A SAFE SYSTEM-BASED FRAMEWORK AND ANALYTICAL METHODOLOGY FOR ASSESSING INTERSECTIONS

U.S. Department of Transportation
Federal Highway Administration

Safe Roads for a Safer Future
Investment in roadway safety saves lives
http://safety.fhwa.dot.gov

FOREWORD

In the United States, the Safe System approach represents a paradigm shift in how road safety is addressed. Foundational to the Safe System approach is that no person should be killed or seriously injured when using the road system, and that it is a shared responsibility by all parties involved to ensure this becomes reality. From a roadway infrastructure perspective, a Safe System approach involves managing the circumstances of crashes such that the kinetic energy imposed on the human body be kept at levels that are tolerable in terms of survivability and degree of harm. At an intersection, this challenge is characterized through managing speed and crash angles, as well as considering risk exposure and complexity. This report proposes a Safe System framework and analytical methodology for intersections that can be applied at the project level, and that can be incorporated into an Intersection Control Evaluation alternatives screening process to provide another metric for safety.

Notice

Quality Assurance Statement

TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-SA-21-008	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Safe System-Based Framework and Analytical Methodology for Assessing Intersections		5. Report Date January 2021 6. Performing Organization Code
7.Author(s) R.J. Porter, Michael Dunn, Jonathan Soika, Ivy Huang, Dylan Coley, Annette Gross, Wes Kumfer, and Stephen Heiny		8. Performing Organization Report No.
9. Performing Organization Name and Address Vanasse Hangen Brustlin, Inc (VHB) 940 Main Campus Drive, Suite 500 Raleigh, NC 27606		10. Work Unit No. 11. Contract or Grant No. DTFH61-05-D-00024 (VHB)
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Safety 1200 New Jersey Ave., SE Washington, DC 20590		13. Type of Report and Period Final Report, April 2018 – January 2021 14. Sponsoring Agency Code FHWA
15. Supplementary Notes This report was produced under the direction of Jeffrey Shaw, Intersections Program Manager, FHWA Office of Safety.		
16. Abstract This report presents a Safe System for Intersections (SSI) method that intersection planners and designers can readily implement, that dovetails with the typical U.S. project development process, and that uses commonly available project-level data. The SSI method is presented in the context of a Stage 1 Intersection Control Evaluation (ICE), at the scoping phase of project development where intersection alternatives are analyzed with respect to whether they meet project needs and are practical to pursue. The method incorporates concepts of conflict point identification and classification, exposure, kinetic energy transfer, conflict point severity, and intersection movement complexity. Application of the SSI method results in multiple measures of effectiveness (MOEs) and a set of SSI scores that characterize the extent to which an intersection alternative in a given context aligns with the principles of kinetic energy management and a Safe System. The SSI MOEs and SSI scores can serve as additional safety metrics to inform the process of screening alternatives and identifying an optimal solution for an intersection. The report includes an overview of Safe System concepts and principles, a detailed description of the SSI method, example project applications, and a future vision for the method.		
17. Key Words: Safe System, intersection, safety performance, Intersection Control Evaluation, conflict point	18. Distribution Statement No restrictions.	

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 159	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed pages authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

AADT	average annual daily traffic
ADT	average daily traffic
ADS	automated driving system
AIS	abbreviated injury scale
AWSC	all-way stop control
BTCAV	base traffic control adjustment value
CAP-X	Capacity Analysis for Planning of Junctions
CFI	continuous flow intersection
CMF	crash modification factor
CRSS	Crash Report Sampling System
DOT	Department of Transportation
EB	eastbound
FDLT	full displaced left turn
FHWA	Federal Highway Administration
FIRST	Fatality and Injury Reporting System Tool
FSI	fatality or serious injury
F&I	fatal and injury
HSM	Highway Safety Manual
ICE	intersection control evaluation
KEMM	Kinetic Energy Management Model
LT	left turn
MAIS	Maximum Abbreviated Injury Scale
MOE	measure of effectiveness
mph	miles per hour
MRSC	minor road stop control
MUT	median U-turn
MUTCD	Manual on Uniform Traffic Control Devices
NASS	National Automotive Sampling System
NB	northbound
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NM	nonmotorized
NSC	National Safety Council
PCDS	Pedestrian Crash Data Study
PDLT	partial displaced left turn
PSL	posted speed limit
QR	quadrant roadway
RAB	roundabout

RCUT	restricted crossing U-turn
ROW	right-of-way
RT	right turn
RTZ	Road to Zero
SB	southbound
SPICE	Safety Performance for Intersection Control Evaluation
SPF	safety performance function
SSI	Safe System for Intersections
USDOT	United States Department of Transportation
V/C	volume-to-capacity ratio
WB	westbound
X-KEMM-X	Extended Kinetic Energy Management Model for Intersections

