyzed. The

TABLE 6.6
Distribution of Annual Crash Probability at 22,506 Randomly Selected Urban Intersections in Indiana

Annual Probability of Crash	Percent of Locations with Lower Probability
0.3234	100
0.0739	99
0.0389	95
0.0258	90
0.0142	75
0.0078	50
0.0047	25
0.0030	10
0.0023	5
0.0016	1
0.0007	0

expected annual number of pedestrian-vehicle crashes at these sites is 194. A safety analyst may select a different target threshold depending on the type of road, traffic control, etc.

6.5.1 Example Road-Focused Screening

The proposed road-focused screening approach was applied to the sample of 46,360 intersection roads (22,506 intersections) described in Section 4.2. A portion of the resulting list of intersection segments ranked by the 3-year crash cost is presented in Appendix A. The complete list can be found as a separate attachment to this report. The results include the safety needs rank, geographical coordinates of the intersection, road segment direction, average crash probability (after EB adjustment), and the adjusted crash cost for 3 years: 2018–2020. In addition, a binary indicator is used to state whether a specific road segment was used to calibrate the crash probability and injury severity models. This list could be used to plan safety audits or prioritize resources as it clearly states the crash cost, which is later transformed to safety benefits in benefit-cost analysis.

7. SAFETY AUDIT FOR PEDESTRIANS

A pedestrian safety audit has two primary outputs: (1) identified conditions that increase the risk of a pedestrian collision and (2) selected relevant countermeasures to address the identified issues. From this perspective, a safety audit aims at crash prevention rather than responding to crashes that have already happened. Therefore, these guidelines are meant to help focus on the two identification tasks.

7.1 Identifying Safety Deficiencies

During a site investigation, at first, the local conditions should be carefully documented. This inspection includes geometric features, speed limit, pedestrian facilities, lighting, sight distance, traffic control devices, signs, and markings. The RSA team should consider whether pedestrian facilities are designed to consider all user groups and also if a particular user group is predominant due to the presence of facilities such as hospitals, schools, parks, and multi-modal centers (including airports, rail stations, intercity bus terminals, and water ports), since pedestrians associated with these facilities may have specific needs that the application of minimum standards alone may not adequately accommodate. Proper analysis of local conditions may help to identify safety deficiencies at the location more efficiently. Causes of safety deficiencies can be classified into physical arrangement, traffic control, and road user behavior. Depending on these factors, the weaknesses are addressed by choosing suitable engineering countermeasures or education or enforcement.

7.2 Physical Arrangement

To address safety deficiencies in physical arrangements, the following factors should be checked during the road safety audit: obstructions that block the view of road users or pedestrian facilities (screening), visibility issues during day and night, lighting condition, pedestrian crossing distance, the interaction between transit infrastructure and pedestrian facilities, on-street parking, presence of the sidewalk, legibility of pavement markings and signs.

7.3 Traffic Control

Traffic operations may affect pedestrian safety. Even in the presence of well-designed and well-maintained pedestrian facilities, the operational characteristics of traffic may compromise pedestrian safety. The factors contributing to traffic control deficiencies are adequacy of signal timing and phasing, restrictions on turning movements, and the speed limit.

7.4 Road User Behavior

Road user behavior is affected by several factors such as physical, psychological, personal characteristics, motivation, experience, psychological state, among others. Before crossing the street, the pedestrian scans the road, perceives traffic, and makes judgments about vehicles' distance, speed, and direction. Judgment errors can lead pedestrians to accept unsafe gaps when crossing the road. The deficiencies in road user behavior to be observed during road safety audit are as follows: driver's compliance with pedestrians' right of way, the safety of pedestrians in school zones, road users' compliance with pedestrian facilities, illegal crossing behavior, pedestrian/driver intoxication or distraction, speeding, and pedestrian darting into the roadway.

7.5 Selection of Potential Countermeasures

The next step is to suggest candidate countermeasures. Specific candidate countermeasures should be considered primarily in light of the identified safety deficiencies at the locations. The candidate countermeasures should be selected based on crash modification factors or crash-based evidence. When CRFs or crash-based studies are not available, there should be significant research or well-documented studies showing safety-related benefits (e.g., driver's compliance with the right of way) or that the treatment itself has design features related to conflict or exposure reduction. (e.g., reduced crossing width, calming traffic effect, among others). Cost may also be a concern. However, absolute cost should not necessarily override cost-effectiveness.

A benefit-cost analysis is recommended for a more expensive choice of countermeasures. The feasibility of implementing countermeasures should also be considered.

Some common local conditions and behavioral issues and their corrective measures are matched and listed in Table 7.1. The CMF and CRF values of the corresponding countermeasures can be found in Appendix C.

TABLE 7.1
Appropriate Countermeasures Addressing Identified Local Conditions and Behavioral Issues

Countermeasure for Consideration	Identified Local Conditions	Identified Behavioral Issues
Curb extensions	Insufficient sight distance of oncoming traffic for pedestrians at a crosswalk High pedestrian volume on a sidewalk Longer crossing distance	Speeding
Flashing yellow arrow left turn signal	Crashes related to turning vehicles Delay at intersections	Speeding Older pedestrians or people with lower mobility Failure to yield to pedestrians
In-roadway warning lights	Reduced visibility at nighttime	Pedestrian distraction and inattention Substance-impaired pedestrians Speeding Failure to yield at unsignalized intersections
Advanced yield or stop lines	Screening or insufficient sight distance	Speeding Failure to yield at unsignalized intersections
Pedestrian hybrid beacon (PHB)	Reduced conspicuity Screening High traffic and pedestrian volume	Driver inattention and distraction Failure to yield at unsignalized locations Speeding
Raised crosswalks	Conspicuity (driver failed to notice)	Failure to yield at unsignalized locations Speeding
Rectangular rapid flashing beacon (RRFB)	Reduced conspicuity Adverse weather conditions	Failure to yield at unsignalized locations Driver inattention and distraction Speeding
In-street pedestrian crossing sign	Reduced conspicuity	Failure to yield at unsignalized locations Speeding
Leading pedestrian interval	Reduced conspicuity The conflict between turning vehicles and pedestrians	Failure to yield at unsignalized locations
Danish offset	Wide roadway with multiple lanes	Failure to yield at unsignalized locations Pedestrian inattention and distraction
Pedestrian refuge island	Wide roadway with multiple lanes Turning speed at intersections	Speeding Older pedestrians or people with lower mobility
Road diets	Wide roadway with multiple lanes Number of conflict points at junctions	Speeding
Speed cushion	–	Speeding Driver inattention and distraction
Puffin crossing	Insufficient crossing time	Older pedestrians or people with lower mobility Pedestrian & driver inattention and distraction Substance-impaired pedestrians
Exclusive pedestrian signal	Heavy pedestrian volume during peak hour Conflicts with turning traffic	–
Smart lighting	Reduced visibility during nighttime	Substance-impaired pedestrians Driver inattention and distraction Failure to yield at unsignalized locations
LED border enhanced warning signs	Reduced visibility during nighttime	Substance-impaired pedestrians Driver inattention and distraction Failure to yield at unsignalized locations Speeding
Automated pedestrian detection	Reduced visibility	Substance-impaired pedestrians Driver inattention and distraction Failure to yield at unsignalized locations

8. PEDESTRIAN SAFETY COUNTERMEASURES

Engineering, education, and enforcement countermeasures aim to address various pedestrian safety concerns and develop strategies to reduce the probability of crashes. However, the engineering dimension is the core of the crash mitigation efforts. The countermeasures discussed in these guidelines focus on the engineering treatments for improved pedestrian safety.

The principal objective of education in road safety is to promote behavioral change in road users (Millicent, 2016). Consequently, the objectives of such educational programs could be classified as those designed to mitigate unsafe behaviors, such as speeding, texting while walking or driving, and driving under the influence. Educational campaigns discourage dark clothing at night and promote wearing retroreflective materials or a yellow-green color if non-fluorescent can make pedestrians significantly more visible in the dark. People may be encouraged to use an application such as PedSafe to make themselves more visible to drivers while crossing roads, especially during nighttime. Educating the parents on the risk their children may face in the traffic can effectively lower the danger of child pedestrians on the street. Suppose there is a prevalence of distracted or substance-impaired pedestrians in some communities. In that case, it may be beneficial to work with other organizations such as health promoters or injury prevention groups to discourage these behaviors and promote risk awareness.

Enforcement is necessary to ensure that road users behave responsibly. Enforcement works best when it is part of a comprehensive approach combined with awareness and education. NHTSA has been collaborating with the enforcement sector to create toolkits and initiatives which improve compliance. For example, the work done on High Visibility Enforcement (HVE) and publicity campaigns to raise public awareness and encourage consensual legal compliance. Although drivers are generally liable in pedestrian-vehicle crashes, implementing pedestrian traffic laws may effectively correct risky pedestrian behaviors, e.g., jaywalking. Enforcing traffic laws involves penalties ranging from a warning to issuing a ticket with varying fine amounts or a more severe charge.

To improve school zone safety, police may be advised to launch checkpoints based on peak hours, such as the first week of school to encourage children to practice safe walking and crossing habits after the summer break and ensure drivers are using care when entering school. Also, campaigns that promote the repercussions of acts done while walking or driving should highlight the problems to raise public awareness and outline the punishments and consequences.

The following section presents countermeasures that traffic and road engineers can consider when addressing behavioral and local environmental conditions identified in pedestrian safety audits as likely factors contributing to the high risk of pedestrian crashes.

8.1 Marked Crosswalk

Marked crosswalks establish a pedestrian's presence in the roadway and warn oncoming traffic to yield. Crosswalk markings should be considered at all controlled approaches where pedestrian traffic is expected and roads near schools, shopping centers, and transit stop locations. When marked crosswalks are installed with raised medians at uncontrolled pedestrian crossings, crashes reduce by 46%, and the crash modification factor (CMF) holds a value of 0.54 (Zegeer et al., 2002).