CHAPTER 1: INTRODUCTION

In October 2016, a partnership between the National Safety Council (NSC), National Highway Traffic Safety Administration (NHTSA), Federal Highway Administration (FHWA), and Federal Motor Carrier Safety Administration announced the Road to Zero (RTZ) coalition (NSC, 2016). The RTZ coalition seeks to eliminate traffic fatalities in the U.S. by 2050, an aim that aligns with the growing number of Vision Zero goals, efforts, and action plans in the U.S. The Vision Zero movement, a goal to eliminate traffic fatalities and severe injuries through leadership, data analysis, community engagement, and accountability, and other similar programs such as Toward Zero Deaths laid the groundwork for RTZ. RTZ is the first national partnership of its kind with more than 740 coalition members (Ecola et al., 2018). The RTZ coalition was announced around the same time annual traffic fatalities in the U.S. increased following years of welcomed decline. U.S. traffic fatalities increased 7.2 percent between 2014 and 2015—the largest percentage increase in nearly 50 years (NHTSA, 2016). U.S. traffic fatalities increased another 5.6 percent between 2015 and 2016, totaling 37,806 in 2016 (NHTSA, 2017). Fortunately, traffic fatalities declined again in 2017 (37,473), 2018 (36,560), and 2019 (36,120) (NHTSA, 2020a).

Some countries with Vision Zero initiatives have identified key principles to guide their national approaches to road safety management—principles that would achieve a *Safe System*. Hauer (2005) noted that road safety management activities are of two kinds. The first comprises activities directed at influencing road safety, including safety-oriented activities of Federal, State, and local agencies; safety councils; law enforcement; and other safety stakeholders. Activities that occur under the Highway Safety Improvement Program are one example. The second kind includes those activities that influence safety, but do not always have safety as their central aim. Examples include transportation planning and engineering activities driven by other transportation needs, such as mobility/congestion mitigation, reliability, and accessibility/connectivity. The Safe System approach applies to both kinds of road safety management activities.

Chapter 2 of this report provides a thorough discussion of the Safe System approach. The concepts of minimizing or preventing crashes between users having large differences in direction, speed, and mass are central to a Safe System approach, as are the following foundational principles:

- Human beings make mistakes, but the consequences of such mistakes should not result in a fatality or serious injury.
- The human body has a limited physiological tolerance of crash forces.
- Roadway designers and users have a shared responsibility in managing crash forces to a level that does not result in death or serious injury.
- To implement a Safe System, a "whole-system" approach is required—one that involves system designers and managers, vehicle manufacturers, and roadway users, among others.

As planned points of conflict—including conflicts between vehicles and nonmotorized users—intersections and intersection safety performance have major implications on the safety performance of the overall transportation system. More than half of all fatal and injury crashes in the U.S. occur at or near intersections (NHTSA, 2020b). In 2019 alone, 10,180 people were killed in intersection and intersection-related crashes (NHTSA, 2020c). For these reasons, intersections become a primary focus of a Safe System approach.

The practice of intersection planning and design has evolved in recent decades to rethink the traditional intersection in search of opportunities to increase multimodal safety and operational performance. Design principles once considered *alternative* (e.g., eliminating direct left turns with a right-turn/U-turn combination) are now widely accepted as common practice in many parts of the country (Hughes et al., 2010). Single isolated applications of innovative intersection designs have expanded into corridor-wide deployments as their numerous benefits have become better quantified, documented, and understood. Many of these innovative designs are now being refined further to better address the needs and concerns of nonmotorized users.

Whereas early installations of innovative intersection designs often relied on unique project circumstances, and perhaps an impassioned champion to spearhead their introduction and acceptance, many agencies have now taken steps to normalize their consideration in project planning processes. A growing number of States have developed or are currently developing Intersection Control Evaluation (ICE) policies, procedures, and tools. ICE is a data-driven, performance-based framework and approach used to objectively screen alternatives and identify an optimal geometric and control solution for an intersection. Although there are differences among ICE policies, they are consistent in emphasizing transparency, flexibility, and adaptability.

In addition to the rise in ICE policies nationwide, other ongoing Federal, State, and local intersection initiatives that align well with Safe System principles include crosscutting speed management strategies, pedestrian and bicyclist enhancements and integration, systemic safety analysis and management, and the strengthening of relationships between project-level impacts and program-level safety performance measurement efforts.

The scoping phase of a roadway project typically comprises confirming the project purpose and need, initiating the environmental review process, and developing initial design alternatives, among other activities. It is at this early stage in the project development process where a Safe System analysis can be most beneficial. While a project purpose and need statement *may* center upon improving traffic safety, there are other common drivers (e.g., reducing traffic congestion and delay, improving network connectivity in support of economic development, replacing deficient infrastructure) that are not explicitly linked to reducing fatal and serious injury collisions. The results of a Safe System analysis are not intended to be the *only* factor in weighing project alternatives; rather, they should be considered as *another* factor alongside traffic operations, impacts to the natural and human environments, alignment with network goals surrounding other modes, constructability and maintenance of traffic, right-of-way and construction costs, etc.