Design Considerations and Guidelines

1. When marked crosswalks are considered for an uncontrolled intersection or mid-block location, an engineering study should be conducted based on several factors such as the number of lanes, presence of median, distance from the nearby signalized intersection, possible consolidation of multiple crossing points, average daily traffic (ADT), speed limit, and visibility condition.
2. According to *MUTCD*, crosswalk markings shall not be less than 6 in or greater than a 24 in width, while the minimum width of the crosswalk should be 6 ft.
3. For bar pair markings, two 8 in stripes should be separated by 8 in to form a 24-in-wide bar pair. The pairs ought to be separated by gaps of 24 in to 60 in.
4. At uncontrolled multi-lane approaches, marked crosswalks must be installed in conjunction with proper signs and treatments to be proven effective under these conditions: four or more travel lanes without a raised median, ADT greater than 12,000 vehicles per day, and speed exceeds 40 mph.
5. The crosswalk must provide adequate sight distance at midblock locations, including vertical, horizontal, and intersection stopping distance (sight distance triangle). Restriction of parking, vegetation, or other obstacles that hampers the visibility of road users might be included in the sight distance triangle.
6. The location of midblock crossings should be 300 ft from any controlled intersection.
7. High-visibility crosswalks use longitudinal, diagonal or ladder style pavement markings, which are highly visible to the approaching traffic. They should be provided at all midblock crossings and are generally preferred over parallel line crosswalks.
8. The longitudinal lines should be striped between 12 in to 24 in in width and separated by gaps of 12 in to 60 in for ladder markings.
9. At controlled intersections, the following supplemental signs should be considered: "Turning Vehicles Yield to Peds" (R10-15), "Crosswalk Stop on Red" (R10-23).
10. At uncontrolled intersections, the following supplemental signs must be considered: "Yield Here to Peds" (R1-5 or 5a), "Stop Here for Peds" (R1-5b or 5c), "Pedestrian" (W11-2), and "Handicapped" (W11-9). In-street pedestrian crossing signs should also be considered if pedestrian right-of-way compliance is a concern.

Estimated Cost

The cost of a striped crosswalk is around $750, and for a high-visibility crosswalk, it is approximately $2,600.

8.2 Raised Crosswalk

Raised crosswalks are speed ramps that span over the entire width of the crosswalk (see Figure 8.1). They are generally constructed at midblock crossings. Raised crosswalks enhance the visibility of pedestrians to drivers, are effective in reducing motor vehicle speeds, and increase driver's yielding behavior. According to FHWA, raised crosswalks reduce pedestrian crashes by 45%.

As raised crosswalks are at the same level as sidewalks, curb ramps are not considered, and the crosswalk itself is marked with paint or unique paving materials. They are most appropriate for locations where pedestrian traffic is significantly high and vehicular traffic needs to move slower, such as near schools, college campuses, and downtown areas. Children can appear more visible to drivers as they are raised by a few inches.

Design Considerations and Guidelines

1. Raised crosswalks can be installed on local and collector roads and near schools, shopping centers, and pick-up/drop-off areas. According to FHWA, they are typically installed on two or three-lane roads with speed limits equal to or less than 30 mph and annual average daily traffic (AADT) below 9,000 vehicles/day.
2. Raised crosswalks are not appropriate for arterial roads, emergency vehicle routes, or bus transit routes. However, raised crosswalk is a good candidate countermeasure for midblock crossings.
3. The crosswalks should be flushed with sidewalks in height.
4. The crosswalk table is recommended to be at least 10-ft-wide so that both front and rear wheels of a passenger vehicle can be on the top of the table simultaneously.
5. Drainage should be adequately accommodated by relocating catch basins or installing trench drains if necessary.
6. ADA ramps and detectable warning strips should be installed near street edges for improved accessibility for the visually impaired

Estimated Cost

Depending on drainage conditions, materials used, and the size of roadways, the cost of raised crosswalks ranges from $7,110 to $30,880.

Figure 8.1 Raised crosswalks.

8.3 Danish Offset or Staggered Crosswalk

A Danish offset or staggered crosswalk, also known as Z-Crossing, allows two-staged pedestrian crossing by using an offset in the middle of a multi-lane intersection and accommodates pedestrians and bicyclists in pedestrian refuge island (see Figure 8.2). This configuration directs the pedestrians' attention towards the oncoming traffic before crossing the second half of the crosswalk. Bicyclists can also safely maneuver across the offset crossings since the crossing distances are minimized. A study revealed statistically significant increases in driver's yielding behavior and yield distance when Danish offsets were installed (Pulugurtha et al., 2012).

Design Considerations and Guidelines

1. Danish offsets should be considered at midblock crossings in urban areas with low to medium pedestrian volumes.
2. Roadways with four or more lanes with a traffic volume of more than 40,000 and a speed limit higher than 30 mph are appropriate candidates for this treatment.
3. Visually impaired pedestrians might be thrown off-course due to changes in the direction of the walkway. Therefore, proper detectable warnings or railings should be considered to realign them to the crosswalk.
4. The crossings should be staggered the width of the crosswalk.

Estimated Cost

Depending on the location and site conditions, the cost may be between $50,000 to $100,000.

8.4 Pedestrian Refuge Island

Pedestrian refuge islands are the most effective engineering treatment for ensuring safe street crossings. While a median separates the opposite flows of traffic with a continuous raised barrier, a pedestrian refuge island is shorter and placed only where pedestrian crossing occurs. Refuge islands allow for two-staged pedestrian crossing and reduce the exposure time for pedestrians from more than 20 seconds to just a few seconds. They result in reduced conflicts, reduced vehicular speed, and improved visibility of the pedestrian crossing. According to NCHRP Research Report 841, pedestrian refuge islands can reduce crashes by 32%.

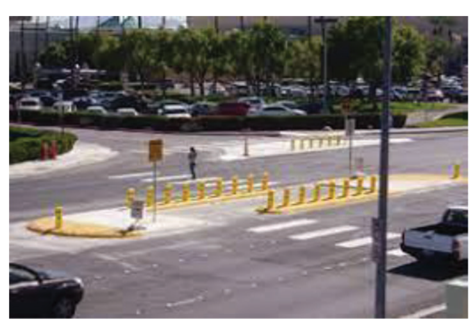

Figure 8.2 Danish offset (Science Applications International Corporation, 2009).

Design Considerations and Guidelines

1. Refuge islands are most appropriate for midblock pedestrian crossings on roads with four or more travel lanes where speed limits are 35 mph or greater or where the annual average daily traffic (AADT) is 9,000 or higher.
2. According to FHWA, uncontrolled pedestrian crossings on 2 or 3 lane roadways with high vehicular speed or volume are also suited for this treatment.
3. At midblock locations, they should be installed in conjunction with a high-visibility crosswalk.
4. The width of the refuge islands should be at least 4 ft (or preferably 10 ft) to accommodate the pedestrians intending to cross.
5. The cut-through must include detectable warnings if the island width is at least 6 ft.
6. If there is on-street parking, refuge islands may be installed in conjunction with curb extensions.
7. Refuge islands must be designed to allow drainage of stormwater and not cause ponding.
8. The approach edge of the refuge island should be outlined in retroreflective white or yellow material.
9. In areas with snow accumulation, reflective delineators shall mark the island for increased visibility to snowplow crews.

Estimated Cost

Depending on the construction materials, size, and location requirements, the cost ranges from $2,140 to $41,170 per island.

8.5 Curb Extensions

Curb extensions, also known as bulb-outs or neckdowns, serve as extensions to the sidewalk into the parking or travel lane at a corner or midblock (see Figure 8.3). Curb extensions improve safety for pedestrians by reducing pedestrian exposure to traffic through shortening crossing distance, enhancing sight distance, and provide additional space for street furniture, bike-sharing, and landscaping. Installation of pedestrian crossings with signed and marked curb ramps and extensions holds a crash modification factor (CMF) value of 0.63.

Applications

1. Offset curb extensions, also known as chicanes, when constructed on residential areas or low traffic volume downtown streets, can effectively slow traffic by curving the alignment of a straight roadway.
2. Midblock curb extensions or chokers can narrow the roadway by widening the curbs on both sides of the road at a midblock location. When they are used at intersections, they create a gateway effect.
3. Bus bulb-outs can be installed on crosswalks with a heavy pedestrian activity where on-street parking may obscure the driver's view of pedestrians.

Design Considerations and Guidelines

Figure 8.3 Curb extensions.

1. Curb extensions must only be considered on streets with on-street parking. According to FHWA, curb extensions should not extend more than 6 ft from the curb and should never encroach into travel lanes or bike lanes.
2. Curb extensions can be installed on arterials, collectors, and local roads. They are appropriate for any speed; however, an adequate distance between the curb extension and travel lane must be provided.
3. The width of the curb extension must be slightly less (typically 2 ft) than that of the parking lane. Curb extensions must be equal to the entire width of the crosswalk at a minimum. The width is typically between 6 and 8 ft.
4. Retroreflective vertical signs should be provided to alert oncoming traffic to the presence of curb extensions.
5. Curb extensions should be implemented preferably at the downstream side of the catch basin to enable proper drainage of stormwater.
6. If installed near a fire hydrant, the length of the curb extension should be equal to No Parking Zone. Moving the fire hydrant onto the curb extension will also ensure improved access by emergency services.
7. Edge treatments or objects must be used around the edges of the curb extensions to ensure better visibility and a better sense of enclosure. For example, the street edge should be red when curb extensions are installed on light-colored sidewalks.
8. Maintenance requirements, for example, street sweeping and snow removal, should be considered while designing curb extensions.
9. Curb extensions may not be appropriate at locations where frequent right turn maneuvers are undertaken by buses or trucks.