The purpose of this report is to provide a technical basis by which practitioners can apply a Safe System approach to initially inform intersection planning and design, as well as to conduct in-service assessments of existing intersections.

Chapter 2 of the report provides background on the concepts and principles of the Safe System approach, including contributions by transportation agencies and researchers around the world. Chapter 3 is a detailed explanation of a method that practitioners can use today to apply the ideas presented in chapter 2 and using readily available data. Chapter 4 showcases application of the method to three example intersections and demonstrates how the Safe System approach can be integrated into existing agency policies and practices. Finally, chapter 5 provides some ideas for future expansion of the method.

CHAPTER 2: SAFE SYSTEM CONCEPTS

2.1 CHAPTER OBJECTIVE

This chapter presents an overview of fundamental Safe System concepts. It provides a brief history of the Safe System approach to road safety management and its tie to Vision Zero. The chapter also presents the central Safe System principle of kinetic energy management and the need for a whole-system approach to manage kinetic energy to a level that eliminates traffic fatalities and serious injuries. The chapter concludes with a framework to outline how road planners and designers can begin assessing road infrastructure from a kinetic energy management perspective.

2.2 HISTORY AND BACKGROUND

While some Safe System principles are already evident in various U.S. road safety management policies and practices, much of the experience in defining and applying a Safe System approach has occurred in a few European countries, Australia, and New Zealand. Sweden was among the first countries to employ a Safe System approach to national road safety management. The Swedish parliament passed a Road Traffic Safety Bill founded on Vision Zero in 1997, concluding that a zero-fatality target was the only justifiable target for road traffic (Johansson, 2009). Vision Zero in Sweden is framed as an ethical approach, where it can never be ethically acceptable that people are killed or seriously injured when moving within the road transportation system (Johansson, 2009). Crashes resulting in less serious injuries and property damage are not considered to be an important part of the road safety problem, even if they do result in significant societal and agency costs (Johansson, 2009). Some of the early Vision Zero documentation noted that a key paradigm shift in implementing Vision Zero is the idea that mobility and safety cannot be “traded off” against each other but instead the level of mobility follows from achieving the desired level of safety.

Tingvall & Haworth (1999) noted two ways to achieve a *Safe System* in which there is no foreseeable event on the road system that could lead to a loss of life or serious injury:

1. Eliminate the events (i.e., crashes) that lead to harm.
2. Manage the events so that the mechanical forces in the events do not exceed human tolerances for harm.

While Vision Zero describes the goal and Safe System describes the approach, both accept the premise that crashes will not be completely avoided, therefore managing the mechanical forces in those crashes becomes the priority. Johansson (2009) further elaborated this point, explaining that functionalizing Vision Zero means that the “basic parameter in the design of the road transport system" should be to not exceed the "level of violence the human body can tolerate without being killed or seriously injured" in the event of a crash (p. 827). Road design practices have historically sought to account for variable driver behavior and performance by making roads wider to allow, for example, a driver to recover in the event of a lane deviation or roadway departure. However, wider roads also tend to result in higher operating speeds, increasing the chances of fatalities and serious injuries when crashes do occur because of the speeds. Design based on the Safe System approach also accommodates driver error, but in a different way, by recognizing that crashes will occur and seeking to manage the kinetic energy that transfers to the human body in crashes.

The overarching principle of kinetic energy management is central to the Safe System approach. Belin et al. (2012) noted that kinetic energy management has a scientific foundation, citing work by DeHaven (1942), Haddon (1980), and Robertson (1983). Vision Zero made this scientific foundation the basis of road design and management in Sweden.

The Netherlands developed its Sustainable Safety vision in the early 1990's and it was fully implemented through a Sustainable Safety Start-Up Program in 1997 (SWOV, 2013). The vision aims to prevent traffic fatalities and serious injuries from occurring and has five fundamental principles (shown in table 1).

Table 1. Five sustainable safety principles[1] (Source: SWOV, 2013).

Sustainable Safety Principle	Description
Functionality of roads	"Monofunctional" roads (i.e., roads have a single function) as either through roads, distributor roads, or access roads in a road hierarchy.
Homogeneity of mass and/or speed and direction	Equality of speed, direction, and mass at moderate and high speeds.
Predictability of road user behavior by recognizable road design	Road environment and road user behavior that support road user expectations through consistency and continuity of road design.
Forgiveness of road design and of road users	Injury limitation through a forgiving road environment and anticipation of road user behavior.
State awareness by the road user	Ability to assess one's capability to handle the driving task.

[1] Table 2 in the *Bikeway Selection Guide* presents a summary of intersection characteristics and performance considerations for a variety of bikeway types, organized by the Sustainable Safety principles (Schultheiss et al., 2019).

A fact sheet on the five sustainable safety principles describes the overarching theme of kinetic energy management in the following way (SWOV, 2013):

- Where road users/vehicles with large mass differences use the same traffic space, the speeds should be so low that the most vulnerable road users and transport modes come out of a crash without any serious injuries. In an ideal situation, this is achieved by evoking low speeds through use of the road infrastructure, not by appealing to the road users' individual choices.
- At locations where traffic is at high speeds, different types of road users and vehicles moving in different directions should be physically separated from each other as much as possible to prevent conflicts leading to serious injury.

Mooren et al. (2011) provided a historical look at how the Safe System approach in Australia, first adopted in principle by the Australian Transport Council in 2004, evolved from Vision Zero and Sustainable Safety. Central to the Safe System approach in Australia is the concept of human tolerance to crash impacts and whole-system efforts spanning roads, speeds, vehicles, and people aimed at preventing crashes that result in death or serious injuries (Wooley et al., 2018). In its National Road Safety Strategy (2011-2020), the Australian Transport Council (2011) identifies three guiding principles to their Safe System approach:

1. **People make mistakes.** Humans will continue to make mistakes and the transportation system must accommodate these mistakes. Death or serious injury should not be the consequence of user errors.
2. **Human physical frailty.** There are known physical limits to the amount of force the human body can withstand before serious injury.
3. **A forgiving road transportation system.** A Safe System is one where forces in collisions do not exceed the limits of human tolerance. System planners, designers, and managers should therefore consider the physical limits of the human body in planning, designing, and maintaining roads and vehicles and in managing speeds.

Safer Journeys 2020: New Zealand's Road Safety Strategy 2010-2020 drew on experience in Australia and guided investments in road safety over this period. New Zealand's vision is "a safe road system, increasingly free of death and serious injury" (New Zealand Ministry of Transport, 2010, p. 10). *Safer Journeys* takes a Safe System approach to working towards this vision. As with other approaches already discussed, human tolerance to crash forces is central to the New Zealand Safe System approach, recognizing that this criterion "will need to be the key design factor for the system. Crash forces will be managed so they do not exceed these limits" (New Zealand Ministry of Transport, 2010, p. 10).

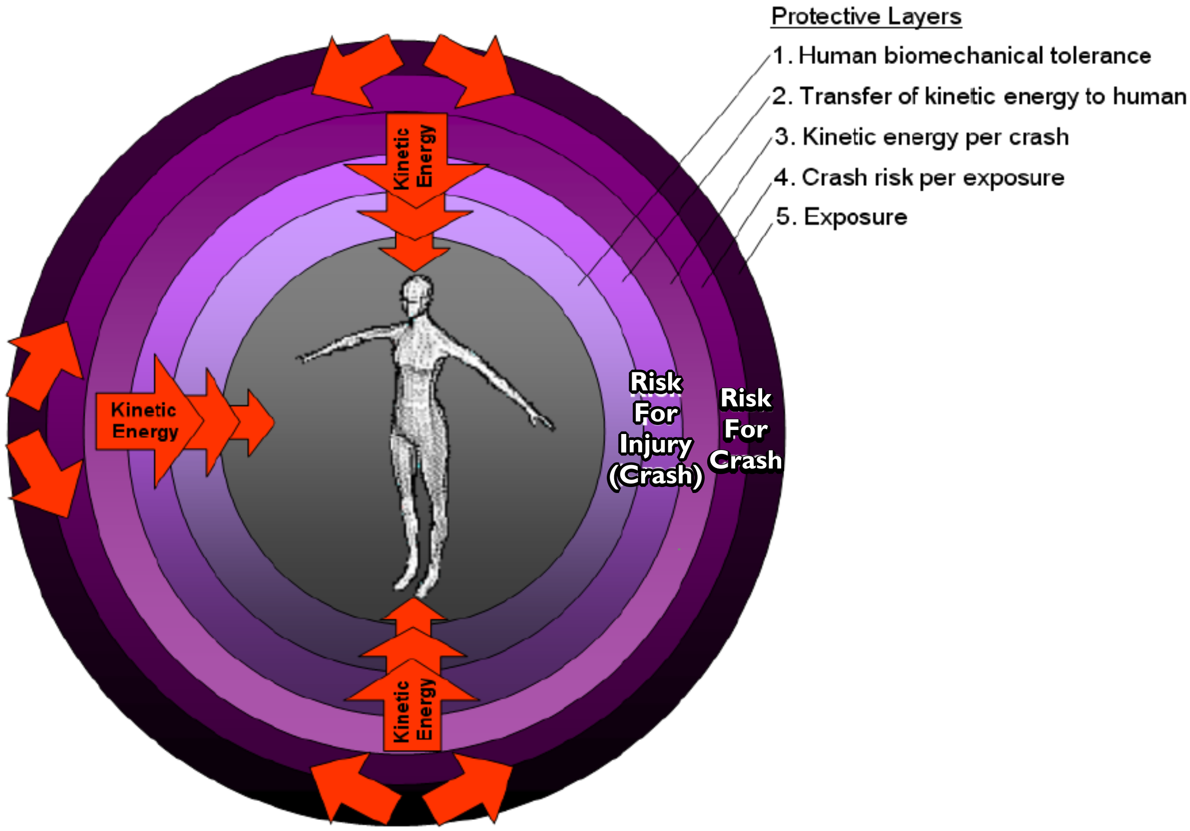
2.3 KINETIC ENERGY MANAGEMENT MODEL

Section 2.2 highlighted human tolerance to crash forces, and management of forces to a level that does not exceed human tolerance, as central to a Safe System approach. To help advance understanding and implementation of this concept, Corben et al. (2010) developed the Kinetic Energy Management Model (KEMM) as a conceptual model. Kinetic energy management to a level that reduces or eliminates (in the case of a Safe System) the chances of fatalities or serious injuries occurs by either avoiding crashes altogether or, in the event of a crash, managing the transfer of kinetic energy.