Estimated Cost

Depending on site conditions and requirements, curb extension costs range from $2,000 to $20,000 each. Facilitating proper drainage can significantly raise this cost.

8.6 Road Diets

Road diets or lane reductions remove travel lanes from the roadway and utilize the space for other purposes such as pedestrian refuge island, curb extensions, on-street parking, bicycle/transit lane (see Figure 8.4). The reduction in travel lane decreases the crossing distance between sidewalks and also reduce vehicle speeds. Road diets are usually distinguished by painted road markings or raised center islands.

Figure 8.4 Road diets.

Figure 8.5 Speed cushions (Source: NACTO, n.d.).

According to FHWA, road diets result in an overall crash reduction of 19% to 47%.

Design Considerations and Guidelines

1. Road diets are most appropriate for roadways with broad cross-sections, one-way streets with excess capacity, and roadways with ADT of 20,000 vehicles per day or less.
2. FHWA's *Road Diet Informational Guide* recommends that the following factors are required to be considered before implementing a road diet: vehicle speed, level of service (LOS), peak hour, and peak direction traffic flow (at or below 750 vehicles per hour per direction), freight usage, vehicle turning volumes and patterns, frequency stopping and slow-moving cars.
3. The impact of alternative routes should be considered before implementing road diets.
4. Road diets with raised medians and left-turn bays should be considered to eliminate the potential for Two-Way Left Turn Lane (TWLTL) to be used as acceleration lanes by some motorists.
5. Pedestrian safety can be improved by adding sidewalks or a shoulder.
6. Generally, travel lane widths are narrowed to no more than 10 ft and left storage lanes to 9 or 10 ft.

Estimated Cost

A road diet is a very effective but relatively low-cost countermeasure if only pavement marking reconfigures the road. However, geometric treatments like pedestrian refuge islands, curb extensions, sidewalks may increase the cost to $100,000 per mile.

8.7 Speed Cushion

Speed cushions are speed humps that feature wheel cutouts to allow large vehicles to pass undisturbed while reducing passenger car speeds (see Figure 8.5). They may be offset to allow unobstructed passage by emergency vehicles and are usually utilized on critical emergency response routes. Speed cushions or speed humps have a crash modification factor (CMF) of 0.50.

Design Considerations and Guidelines

1. Speed cushions are appropriate for local streets or collectors where the posted speed limit is 30 mph or less and ADT is less than 4,000 vehicles per day.
2. They should be placed at midblock locations, 150 ft away from an unsignalized intersection and 250 ft from a signalized intersection.
3. Speed Cushions shall be supplemented by a sign warning the drivers (MUTCD W17-1).
4. Vertical speed control elements should be designed based on the following criteria: slopes should not exceed 1:10 or be less steep than 1:25, side slopes on tapers should be no greater than 1:6, the vertical lip should be no more than a quarter-inch high.
5. Speed cushions are located where there is sufficient visibility and available lighting.

Estimated Cost

Speed cushions approximately cost $2,000 each.

8.8 Curb Radius Reduction

While the actual curb radius indicates the exact curvature along a road's curb line, effective curb radius is the curvature that vehicles follow during turning maneuvers. Curb radius design is based primarily upon the design vehicle. Large curb radii allow motorists to take high-speed turning maneuvers and risk pedestrian-vehicle collision by right-turning vehicles. Conversely, motorists slow down to take sharper turns when smaller curb radii are used, sight distances improve, and crossing distance for pedestrians shortens.

Design Considerations and Guidelines

1. Curb radii reduction is generally considered when the functional class of a road has been reduced.
2. According to FHWA, actual curb radii of 5 to 10 ft should be used, whereas effective curb radii for urban streets should be maintained between 15 and 20 ft. For arterial roads with a high percentage of larger vehicles, this can be extended up to 30 ft.
3. As actual curb radii shall be calculated based on effective curb radii, to accommodate larger vehicles, considerations should be given to the following factors to achieve larger effective curb radii: adding on-street parking or bike lanes, angle of intersections, presence of curb extension, lane width, turning speed.
4. Creating a compound curve by reducing curb radius as they approach a crosswalk and increasing after the crosswalk to allow for turn maneuvers can also improve safety at the corner.

Estimated Cost

Depending on site conditions (existing turning radii, drainage, and utilities), construction cost range from approximately $15,000 to $40,000 per corner.

8.9 Illumination

Sufficient quality and lighting design can improve an ambiance and enhance convenience and health. Drivers may fail to see pedestrians in time to stop without enough illumination. For the approaching driver, streetlights placed on both sides of arterial streets are safest and provide a precise illumination degree along a roadway. A study conducted by the Virginia Tech Transportation Institute revealed that 20 lx (a lighting unit) was required for a motorist to detect a pedestrian in the crosswalk. The luminaire should be positioned 10 ft from the crosswalk to achieve 20 lx between the approaching vehicles and the crosswalk.

Specialty pedestrian-level lighting can be installed over commercial or downtown sidewalks to enhance pedestrians' convenience, accessibility, and safety. As a result, people feel comfortable walking through a well-lit area in a city. In addition, clearer or extra lighting at night can augment pedestrian crossing areas.

Design Considerations and Guidelines

1. Streetlights should be installed on both sides of wide streets and streets in downtown areas.
2. A uniform lighting level should be achieved.
3. Streetlights should be positioned in front of midblock crossings and intersecting crosswalks on both approaches to highlight the front of the pedestrian and prevent producing a shadow.

8.10 Bus Stop Location

Pedestrians are more likely to cross streets while walking to and from transit stops. Therefore, the bus stops should be installed at appropriate intervals to prevent a street crossing at unmarked mid-block locations (especially on multi-lane highways) and ensure convenience for passengers. Installation of bus stops at intersections is most feasible as intersections are more favorable for passengers to intercept other transit transfers, reach crosswalks, and link to pedestrian routes. Bus stops should be set forward a minimum of 5 ft from crosswalks; where feasible, 10 ft is preferred.

Design Considerations and Guidelines

1. Transit stops should be connected to the sidewalk network, or where sidewalks are absent, to the nearest intersection or destination land use through a short sidewalk connection.
2. It is to be ensured that transit users do not have to go significantly out of their way to access transit stops by placing transit stops near the intersection of mid-block crossings where intersections are spaced far apart.
3. Bus stops should be placed on the far side of intersections. This measure allows pedestrians to cross the street behind the bus where they are more accessible for proximity to traffic, eliminating bus delays and mitigating conflicts between right-turning vehicles and buses.
4. Pedestrian crossings adjacent to transit stops must integrate alternative treatments such as refuge islands, high visibility crosswalks, curb extensions, active warning signals, and warning signage where a signal is not warranted.
5. Crosswalks should be placed behind bus stops at mid-block crossings so that oncoming motorists can see the pedestrian.
6. Other factors to take into consideration when selecting a bus stop location include available curbside space, conditions of sidewalks, the width of sidewalks, Average Daily Traffic (ADT), the number and width of travels lanes, speed, turning movements, sight distances, parking, bicycle facilities, and crosswalks.

8.11 Pedestrian Overpass/Underpass

A pedestrian overpass or underpass refers to a grade-separated pedestrian facility (typically, a bridge or tunnel structure) built over or under a major highway or railroad that allows safe continuous pedestrian flow. Although effective, these are costly and should only be considered as a last resort.

Design Considerations and Guidelines

1. A pedestrian overpass or underpass is most appropriate when pedestrians must cross high-speed, high-volume arterials or freeways.
2. The width of the overpass should be at least 8 ft. Although in case the sidewalk leading up to the overpass is wider, the width should be increased.
3. Underpass width should be between 14 ft and 16 ft. However, if the tunnel is longer than 60 ft, the width may be increased.
4. According to ADA, overpass and underpass must be accessible to all persons. Long ramps should be considered to make wheelchairs accessible on either end of the overpass.

Estimated Cost

Depending on site conditions, underpass construction costs around $120 per square foot, while overpass construction cost ranges from $150 to $250 per square foot.

8.12 Advanced Yield/Stop Lines

Advanced yield or stop lines include stop or yield markings placed in advance of marked crosswalks to warn the approaching traffic to stop or yield (see Figure 8.6). It prevents drivers from stopping too close to crosswalks and obscuring drivers' view of pedestrians and pedestrians' view of drivers. An AASHTO (2012) study revealed that advanced yield or stop line, when used with accompanying signs (signs R1-6, R1-6a, R1-9, and R1-9a), reduced conflict of this type by 90% compared to baseline level.

Figure 8.6 Advance yield lines at a midblock crossing (Source: Toole Design Group, as cited in Pedsafe, n.d.).

Design Considerations and Guidelines

1. Advanced stop/yield lines should not be placed too far in advance of a crosswalk as this might discourage drivers from complying with the marks and signs.
2. Section 3B.16 of the *MUTCD* specifies that the yield lines or stop lines should be placed 20 to 50 ft before the marked crosswalk in uncontrolled locations. In this case, on-street parking shall be prohibited between the yield or stop line and the crosswalk to increase visibility.
3. It is recommended that the yield or stop lines be accompanied with "STOP Here for Pedestrians" or "YIELD Here to Pedestrians" (signs R1-6, R1-6a, R1-9, and R1-9a) signs.

Estimated Cost

The cost for each advanced yield or stop markings and signs are respectively $300 and $320 approximately.

8.13 In-Street Pedestrian Crossing Signs

The in-street pedestrian crossing sign (MUTCD R1-6 or R1-6a) can be placed in the roadway on the road's centerline or in a median at uncontrolled intersections (see Figure 8.7). The sign's dimensions are 12" × 44", and the color is a fluorescent yellow-green diamond sheeting with 10" × 24" white high-intensity sheeting inserts. The purpose of this sign is to warn road users of laws concerning the right-of-way of pedestrians. Upon utilization of this sign, the city of Madison, Wisconsin, found that the number of drivers yielding to pedestrians increased from 6% to 15%.