Corben et al. (2010) created five "layers" to make up the KEMM that are illustrated in figure 1 and described below:

- Layer 1 – Human Biomechanical Tolerance: This layer captures how the human body absorbs and distributes kinetic energy during a crash and how this can result in pain and/or injuries. Characteristics of this layer can vary as a function of age, gender, size, and other characteristics of the user.
- Layer 2 – Transfer of Kinetic Energy to the Human: This layer is comprised of the mechanics by which kinetic energy is transferred from the vehicle to humans in a crash. For vehicle occupants, safety features such as seat belts and air bags extend the time and area over which kinetic energy is transferred, easing the absorption by the body. The crashworthiness of vehicles captured in this layer may also depend on the points of impact and impact angles. For nonmotorized users, the contact is direct, without much chance for increasing the time and area over which the energy is transferred.
- Layer 3 – Kinetic Energy per Crash: This layer quantifies the level of kinetic energy in a crash. Vehicle speeds, relative directions, and vehicle masses are primary drivers of the amount of kinetic energy in a crash.
- Layer 4 – Crash Risk given Exposure: This layer focuses on the risk of a crash for different levels of exposure. Research has found that crash risk given exposure is influenced by a wide range of characteristics of the users, vehicles, roads, and environment.
- Layer 5 – Exposure: For single-vehicle crashes to occur, vehicles must travel over some length of road. For multivehicle and nonmotorized crashes to occur, vehicle or user paths must conflict. This layer captures the level to which users are exposed to the chances of different crash types.

As part of implementing a kinetic energy management approach, planners, designers, and managers of the road network are seeking to reduce the risk of crashes occurring by reducing exposure (Layer 5) and/or reducing risk for a given level of exposure (Layer 4). In other words, these Layers 4 and 5 determine crash frequency. In the cases where crashes occur, Layers 1, 2, and 3 determine crash severity. The numerical ordering of the layers may seem counterintuitive, but Corben et al. (2010) note that this is to reinforce that the priority of Vision Zero and the Safe System approach is minimizing harm (Layers 1 through 3) as opposed to crash elimination (Layers 4 and 5).



© Corben et al. 2010

Figure 1. Graphic. The five layers of protection in the KEMM.

2.4 WHOLE-SYSTEM APPROACH

It is not possible to achieve a Safe System through road infrastructure planning, design, and operation alone. While infrastructure characteristics such as geometrics and traffic operation and control strategies affect user exposure, crash risk, and crash severity, achieving a Safe System depends on contributions from the whole transportation system. This "whole-system approach," as identified by Wooley et al. (2018), considers speeds, people, and vehicles in addition to roads.

Implementing a whole-system approach involves system planners, designers, and operators, vehicle manufacturers, emergency services, and system users. This is sometimes represented as interacting elements such as "safe roads," "safe speeds," "safe vehicles," "safe road users," and "post-crash care". This approach is commonly reflected in State Strategic Highway Safety Plan efforts, which outline strategies for leveraging resources that span engineering, education, enforcement, and emergency medical services to collectively address safety challenges and reduce fatalities and serious injuries (FHWA, 2017). The remaining sections of this chapter briefly address selected topics across the interacting Safe System elements. FHWA has incorporated these principles and elements into its Safe System guidance. Figure 2 displays an example of this.

Source: FHWA.

Figure 2. Graphic. Portrayal of the Safe System in FHWA's Safe System Approach brochure.

2.4.1 Safe Speeds

Speed and speed management practices are central to the level at which a Safe System can be achieved. Speed is the key determinant of kinetic energy per crash (i.e., kinetic energy related to mass and the square of velocity). Consolidating concepts of the KEMM Layers 1, 2, and 3, Tingvall & Haworth (1999) provided the speed thresholds shown in table 2 as representing an "inherently safe system."

Table 2. Possible long-term maximum travel speeds related to infrastructure, given best practices in vehicle design and 100 percent restraint use (Source: Tingvall & Haworth, 1999).