Design Considerations and Guidelines

1. In-street pedestrian signs should only be considered on multi-lane roads at unsignalized intersections where the speed limit is 30 mph or less.
2. Turning movements, lane width, and bus routes are essential factors in determining the location for sign placement.
3. It is preferable to install the signs on raised medians since they may be susceptible to knockdowns by vehicles. In

Figure 8.7 In-street pedestrian crossing sign (Source: Pexco, n.d.).

addition, the sign must comply with AASHTO breakaway requirements if placed in the roadway.
4. The sign may be used seasonally to prevent damage in winter due to snow plowing operations.

Estimated Cost

The signs cost $240 each.

8.14 Puffin Crossing

Puffin stands for Pedestrian User-Friendly Intelligent Intersection. Puffin signal uses active detection and passive presence of pedestrians to determine whether the pedestrian phase of the traffic signal should be canceled or extended (see Figure 8.8). It provides adequate timing for pedestrian crossing, especially for slower pedestrians at crosswalks. The two sensors used in this system are placed on top of the traffic lights (pedestrian crossing detector and pedestrian curb detector). When a pedestrian presses the push button to cross the street, the curbside sensor can monitor pedestrian presence at the crossing. The pedestrian walks away from the detection area, and the request will be automatically canceled. The on-street crossing detector ensures the WALK phase remains until the pedestrian completes the crossing maneuver. Puffin crossing reduces crashes by 19% (Maxwell et al., 2011).

Design Considerations and Guidelines

1. Puffin crossing is most applicable at signalized intersections with high bus flows, and a high frequency of

Figure 8.8 Puffin crossing.

slower-moving pedestrians is anticipated, especially near senior centers or hospitals. However, it can be used wherever deemed necessary.
2. The puffin crossing may be used in conjunction with Pedestrian hybrid beacons (HAWK).
3. The delay time, after which the request is canceled if the curb-side detector does not detect a pedestrian, should be set between 2–4 seconds.

Estimated Cost

When used in conjunction with pedestrian hybrid beacon, Puffin crossing may cost around \$80,000 to \$150,000.

8.15 Flashing Yellow Arrow Left Turn Signal

Turn signals improve safety for pedestrians and bicyclists and also ensure greater mobility for motorists (see Figure 8.9). Flashing yellow arrow left-turn signals are mounted over left-turn lanes at signalized intersections. The flashing yellow arrow indicates YIELD to oncoming traffic and pedestrians and then proceed with caution. It is used in place of the standard circular green indicator for left turns. A National Cooperative Highway Research Program (NCHRP) study showed drivers understand and comply with flashing yellow arrow (FYA) left-turn arrows more than traditional yield-on-green indications. They also prove to reduce crashes by 25% while reducing delay. The crash modification factor is 0.857 for left-turn crash types for FYA when used with supplemental traffic signs.

A flashing yellow arrow signal indicates a *permissive* phase where drivers may take left turns if there are no pedestrians, bicyclists, or oncoming through traffic. The flashing yellow arrow signal may be used before or after the protected green or solid yellow arrows to improve traffic flow.

Design Considerations and Guidelines

1. Flashing yellow arrow (FYA) signal should be considered for protective-permissive left-turn phasing. Monitoring the crash data in the area for at least 1 year after installation of FYA is required.
2. Signalized intersections with the following characteristics are typically considered for FYA installation: one left turn lane per approach, three or fewer through lanes, low-speed limit, low traffic volume, adequate driver sight distance of oncoming traffic.
3. The flashing YELLOW ARROW indication is displayed while adjacent through signals displays a steady circular RED light.
4. Before installing or converting an intersection to FYA left-turn operations, it will be necessary to ensure adequate field wiring. The signal controller cabinet has sufficient channels (load switches), and the controller and Malfunction Management Unit (load switches–MMU) are capable of FYA operation.
5. The *MUTCD* (2011) does not recommend any supplemental signs. However, a “Left-Turn Signal–Yield on Flashing Arrow” (R10-17T) sign should be installed adjacent to the signal head for clarification.

Estimated Cost

Adjustment of existing signal phasing/timing settings is a meager cost. However, installing new signal equipment may range from \$8,000 to \$150,000, depending on the item requirements.

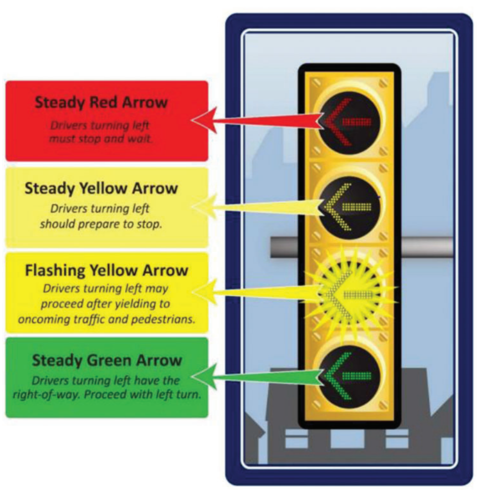

Figure 8.9 Typical configuration of FYA signal (Source: PennDOT, n.d.).

8.16 Pedestrian Hybrid Beacon

A Pedestrian Hybrid Beacon (PHB), also known as HAWK, is a hybrid beacon installed at unsignalized locations to warn oncoming traffic and facilitate pedestrian crossings at marked crosswalks (see Figure 8.10). A Federal Highway Administration (FHWA) study in 2010 (Fitzpatrick & Park, 2010) found that the installation of pedestrian hybrid beacons resulted in a 69% reduction in pedestrian crashes. They effectively reduce rear-end collisions and multiple-threat crashes and alert inattentive drivers about the presence of pedestrians at crosswalks. PHBs are appropriate at locations where traffic signals are not warranted or considered.

The pedestrian push button can activate the PHB signal. Upon activation, the PHB signal begins flashing yellow light to warn oncoming traffic. The flashing

Figure 8.10 Pedestrian hybrid beacon (Source: Michigan Complete Streets Coalition, 2013).

yellow signal is followed by a steady yellow signal and then by a constant red signal. Next, the WALK signal activates for pedestrians while the steady red is displayed to motorists. When the WALK phase ends, the flashing DON'T WALK phase begins for pedestrians, and PHB displays flashing red lights to motorists. The flashing red lights indicate that motorists should yield or stop pedestrians in the crosswalk and may proceed once pedestrians are clear.

Design Considerations and Guidelines

1. A PHB should be installed in conjunction with pedestrian push buttons and an overhead sign labeled "CROSSWALK STOP ON RED" (R10-23 sign) at a marked crosswalk in busy unsignalized locations including mid-block crossings.
2. According to FHWA, PHBs should be considered at major streets with three or more lanes with an annual average daily traffic (AADT) greater than 9,000.
3. PHB is a strong candidate countermeasure for all unsignalized pedestrian crossings where the roadway speed limit is equal to or greater than 40 mph.
4. At least two hybrid beacons are required to be installed for each approach of the main street.
5. A stop line must be placed before each approach to the crosswalk.
6. Parking and other sight obstructions should be prohibited for at least 100 ft in advance and 20 ft beyond the marked crosswalk to provide adequate sight distance. Otherwise, curb extensions may be considered to allow for improved sight distance.
7. According to *MUTCD* standard design guidance, the steady yellow signal should last between 3–6 seconds.
8. If installed on roads with coordinated traffic signals, the *MUTCD* recommends that PHB be coordinated with the other signals.

Estimated Cost

The cost of pedestrian hybrid beacons ranges from $21,000 to $128,000 depending on the location characteristics, speed limits, engineering constraints, and other factors. Signals suspended by span wire are less expensive, and signals attached to a mast arm are generally more expensive. Poles need foundations, each beacon needs metal box holding electrical equipment and typically wires get laid underground which results in higher cost.

8.17 Rectangular Rapid Flashing Beacon

Rectangular Rapid Flashing Beacons (RRFB) are pedestrian actuated devices that effectively improve visibility and driver's yield rates at uncontrolled locations, unsignalized intersections, and mid-block pedestrian crossings (see Figure 8.11). RRFBs use high-intensity amber LED lights that flash quickly, and thus, they are easily noticeable when nighttime lighting conditions deteriorate due to headlight glare and inclement weather. An NCHRP research report in 2017 found that RRFBs reduce pedestrian crashes by 47%.

RRFBs are only activated with pedestrian pushbuttons or automated pedestrian detection (i.e., camera or infrared sensors). They are installed on both sides of the marked crosswalks below the pedestrian crossing sign. Also, they shall be equipped to provide 75 flashing sequences per minute.

Figure 8.11 Rectangular rapid flashing beacon (RRFB).

Design Considerations and Guidelines

1. According to the exiting guidelines, RRFBs should be considered on multilane urban roads with speed limits equal or greater than 35 mph. INDOT's initial experience with RRFBs installed in such conditions was not favorable. Drivers may have had difficulty seeing the activated device across multiple lanes.
2. There are examples of RRFB installations on urban local two-lane roads where pedestrian crossing activity is considerable. RRFB is recommended where a minimum of 20 pedestrians per hour is expected.
3. According to *MUTCD*, RRFBs must be used in conjunction with W11-2 (Pedestrian), S1-1 (School), or W11-15 (Trail) crossing warning signs with a diagonal downward arrow (W16-7P) plaque, or an overhead-mounted W11-2, S1-1, or W11-15 crossing warning sign. In addition, for push-button actuated RRFBs, a Push Button To Turn On Warning Lights (R10-25) sign shall also be provided.
4. An automatic signal dimming device should be provided to reduce excessive glare during nighttime.
5. Section 4E.06 of the 2009 MUTCD should be followed for the appropriate duration of a predetermined period of operation of RRFBs.
6. In the presence of a pedestrian refuge island or median, RRFB is advised to be installed on the median.
7. The power source may be either hard-wired or solar-powered.