Type of Infrastructure and Traffic	Possible Travel Speed, km/hr (miles per hour [mph])
Locations with possible conflicts between pedestrians and cars	30 km/hr (20 mph)[2]
Intersections with possible side impacts between cars	50 km/hr (30 mph)
Roads with possible frontal impacts between cars	70 km/hr (45 mph)
Roads with no possibility of a side impact or frontal impact (only impact with the infrastructure)	100+ km/hr (60+ mph)

[2] Conversions added using "Corresponding Design Speeds in Metric and US Customary Units" from The American Association of State Highway and Transportation Officials' *A Policy on Geometric Design of Highways and Streets* (2018).

Johansson (2009) provided the following "boundary values" and provided guidance for "integration" versus "separation[3]":

- Vulnerable road users should not be exposed to motor vehicles at speeds exceeding 30 km/hr (20 mph).
  - If this cannot be satisfied, separate or reduce vehicle speeds to 30 km/hr (20 mph).
- For 90-degree crossings, car occupants should not be exposed to other motorized vehicles at speeds exceeding 50 km/hr (30 mph).
  - If this cannot be satisfied, then separate, reduce the crossing angle, or reduce speeds to 50 km/hr (30 mph).
- For oncoming traffic, car occupants should not be exposed to other motorized vehicles at speeds exceeding 70 km/hr (45 mph) when the opposing motorized vehicles are of the same size or 50 km/hr (30 mph) when the opposing motorized vehicles are of considerably different weight.
  - If this cannot be satisfied, then separate, homogenize weights, or reduce speeds.
- Car occupants should not be exposed to the roadside at speeds exceeding 70 km/hr (45 mph). This maximum speed is 50 km/hr (30 mph) if the roadside contains trees or other fixed objects.

Achieving the speeds and separation targets outlined by Tingvall & Haworth (1999) and Johansson (2009) requires broad political will and societal acceptance. Outside of these targets, however, research exists to link vehicle speeds, relative directions, and masses to the chances of one or more fatalities or serious injuries in the event of a crash. In addition, speed also plays roles in the crash risk for a given level of exposure (Layer 4 in the KEMM). Such information could be used by system planners, designers, and operators to inform infrastructure decisions in terms of kinetic energy management, even if there is not broader political and societal commitment for achieving a Safe System.

[3] Johansson (2009) notes that separation is physical separation, usually a barrier, and is never a temporal one (e.g., traffic signal timing to separate conflicting movements). Later discussion will address distinctions as part of Safe System treatment hierarchies.

2.4.2 Safe Road Users

User performance and behavior also play central roles in a Safe System approach to road safety management. Of the five "Sustainable Safety Principles" from the Netherlands, two focus on user capabilities as well as "user expectations through consistency and continuity of road design" (SWOV, 2012, p. 2). Factors such as user experience, workload, fatigue, compliance, distraction, and fitness to drive influence the crash risk for a given level of exposure (Layer 4 in the KEMM). The characteristics of people involved in crashes are also part of Layer 1 of the KEMM, influencing whether a crash that transferred a given amount of kinetic energy to the humans involved results in a fatality or serious injury.

Shared responsibility is another Safe System concept that relates to the "safe road users" element and to the idea of traffic safety culture across users and transportation agencies. Shared responsibility generally means the responsibility for creating and maintaining a Safe System falls on both the system managers and the road users. Shared responsibility is laid out in three points from Sweden's Vision Zero (Tingvall & Haworth, 1999):

- The managers of the system are ultimately responsible for the design, operation, and use of the road transportation system and therefore responsible for the level of safety within the entire system.
- Road users are responsible for following rules set by the system managers for using the road system.
- If road users fail to obey these rules due to lack of knowledge, acceptance, or ability, or if serious injuries occur, the system managers are responsible for taking necessary steps to address people being killed or seriously injured.

2.4.3 Safe Vehicles

Vehicle design plays a key role in multiple KEMM layers. Vehicle size can affect crash risk for a given level of exposure (Layer 4 in the KEMM) due to lane keeping, maneuverability, and acceleration and deceleration performance. The presence and type of crash avoidance technologies will also affect crash risk per exposure. The size of the vehicle, in addition to impact speed and impact angle, is a key factor determining the amount of kinetic energy in a crash (Layer 3 in the KEMM). The crashworthiness of vehicles – which may depend on the points of impact and impact angles, structural design, and related devices (e.g., seatbelts, airbags)—determines how much energy is ultimately transferred to vehicle occupants (Layer 2 in the KEMM). Vehicle size also determines how much and at which impact points kinetic energy is transferred to non-motorized users (also Layers 3 and 2 in the KEMM).

2.4.4 Safe Roads

The classification of roads based on their function—and the extent to which their function is made evident to users by their design is key to achieving a Safe System. This is most notably the case with the Functionality and Predictability principles of Sustainable Safety in the Netherlands (see table 1), and the corresponding design features of through roads, distributor roads, and access roads in the Netherlands (Wegman et al., 2008). Network-wide road classification and self-explaining design approaches consistent with context and function continue to evolve in the U.S., a major advancement being the development of a context sensitive functional classification system (Stamatiadis et al., 2018), which was incorporated into the latest edition of *A Policy on Geometric Design for Highways and Streets* (AASHTO, 2018).