Estimated Cost

Depending on the locations, the cost of installation of RRFBs range from $4,500 to $52,000.

8.18 Leading Pedestrian Interval

Leading Pedestrian Interval (LPI) gives the pedestrians a WALK signal 3–7 seconds before the drivers proceed through the intersection. LPI can help increase crossing pedestrians' visibility and minimize traffic conflicts between pedestrians crossing the roadway and a vehicle turning left or right. LPIs also increase drivers' yield rate as pedestrians establish their presence in the crosswalk when the traffic signal turns green for parallel vehicle movements. According to FHWA, LPIs can reduce pedestrian-vehicle crashes by 13%.

Design Considerations and Guidelines

1. LPIs should be considered where consistent conflicts are prevalent between turning vehicles and pedestrians. Roadways with a speed limit of 45 mph or less, low to medium-high traffic volume (<10,000–25,000 ADT), and one or more lanes should be considered.
2. Depending on the crossing distance, LPIs should give a head start of 3–7 seconds. However, intervals up to 10 seconds may be considered if the crossing distance is more considerable with high pedestrian volume.
3. The visibility of pedestrians can be further improved with the installation of a curb extension at the intersection.
4. Right, Turn on Red should be restricted as this may affect the effectiveness of LPIs.
5. The use of accessible pedestrian signals (MUTCD Section 4E.09 through 4E.13) should be considered.

Estimated Cost

Alteration of signal timing is very inexpensive; it usually ranges from $0 to $3,500 depending on the location and size of the city.

8.19 Exclusive Pedestrian Signal (Pedestrian Scramble)

An exclusive pedestrian phase is a portion of a traffic signal cycle reserved for pedestrian movements while displaying red on all traffic signals for vehicles. Complete phasing is often considered for intersections in downtown areas or central business districts with high pedestrian volumes. The cycle length must be lengthened, or other phase lengths in the signal cycle must be shortened to add an exclusive pedestrian phase to the overall traffic signal cycle. Compared with concurrent signal phasing or none at all, exclusive pedestrian phasing yields measurable reductions in collisions only when pedestrian volume exceeds 1,200 persons per day (Zegeer et al., 2002).

Design Considerations and Guidelines

1. An exclusive pedestrian signal should be considered when conflicting turning vehicle volumes are equal to or greater than 250 vehicles per hour, pedestrian volume is very high (more than 1,000 pedestrians per hour) during at least 4 hours a day, intersections are predominantly used by the elderly, children, and hospital patients.
2. Incorporating an exclusive phase for pedestrians may decrease the intersection's capacity and increase delays for motorized vehicles and pedestrians. Therefore, more minor intersections with exclusive pedestrian phasing will result in fewer vehicular delays.
3. The total intersection approach volume is recommended to be less than 2,000 vehicles per total approach per hour.
4. Caution is recommended in selecting intersections for an exclusive pedestrian phase where both streets are two ways or exclusive left turn or right turn phases.

Estimated Cost

Alteration of signal timing is very inexpensive; it usually ranges from $0 to $3,500 depending on the location and size of the city.

8.20 Smart Lighting

Smart lighting strategy aims to increase the intensity of illumination at the crosswalk once a pedestrian is detected in the crosswalk. The sudden increase in lighting intensity alerts motorists that pedestrians are in crosswalks more than when continuous intensity light is used in the crosswalk. Adaptive street lighting dims when no activity is detected.

Streetlights can be made intelligent by placing cameras or other sensors on them to detect movement. For example, when a camera or sensor detects a passer-by, it will communicate this to neighboring streetlights, and they will brighten so that a safe circle of light always surrounds people. In addition, intelligent LED-based lighting can reduce energy costs up to 70%.

Design Considerations and Guidelines

When implementing intelligent or adaptive lighting, the following factors should be considered: traffic volume, speed limit, conflict or crash characteristics, pedestrian volume, ambient luminance, roadway characteristics.

1. Illumination should be designed so that pedestrians when crossing the road is highly visible and glare is minimized for motorists.
2. The potential for conflict increases with additional pedestrians. The lighting levels should therefore be increased with other pedestrian presence.
3. *Design Criteria for Adaptive Roadway Lighting* by FHWA should be used as a reference to achieve adequate lighting conditions.

8.21 In-Roadway Warning Lights

In-roadway warning lights are embedded in the pavement's surface to warn oncoming traffic about the presence of pedestrians crossing ahead and indicates to slow down or yield (see Figure 8.12). According to *MUTCD 2009* (FHWA, 2009), they are only considered in marked crosswalks on uncontrolled approaches and should not be used in crosswalks controlled by YIELD, STOP, or traffic signals. In-roadway lights improve the nighttime visibility of pedestrians, increase the rate of drivers yielding to pedestrians, and decrease the rate of traffic conflicts. (Hakkert et al., 2001).

Design Considerations and Guidelines

1. In-roadway warning lights may be considered in marked crosswalks at uncontrolled intersections where high pedestrian activity is expected, especially at night.
2. The lights may be activated based on pedestrian actuation in two ways: traditional push buttons and an automatic pedestrian detection system. According to

Figure 8.12 In-roadway lights in a northern Virginia suburb (photo by Ted Shafer; Miller et al., 2004).

MUTCD 2009, a "Push Button to Turn on Warning Lights" (with pushbutton symbol) (R10-25) sign should be mounted adjacent or integral with each pedestrian pushbutton (FHWA, 2009).

3. A flashing yellow light at the rate of at least 50 but no more than 60 flash periods per minute shall be displayed when actuated.
4. On two-lane roadways, at least three in-roadway warning lights shall be installed along both sides of the crosswalk. On roads with more than two lanes, at least one in-roadway warning light per lane shall be installed along both sides of the crosswalk.
5. Proper maintenance is required as the lights might drift out of alignment over time.

Estimated Cost

In-roadway warning lights can be expensive to install and maintain and only should be installed after considering other feasible solutions. The installation cost of the in-roadway warning light system ranges from $6,480 to $40,000.

8.22 LED Border Enhanced Traffic Warning Signs

LED border enhanced traffic warning signs involve automatic detection of pedestrians and activation of LED lights on the border of the warning sign (see Figure 8.13). This system warns the motorists to slow down and encourage them to yield to pedestrians, especially during nighttime. LED signage reinforces existing traffic control and pedestrian warning measures without the need to install additional beacons or expensive over-hanging equipment. The LEDs can be embedded on the border of MUTCD W11-2 (Pedestrian Crossing Sign), S1-1 (School Crossing Sign), R1-1-B (Stop Sign). The sign may be pushbutton activated or activated with passive detection (pedestrian detection bollards, infrared motion sensors, or RADS). They can be either solar-powered or hard-wired.

Design Considerations and Guidelines

1. LED border enhanced traffic warning signs should be considered at intersections where a high volume of pedestrians is anticipated during nighttime.

Figure 8.13 LED border enhanced traffic warning sign (Electrotechnics Corporation, n.d.).

2. If flashed, all LED units shall flash simultaneously at a rate of more than 50 and less than 60 times per minute.
3. An audible warning tone might also be included in the system to alert pedestrians that the system has been activated. Audible warning tones are to be considered at crosswalks longer than 70 ft, crosswalks that are skewed, intersections with irregular geometry such as five or more legs or at crossings where it is advised to include an audible warning beacon. Audible warning may not appropriate at sites with channelized turns or split phasing since the signal may cause confusion if hear at wrong crosswalks.

8.23 Automated Pedestrian Detection

In this system, pedestrian presence is sensed using a pressure-sensitive mat, video detectors, ultrasonic radar, microwave radar, or infrared detector mounted above the crossing location. When the device senses a pedestrian waiting at the crosswalk, it automatically sends a signal to switch to a pedestrian WALK phase.

Studies have shown that many pedestrians ignore the button or believe that the switch is malfunctioning if there is a significant delay in receiving a signal (Hughes et al., 2000). Visually impaired pedestrians also might not know that pushing a button to cross the roadway is necessary. Therefore, automated pedestrian detection results in a significant decrease in vehicle-pedestrian conflicts. Also, the percent of pedestrian crossings initiated during the DON'T WALK phase.

Design Considerations and Guidelines

1. The locations where this system may be installed should be considered carefully by examining factors such as pedestrian volume at nighttime, ambient luminance, the speed limit.
2. A buffer area that separates the sidewalk and the street may reduce the number of false accusations from pedestrians walking along the sidewalk who do not intend to cross the street.
3. The sensors should be considered primarily at midblock crossings with no problem with right-turning vehicles giving false signals.

Estimated Cost

Adding automated detectors to an existing pedestrian signal can range from $10,000 to $70,000 per crosswalk.

9. BENEFIT-COST ANALYSIS

Potential pedestrian safety countermeasures are evaluated by conducting a benefit-cost analysis. First, the safety benefits and construction costs are converted to monetary value to facilitate their comparison in such a study. Then, a benefit-cost ratio (BCR) indicator is used to summarize the overall attractiveness of implementing a potential countermeasure.

$$BCR = \frac{(1 - CMF)\sum_i (C_i \cdot N_i)}{C} \quad \text{(Eq. 9.1)}$$

where:

- BCR is the benefit-cost ratio indicator.
- CMF is the countermeasure's crash modification factor.
- Ci is the unit crash cost at the i^{th} severity level (see Table 6.5).
- Ni is the expected number of crashes at the i^{th} severity level during the countermeasure expected lifetime.
- C is the sum of all costs associated with implementing and maintaining the countermeasure.

The BCR should be greater than 1 for a countermeasure to be labeled as attractive. Any BCR values below one will not produce a return on the investment.

The countermeasure costs primarily include several components: construction costs, environmental costs, planning, design costs, and routinary maintenance costs. Such cost components need to be considered thorough the service life of the countermeasure. In addition, in more rigorous benefits-cost analysis applications, societal costs such as health care costs, pain, and suffering, and insurance costs and benefits should also be considered and quantified.

To illustrate this method, a sample calculation is presented below.

Sample Calculation

Step 1. Estimate the expected number of crashes at the target intersection. To do so, we calculate the predicted annual probability of crash as described in Sections 6.2 and 6.4. This probability is then multiplied by the number of years in the analysis period (countermeasure lifetime).

$$N_{total} = \Pr(Crash) * Y = 0.1853 * 3 = 0.5559$$

Step 2. Allocate the expected number of crashes to specific injury severity levels. This step follows the procedure described in Section 6.3 and 6.4.

$$N_{pdo} = N_{total} * \Pr(PDO) = 0.5559 * 0.3732 = 0.2075$$

$$N_{nin} = N_{total} * \Pr(Noincap) = 0.5559 * 0.3235 = 0.1798$$

$$N_{inc} = N_{total} * \Pr(Incap) = 0.5559 * 0.2613 = 0.1453$$

$$N_{fat} = N_{total} * \Pr(Fatal) = 0.5559 * 0.0420 = 0.0233$$

Step 3. Calculate the total safety benefits by multiplying the expected number of crashes by severity level with their corresponding unit crash costs (see Table 6.5).

$$\sum_i C_i * N_i = (\$23{,}854 * 0.2075) + (\$367{,}627 * 0.1798) + (\$1{,}320{,}006 * 0.1453) + (\$9{,}048{,}774 * 0.0233) = \$473{,}682.35$$

Step 4. Determine the CMF and total cost of the candidate pedestrian countermeasure. In this example, the recommended countermeasure is a *pedestrian refuge island with a marked crosswalk*.

Average installation cost = $22,405.

Average annual maintenance cost = $6,000.

Crash Modification Factor (CMF) = 0.54.

Step 5. Calculate the BCR indicator as described in Equation 9.1 and assess the countermeasure's economic feasibility.

$$BCR = \frac{(1 - 0.54)(\$473{,}682.35)}{\$22{,}405 + (\$6{,}000 * 3)} = 5.39$$

In conclusion, as the value of BCR is greater than 1, the countermeasure considered is feasible.

Note that the previous is an illustrative simplified example. The complete benefit-cost analysis should also consider traffic growth and changes due to inflation. The complete method is currently implemented in RoadHAT 4D.

10. CLOSURE

The presented research study was focused on the methodology helpful to identify roads and areas where the frequency and severity of pedestrian collisions are heightened above the acceptable level and on selecting effective methods of mitigating or eliminating these situations. The following two general forms of identifying specific pedestrian safety issues were proposed.

1. *Areawide analysis* of crash data from various angles and at different levels of spatial and temporal aggregation and with alterative safety level indicators to detect areas where certain conditions likely lead to an excessive number of pedestrian crashes. A suitable tool, SNAP, has been pointed out as the near-future means to implement this type of analysis. The research team is developing SNAP, and its first version should be available within several months.
2. *Road-focused analysis* that follows the general approach of Indiana safety management for all other types of crashes. The proposed management procedure focuses on crosswalks at urban intersections—the kind of spot identified in this project as contributing most to the pedestrian safety issue in Indiana. The developed models and procedures are ready for an envisioned implementation in RoadHAT 4D via an additional form specialized in analyzing pedestrian safety.

A set of models have been developed to facilitate the road-focused analysis: (a) pedestrian crossing activity level to fill the gap in pedestrian traffic data, and (b) probabilistic models to estimate the risk of pedestrian crashes around urban intersections. The first model addresses the primary challenge faced by similar studies in the past—the lack of pedestrian traffic data. This study reached for a new source of pedestrian data that has recently become available from *StreetLight*. An extensive effort was undertaken to extract the pedestrian data and land use data around studied intersections. A successful linking of the land use and other spatial features with the pedestrian crossing activities provided an unprecedented ability to estimate the pedestrian activity level around any urban intersection in Indiana.

The knowledge of the pedestrian activity level allowed the research team to separate the pedestrian exposure factor from other safety factors and develop crash probability and severity models that include properly estimated the effects of traffic, speed limits, built environment, COVID-19, and other factors. Consequently, the developed models help assess the risk of crash and severe injury, including fatality at any intersection in Indiana. This model provides a valuable tool to identify urban intersection segments for safety audits and improvements. The screening criteria include the crash cost calculated with the crash risk and severity models. The result is improved by combining it with the crash occurrence and its severity with the EB method adjusted to the probabilistic safety representation. The obtained crash probabilities and crash cost estimates are used for screening intersection segments for high-risk pedestrian locations.

The extensive literature review resulted in many potential pedestrian safety countermeasures with specific behavioral and road conditions that justify these countermeasures and help select the correct ones. Associated crash reduction factors and computational procedures enable predicting the economic effectiveness of proposed countermeasures. A computational process with required analytical elements and sources of needed data are documented in the research report.

The COVID-19 pandemic has changed the traffic of vehicles and pedestrians. Thus, the planned observations of road user behaviors related to pedestrian safety could not be conducted. Instead, the historical traffic and safety data were used to develop a method described in this report.

The mentioned SNAP will be developed within several months, and funds will be requested to expand the current RoadHAT 4D to incorporate the pedestrian safety analysis module. In addition, informational sessions at the Indiana Road School and special workshops for INDOT and local agencies will be considered in the post-study period. These events will be organized by the Center for Road Safety with the active involvement of delegated INDOT and LTAP personnel.

REFERENCES

AASHTO. (2012). *Guide for the development of bicycle safety*. American Association of State Highway and Transportation Officials.

Electrotechnics Corporation. (n.d.). *LED enhanced signs*. https://elteccorp.com/products/warning-systems/led-enhanced-signs/

FHWA. (2008). *Step-by-step guide - national pedestrian safety campaign*. Federal Highway Administration.

FHWA. (2009). *Manual on uniform traffic control devices for streets and highways* (2009 ed.). U.S. Department of Transportation, Federal Highway Administration.

Fitzpatrick, K., & Park, E. S. (2010). *Safety effectiveness of the HAWK pedestrian crossing treatment* (Report No. FHWA-HRT-10-0421). https://www.fhwa.dot.gov/publications/research/safety/10042/10042.pdf

Goughnour, E., Albee, M., Thomas, L., Gelinne, D., & Seymour, J. (2020, September). *Pedestrian and bicyclist road safety audit (RSA) guide and prompt lists* (Report No. FHWA-SA-20-042). https://safety.fhwa.dot.gov/ped_bike/tools_solve/docs/fhwasa20042.pdf

Hakkert, A. S., Gitelman, V., Cohen, A., Doveh, E., & Umansky, T. (2001). The evaluation of effects on driver behavior and accidents of concentrated general enforcement on interurban roads in Israel. *Accident Analysis and Prevention*, *33*(1), 43–63.

Hughes, R., Huang, H., Zegeer, C., & Cynecki, M. (2000). Automated detection of pedestrians in conjunction with standard pedestrian push buttons at signalized intersections. *Transportation Research Record: Journal of the Transportation Research Board*, *1705*(1), 32–39.

Indiana University Public Policy Institute. (2019). *Indiana crash facts 2019*. https://www.in.gov/cji/research/files/Indiana-Crash-Fact-Book-2019.pdf

Michigan Complete Streets Coalition. (2013, November 26). *Pedestrian hybrid beacons (HAWK signals) explained*. Retrieved February 21, 2022, from https://michigancompletestreets.wordpress.com/2013/11/26/pedestrian-hybrid-beacons-hawk-signals-explained/

Miller, S., Rousseau, G. K., & Do, A. H. (2004). Seeing crosswalks in a new light. *Public Roads*, *67*(4). Retrieved February 21, 2022, from https://highways.dot.gov/public-roads/januaryfebruary-2004/seeing-crosswalks-new-light

Millicent, S. (2016). *The 4 E's of road safety*. https://slideplayer.com/slide/13283161/

NACTO. (n.d.). *Speed cushion* [Webpage]. National Association of City Transportation Officials. Retrieved February 21, 2022, from https://nacto.org/publication/urban-street-design-guide/street-design-elements/vertical-speed-control-elements/speed-cushion/

NHTSA. (2019). *2019 Ranking of STATE pedestrian fatality rates - State*. National Highway Traffic Safety Administration. https://www-fars.nhtsa.dot.gov/states/statespedestrians.aspx

Pedsafe. (n.d.) *Advance yield/stop lines* [Webpage]. Federal Highway Administration. http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=13

PennDOT. (n.d.). *Traffic signals, management.* Pennsylvania Department of Transportation. Retrieved February 21, 2022, from https://www.penndot.gov/TravelInPA/TrafficSignalsManagement/Pages/default.aspx?fbclid=IwAR0p21hZleYNQsZESTzgyj3MZYzWeIR8lQuXN0gxaPdnkq7_UlTXnsPh6CU#.Vyuoy4QrKV4

Pexco. (n.d.). *Pedestrian crosswalk signs* [Webpage]. Retrieved February 21, 2022, from https://www.pexco.com/traffic/products/pedestrian-safety-products/in-street-pedestrian-crosswalk-signs/

Pulugurtha, S. S., Vasudevan, V., Nambisan, S. S., & Dangeti, M. R. (2012). Evaluating effectiveness of infrastructure-based countermeasures for pedestrian safety. *Transportation*

Research Record: Journal of the Transportation Research Board, *229*(1), 100–109.