In addition to broader classification practices and reinforcement of road function with self-explaining design, road geometrics and traffic control devices can reduce workload, reinforce user expectations, and simplify user decision making (all part of Layer 4 of the KEMM). Importantly, geometrics can also determine both the angles and speeds of crashes that do occur, thereby influencing the kinetic energy per crash (KEMM Layer 3).

Tingvall & Haworth (1999) noted that one of the first steps road planners, designers, and operators can take is to analyze and/or rank infrastructure from a kinetic energy management perspective. They described the ranking primarily through the lens of speed but noted traffic volumes are also key to the analysis to show the importance of modifications (i.e., from an exposure perspective). Tingvall & Haworth (1999) recognized that the analysis and/or ranking can be used for long-term planning, project planning, and as a "performance measure" for moving towards an inherently Safe System.

A framework by Jurewicz et al. (2015), shown in figure 3, is helpful in visualizing road infrastructure elements and their connection to kinetic energy management. The framework begins with consideration of users, including traffic composition and local demographics, and the dimensions of the infrastructure. Ultimately, exposure by user group will play a significant role in crash frequency and severity.

The second element of the framework looks at combinations of factors related to the crash likelihood given levels of exposure. Conflict points between different road users and how user workload and behavior might contribute to crashes occurring at these points are a focus of this part of the assessment. Infrastructure elements that emerge as risk or protective factors (e.g., absence/presence of channelization, intersection sight distance, right-turn-on-red).

The third element of the framework is highly relevant to the Safe System approach, looking at factors influencing injury severities should a crash occur. These factors include impact speeds, impact angles, objects impacted, vehicle characteristics, and the characteristics of who is involved in the crashes (i.e., vehicle occupants, pedestrians, cyclists). Most of these factors relate to the amount of kinetic energy passed to vehicle occupants or other road users and whether it exceeds thresholds that will increase the probability of fatality or serious injury. This framework informed the development of a Safe System for Intersections (SSI) method described in chapters 3.

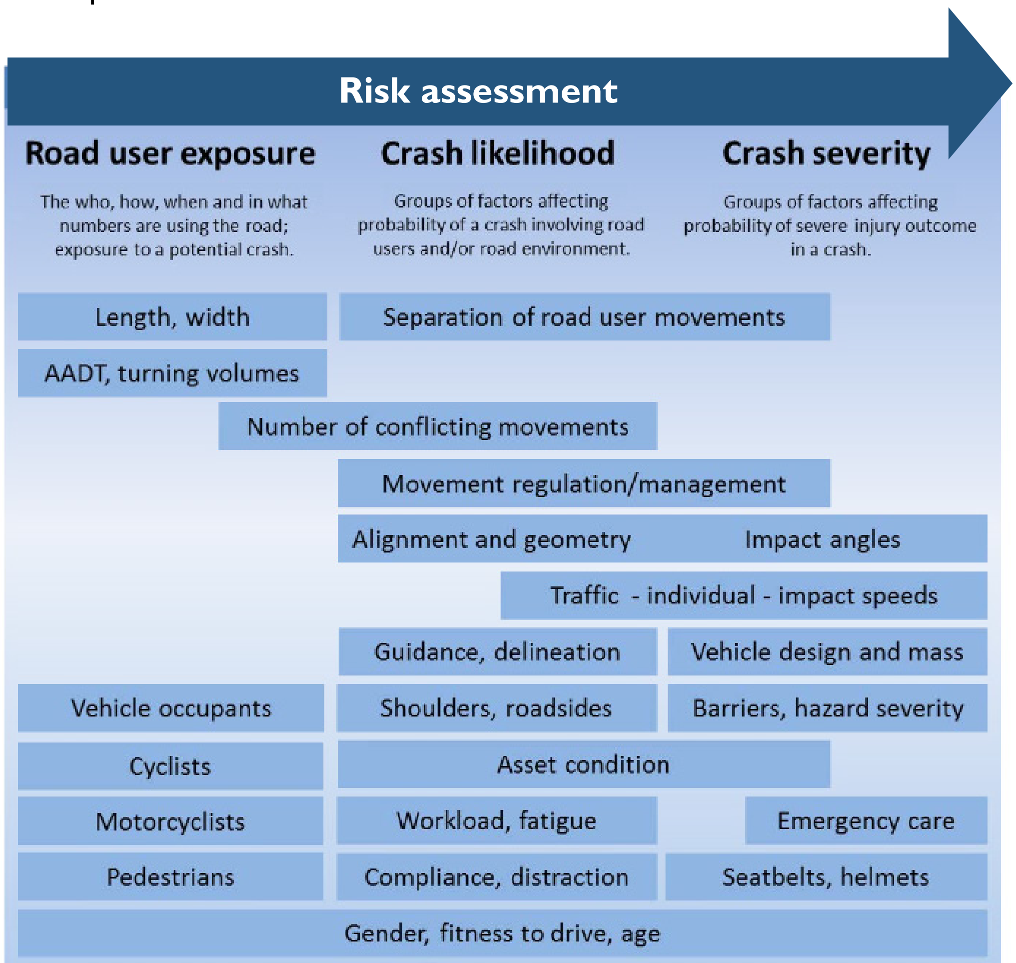


Figure 3. Graphic. Risk assessment framework.