Science Applications International Corporation. (2009). Pedestrian safety and ITS-based countermeasures program for reducing pedestrian fatalities, injury conflicts, and other surrogate measures draft zone/area-wide evaluation technical memorandum (Contract No. DTFH61-96-C-00098). https://safety.fhwa.dot.gov/ped_bike/tools_solve/ped_scdproj/sys_impact_rpt/sys_impact_rpt.pdf

Thomas, L., Sandt, L., Zegeer, C., Kumfer, W., Lang, K., Lan, B., Horowitz, Z., Butsick, A., Toole, J., & Schneider, R. J. (2018). *Systemic pedestrian safety analysis* (NCHRP Research Report 893). National Cooperative Highway Research Program. https://doi.org/10.17226/25255

U.S. Census Bureau. (2019). Chapter 12: The urban and rural classifications [PDF file]. In *Geographic Areas Reference Manual*. https://www2.census.gov/geo/pdfs/reference/GARM/Ch12GARM.pdf

Washington, S., Karlaftis, M., Mannering, F., & Anastasopoulos, P. (2020). *Statistical and econometric methods for transportation data analysis* (3rd ed.). Chapman and Hall/CRC.

Zegeer, C. V., Stewart, J. R., Huang, H. H., & Lagerwey, P. A. (2002). *Safety effects of marked versus unmarked crosswalks at uncontrolled locations: Executive summary and recommended guidelines* (Report No. FHWA-RD-01-075). University of North Carolina.

APPENDICES

Appendix A. Example Road-Focused Screening

Appendix B. City Centers

Appendix C. Crash Modification Factors and Crash Reduction Factors

Appendix D. Primary and Secondary Safety Factors

APPENDIX A. EXAMPLE ROAD-FOCUSED SCREENING

Table A.1 Top 50 Intersection Segments with Pedestrian Safety Needs Sorted by Cost of Crashes Expected (EB Estimates) in 2018–2020

Rank	Latitude	Longitude	Direction	Annual Crash Probability	Crash Cost	Crash Occurrence
1	41.0831	-85.13565	N_S	0.0857	$314,263.31	0
2	41.08114	-85.13508	N_S	0.0796	$292,989.46	0
3	41.07696	-85.13398	N_S	0.0790	$289,557.15	1
4	41.06068	-85.13305	N_S	0.0875	$289,431.91	1
5	41.08004	-85.13479	N_S	0.0775	$285,745.71	0
6	41.07900	-85.13449	N_S	0.0760	$277,258.90	0
7	39.76729	-86.16699	N_S	0.1441	$262,805.10	1
8	37.97354	-87.54378	N_S	0.0643	$262,402.22	1
9	39.76715	-86.16173	N_S	0.1382	$260,298.71	1
10	37.97001	-87.54368	N_S	0.0748	$258,609.52	1
11	41.05388	-85.13267	N_S	0.0804	$234,364.97	0
12	41.60097	-87.50894	N_S	0.0793	$221,734.83	1
13	41.63897	-87.44730	E_W	0.0776	$210,249.94	1
14	39.76729	-86.16699	E_W	0.1462	$210,163.43	0
15	39.76715	-86.16173	E_W	0.1656	$205,643.12	1
16	41.63902	-87.44968	E_W	0.0697	$203,563.15	1
17	41.59525	-87.50892	N_S	0.0678	$200,796.87	1
18	37.97764	-87.62785	E_W	0.0353	$183,996.54	1
19	41.63895	-87.44490	E_W	0.0681	$179,939.69	1
20	37.95108	-87.54242	N_S	0.0497	$177,889.85	1
21	41.63906	-87.45208	E_W	0.0646	$173,589.86	1
22	41.59187	-87.50895	N_S	0.0675	$170,010.37	1
23	41.05569	-85.13277	N_S	0.0408	$166,842.91	1

Rank	Latitude	Longitude	Direction	Annual Crash Probability	Crash Cost	Crash Occurrence
24	37.95559	-87.54221	N_S	0.0642	$166,301.00	1
25	40.41732	-86.89061	E_W	0.0548	$164,180.58	1
26	41.59548	-87.50893	N_S	0.0641	$163,682.12	0
27	41.03890	-85.13203	N_S	0.0676	$162,145.37	1
28	37.99952	-87.56076	E_W	0.0413	$160,208.72	1
29	41.09617	-85.13684	N_S	0.0682	$159,947.31	1
30	41.08065	-85.13837	N_S	0.0799	$155,783.37	1
31	41.07587	-85.14802	N_S	0.0453	$155,455.54	1
32	41.63907	-87.45446	E_W	0.0583	$153,435.18	1
33	41.07747	-85.13753	N_S	0.0412	$153,071.21	1
34	40.39553	-86.86678	E_W	0.0415	$151,994.71	0
35	41.60205	-87.33713	E_W	0.0469	$151,514.91	0
36	41.60205	-87.33713	N_S	0.0454	$151,359.17	1
37	41.05086	-85.13253	N_S	0.0377	$148,866.68	0
38	41.60652	-87.50891	N_S	0.0934	$147,074.06	0
39	41.04617	-85.13234	N_S	0.0696	$146,373.58	0
40	41.07606	-85.14676	E_W	0.0446	$141,461.79	1
41	41.60462	-87.50893	N_S	0.0889	$140,687.66	0
42	41.61458	-87.50886	N_S	0.0873	$140,141.06	0
43	37.97679	-87.51090	E_W	0.0437	$137,844.13	0
44	41.06681	-85.13333	N_S	0.0287	$136,469.97	1
45	41.66114	-86.18063	E_W	0.0464	$135,510.95	1
46	41.61029	-87.50891	N_S	0.0860	$135,145.69	0
47	41.63896	-87.44610	E_W	0.0360	$134,425.48	1
48	41.66963	-86.25021	N_S	0.0471	$134,206.14	1
49	40.39544	-86.87169	E_W	0.0529	$134,078.30	1
50	41.62919	-87.48083	N_S	0.0448	$132,582.54	1

Note: Crash costs expressed in 2019 U.S. dollars.

APPENDIX B. CITY CENTERS

This table shows the city centers for cities with more than 2,500 people in Indiana (2019).

Table B.1 Location of City Centers with Population > 2,500

City	Latitude	Longitude
Alexandria	40.2632	-85.6763
Anderson	40.10959	-85.677
Angola	41.6348	-84.9994
Attica	40.29	-87.24
Auburn	41.367	-85.0589
Aurora	39.057	-84.9013
Austin	38.7415	-85.806
Avon	39.7628	-86.3997
Bargersville	39.5209	-86.1678
Batesville	39.3	-85.21
Bedford	38.86	-86.49
Beech Grove	39.722	-86.09
Berne	40.6578	-84.9519
Bicknell	38.7742	-87.3078
Bloomington	39.16	-86.53
Bluffton	40.7387	-85.1716
Boonville	38.05	-87.27
Brazil	39.5237	-87.125
Bremen	41.4464	-86.1481
Bright	39.2184	-84.8561
Brookville	39.4231	-85.0127
Brownsburg	39.8434	-86.3978
Brownstown	38.8789	-86.0419
Butler	41.43	-84.87
Carmel	39.9784	-86.118
Cedar Lake	41.37	-87.44
Centerville	39.8178	-84.9964
Chandler	38.04	-87.37
Charlestown	38.4531	-85.6702
Chesterton	41.6	-87.05
Cicero	40.1239	-86.0133
Clarksville	38.2967	-85.76
Clinton	39.65698	-87.3981
Columbia City	41.16	-85.49
Columbus	39.21	-85.92
Connersville	39.66	-85.14
Corydon	38.212	-86.1219
Covington	40.14	-87.39
Crawfordsville	40.04	-86.9
Crown Point	41.41	-87.35
Cumberland	39.79	-85.95
Danville	39.76	-86.51
De Motte	41.2	-87.2
Decatur	40.83	-84.93
Delphi	40.58	-86.67
Dunlap	41.63	-85.92
Dyer	41.5	-87.51
East Chicago	41.65	-87.45
Edinburgh	39.35	-85.96
Elkhart	41.69	-85.97
Ellettsville	39.23	-86.62
Elwood	40.27	-85.84
Evansville	37.99	-87.54
Fairmount	40.42	-85.65
Fishers	39.96	-85.97
Fort Branch	38.25	-87.57
Fort Wayne	41.09	-85.14
Fortville	39.92	-85.85
Frankfort	40.28	-86.51
Franklin	39.49	-86.05
Garrett	41.35	-85.12
Gary	41.6	-87.35
Gas City	40.49	-85.6
Georgetown	38.3	-85.96
Goshen	41.57	-85.83
Granger	41.74	-86.14
Greencastle	39.64	-86.84
Greendale	39.13	-84.85
Greenfield	39.79	-85.77
Greensburg	39.35	-85.5
Greenwood	39.61	-86.11
Griffith	41.53	-87.42
Hammond	41.62	-87.49

Hanover	38.71	-85.47
Hartford City	40.45	-85.37
Hebron	41.32	-87.2
Highland	38.05	-87.56
Hobart	41.51	-87.27
Huntertown	41.21	-85.18
Huntingburg	38.3	-86.96
Huntington	40.88	-85.51
Indian Heights	40.42	-86.12
Indianapolis	39.77	-86.16
Jasper	38.39	-86.94
Jeffersonville	38.34	-85.7
Kendallville	41.44	-85.26
Knox	41.29	-86.62
Kokomo	40.48	-86.13
La Porte	41.61	-86.71
Lafayette	40.4	-86.86
Lagrange	41.65	-85.42
Lake Station	41.57	-87.26
Lakes of the Four Seasons	41.41	-87.22
Lawrence	39.87	-85.99
Lawrenceburg	39.1	-84.87
Lebanon	40.03	-86.45
Leo-Cedarville	41.22	-85.02
Ligonier	41.47	-85.59
Linton	39.04	-87.16
Logansport	40.75	-86.36
Loogootee	38.68	-86.91
Lowell	41.29	-87.42
Madison	38.76	-85.4
Marion	40.55	-85.66
Martinsville	39.42	-86.42
McCordsville	39.9	-85.92
Melody Hill	38.02	-87.51
Merrillville	41.47	-87.32
Michigan City	41.71	-86.88
Middlebury	41.67	-85.71
Mishawaka	41.67	-86.17
Mitchell	38.74	-86.47
Modoc	40.05	-85.13
Monticello	40.75	-86.77
Mooresville	39.6	-86.37
Mount Vernon	37.94	-87.9

Muncie	40.2	-85.39
Munster	41.55	-87.5
Nappanee	41.45	-86
New Albany	38.31	-85.82
New Castle	39.92	-85.37
New Haven	41.07	-85.03
New Palestine	39.72	-85.89
New Whiteland	39.56	-86.1
Newburgh	37.95	-87.4
Noblesville	40.04	-86.01
North Manchester	41	-85.78
North Terre Haute	39.54	-87.37
North Vernon	39.02	-85.63
Ossian	40.88	-85.17
Paoli	38.56	-86.47
Pendleton	40.01	-85.76
Peru	40.76	-86.07
Pittsboro	39.87	-86.46
Plainfield	39.7	-86.37
Plymouth	41.35	-86.32
Portage	41.59	-87.18
Porter	41.63	-87.08
Portland	40.44	-84.98
Princeton	38.36	-87.58
Rensselaer	40.94	-87.15
Richmond	39.83	-84.89
Rochester	41.06	-86.2
Roselawn	41.15	-87.29
Rushville	39.62	-85.45
Salem	38.6	-86.1
Schererville	41.49	-87.44
Scottsburg	38.69	-85.78
Sellersburg	38.39	-85.76
Seymour	38.95	-85.89
Shelbyville	39.53	-85.78
Sheridan	40.13	-86.22
Simonton Lake	41.75	-85.97
South Bend	41.68	-86.27
South Haven	41.54	-87.14
Speedway	39.79	-86.25

St. John	41.44	-87.47
Sullivan	39.1	-87.41
Syracuse	41.42	-85.75
Tell City	37.95	-86.76
Terre Haute	39.47	-87.38
Tipton	40.28	-86.04
Union City	40.2	-84.82
Upland	40.46	-85.5
Valparaiso	41.48	-87.05
Vevay	38.74	-85.08
Vincennes	38.68	-87.51
Wabash	40.8	-85.83
Warsaw	41.24	-85.85
Washington	38.66	-87.17
West Lafayette	40.46	-86.91
Westfield	40.03	-86.15
Westville	41.54	-86.91
Whiteland	39.55	-86.08
Whitestown	39.96	-86.37
Whiting	41.68	-87.48
Winchester	40.17	-84.98
Winfield	41.41	-87.26
Winona Lake	41.22	-85.81
Yorktown	40.19	-85.48
Zionsville	39.96	-86.27

APPENDIX C. CRASH MODIFICATION FACTORS AND CRASH REDUCTION FACTORS

Table C.1 Inventory of Pedestrian Safety Countermeasures

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF (%)	CMF	States and (Reference Number)
Pedestrians	Installation of pedestrian crossings with signed and marked curb ramps and extension	Not specified	Not specified	Pedestrian	37	0.63	
Pedestrians	Flashing Yellow Arrow Left Turn Signal when used with supplemental traffic signs	Urban	All	Left turn	14	0.86	IL
Pedestrians	Install advanced yield or stop markings and signs	Urban and Suburban		Pedestrian	25	0.75	
Pedestrians	Install a hybrid pedestrian beacon (PHB or HAWK)	Urban and Suburban	Minor Arterial	Pedestrian	55	0.45	–
Pedestrians	Install raised pedestrian crosswalks	Urban and Suburban	Not Specified	Pedestrian	45	0.55	
Pedestrians	Install rectangular rapid flashing beacon (RRFB)	Urban and Suburban	Minor Arterial	Pedestrian	47	0.53	AZ, FL, IL, MA, NY, NC, OR, VA, WI
Pedestrians	Modify signal phasing (implement a leading pedestrian interval)	Urban	Principal Arterial	Pedestrian	59	0.41	
Pedestrians	Construct pedestrian Overpass/Underpass	Urban	Not Specified	Pedestrian	86	0.14	AK, AZ, KY, MO (13)
Pedestrians	Install sidewalk	Urban	Not specified	Pedestrian	74	0.26	AK, AZ, KY, MO, OK (13)
Pedestrians	Install raised median with a marked crosswalk	Urban and Suburban	Principal Arterial Other	Pedestrian	46	0.54	AZ, CA, FL, KS, LA, MD, MA, MO, NC, OH, OR, PA, TX, UT, WA, WI
Pedestrians	Convert Pelican crossing to Puffin crossing	Urban	Not Specified	Pedestrian	24	0.76	United Kingdom
Pedestrians	Install high-visibility crosswalk	Urban	Not Specified	Pedestrian	40	0.60	NY

APPENDIX D. PRIMARY AND SECONDARY SAFETY FACTORS

Table D.1 Primary Factors of Pedestrian-Vehicle Crashes (2016–2018 Indiana Crashes)

Factor Group	Urban	Rural	Primary Factor	Frequency		Percentage	
				Urban	Rural	Urban	Rural
Driver	2,627	320	Failure to yield right of way	1,119	61	43%	19%
			Other (driver)–explain in narrative	542	101	21%	32%
			Unsafe backing	404	37	15%	12%
			Driver distracted–explain in narrative	132	25	5%	8%
			Ran off road	78	27	3%	8%
			Unsafe speed	67	19	3%	6%
			Disregard signal/reg sign	59	10	2%	3%
			Improper turning	58	5	2%	2%
			Improper lane usage	52	8	2%	3%
			Speed too fast for weather conditions	27	8	1%	3%
			Following too closely	20	5	1%	2%
			Overcorrecting/oversteering	16	0	1%	0%
			Improper passing	13	4	0%	1%
			Cell phone usage	11	1	0%	0%
			Left of center	10	4	0%	1%
			Driver illness	10	1	0%	0%
			Driver asleep or fatigued	5	3	0%	1%
			Other telematics in use	2	1	0%	0%
			Wrong way on one way	2	0	0%	0%
			Alcoholic beverages	0	0	0%	0%
			Illegal drugs	0	0	0%	0%
			Prescription drugs	0	0	0%	0%
			Passenger distraction	0	0	0%	0%
			Violation of license restriction	0	0	0%	0%
			Jackknifing	0	0	0%	0%
			None (driver)	0	0	0%	0%
Pedestrian	1,470	224	Pedestrian action (not identified)	868	118	59%	53%
			Crossing not at intersection	221	30	15%	13%
			On roadway	128	42	9%	19%

			Crossing at intersection	116	4	8%	2%
			Other	55	8	4%	4%
			Moving	20	5	1%	2%
			Against traffic	13	3	1%	1%
			With traffic	12	6	1%	3%
			Not in roadway	9	2	1%	1%
			Getting in or out of vehicle	8	0	1%	0%
			Standing	7	4	0%	2%
			On shoulder	6	1	0%	0%
			Working	4	0	0%	0%
			On designated non-motorist lane	3	1	0%	0%
			Getting off or on school bus	0	0	0%	0%
Environment	57	15	Other (environmental)–explain in narrative	57	15	100%	100%
			Glare	0	0	0%	0%
			Severe crosswinds	0	0	0%	0%
			None (environmental)	0	0	0%	0%
Road	73	23	View obstructed	54	6	74%	26%
			Animal/object in roadway	14	15	19%	65%
			Roadway surface condition	3	2	4%	9%
			Obstruction not marked	2	0	3%	0%
			Holes/ruts in surface	0	0	0%	0%
			Shoulder defective	0	0	0%	0%
			Road under construction	0	0	0%	0%
			Lane marking obscured	0	0	0%	0%
			Traffic control inoperative/missing/obscured	0	0	0%	0%
			Utility work	0	0	0%	0%
Vehicle	71	12	Other (vehicle)–explain in narrative	32	6	45%	50%
			Brake failure or defective	22	3	31%	25%
			Accelerator failure or defective	8	1	11%	8%
			Other lights defective	2	1	3%	8%
			Engine failure or defective	2	0	3%	0%
			Steering failure	2	0	3%	0%
			Insecure/leaky load	1	1	1%	8%

			Tire failure or defective	1	0	1%	0%
			Tow hitch failure	1	0	1%	0%
			Headlight defective or not on	0	0	0%	0%
			Window/windshield defective	0	0	0%	0%
			Oversize/overweight load	0	0	0%	0%
Total				***4,298***	***594***	***100%***	***100%***

Table 11.1 Secondary Factors of Pedestrian-Vehicle Crashes (2016–2018 Indiana crashes)

	Frequency		**Percentage**	
Secondary Factor	**Urban**	**Rural**	**Urban**	**Rural**
Crossing at intersection	347	15	30%	10%
Other	161	24	14%	15%
On roadway	125	25	11%	16%
Not in Roadway	124	18	11%	12%
Moving	86	13	7%	8%
Crossing not at intersection	86	7	7%	5%
Standing	76	16	7%	10%
On designated non-motorist lane	34	2	3%	1%
Getting in or out of the vehicle	31	4	3%	3%
On shoulder	26	15	2%	10%
Working	18	7	2%	5%
Against traffic	17	4	1%	3%
With traffic	15	3	1%	2%
Getting off or on school bus	3	2	0%	1%
Total	***1,149***	***155***	***100%***	***100%***

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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