2.4.5 Post-Crash Care

When a crash does occur and result in an injury, injured persons rely on a quick response from emergency personnel (FHWA, 2020). The speed of this response may mean the difference between a minor injury and a serious injury or fatality occurring as a result of the crash. A proper emergency response involves quickly locating and traveling to the site of the crash, stabilizing the injured person(s), and efficiently transporting them to the appropriate medical facility.

In addition to this emergency medical response, the post-crash care element also encompasses forensic analysis at the crash site, traffic incident management (to prevent or minimize the occurrence of secondary crashes), and other activities.

CHAPTER 3: SSI METHOD FOR INTERSECTION CONTROL EVALUATION

3.1 CHAPTER OBJECTIVE

The objective of this chapter is to present an analytical SSI methodology that intersection planners and designers can readily implement that dovetails with the typical project development process— i.e., one that incorporates Safe System principles from chapter 2 and relies upon commonly available project-level data. The goal is to provide a technical basis by which intersection planners and designers can apply kinetic energy management to common intersection projects in the U.S. However, the method's framework provides flexibility to incorporate broader system efforts and characteristics (e.g., users, vehicles, speeds) in the future if supporting data are available. Chapter 5 contains ideas for future enhancements.

This chapter describes the characteristics, data needs, assumptions, computations, and output of the SSI method. The information is presented in the context of a Stage 1 Intersection Control Evaluation (ICE), at the scoping phase of project development where intersection alternatives are analyzed with respect to whether they meet project needs and are practical to pursue. The chapter concludes with ideas for possible extensions of the SSI method to a Stage 2 ICE, a more detailed process that coincides with the preferred alternative selection phase. Chapter 4 provides a series of project-specific example applications of the method.

The framework and method were developed and refined through input from a group of stakeholders from FHWA, as well as several State Departments of Transportation (DOTs) and local agencies.

3.2 SSI METHOD OVERVIEW

The SSI method in this chapter represents a first step towards the development of objective analysis approaches that capture key Safe System concepts and are implementable by intersection planners and designers in the U.S. This method is intended to be adaptable to adjustments in its assumptions based on local data or improved knowledge through future research. The following paragraphs highlight key characteristics of the SSI method. Subsequent sections of this chapter provide additional details and supporting background information.

Conflict Point Identification and Classification. The kinetic energy transferred to people involved in a crash, and the human body's tolerance to the resulting forces, are central to the Safe System approach. The KEMM in chapter 2 identified a variety of factors that affect the amount of kinetic energy transferred to people in a crash (Layers 2 and 3). The SSI method focuses on vehicle speeds and impact angles for multiple vehicle crashes and vehicle speeds for crashes involving nonmotorized users. With these distinctions, the identification and classification of conflict points by conflicting users and conflicting movements are fundamental to the SSI method.

Exposure. Applying Layer 5 of the KEMM to intersections, the likelihood of a crash at a given conflict point is related to the number of conflicting movements that pass through that conflict point. The SSI method accounts for this concept through an exposure index, which is estimated for each conflict point, and represents the product of daily conflicting flows through the conflict point.

Conflict Point Severity. The SSI method defines conflict point severity as an estimate of the probability of at least one fatality or serious injury (*P(FSI)*) resulting from a crash between conflicting road users making movements that define the conflict point. The method defines serious injury as an injury with a Maximum Abbreviated Injury Scale (MAIS) score of 3 or above, which includes serious, severe, critical, and maximum (i.e., fatal) injury classifications (Harmon et al., 2018). The computation of the *P(FSI)* is based on a mechanistic approach to determining crash severity based on key crash characteristics (i.e., collision speed, collision angle) and injury level as defined by medical and public health professionals. It represents an aggregation of Layers 3, 2, and 1 of the KEMM in chapter 2.

Movement Complexity. Human factors play a key role in the Safe System approach. User behavior and performance, along with the workload imposed (or mitigated) by the design and operation of the intersection will affect the crash risk per given level of exposure (Layer 4 of the KEMM). The SSI method focuses on intersection features that represent the overall intersection form and size and that could affect the task complexity for users making specific movements (i.e., passing through specific conflict points) at an intersection. The current SSI method focuses on the following features in characterizing the complexity of a movement:

- Type of traffic control (applicable to both motorized and nonmotorized users).
- Number of lanes on approaches carrying conflicting traffic that a user must cross or merge with (applicable to both motorized and nonmotorized users).
- Speed of conflicting traffic (applicable to both motorized and nonmotorized users).
- Presence of indirect crossing paths and nonintuitive vehicle movements (applicable to nonmotorized users only).

The first feature is reliant on user compliance with the traffic control devices at the intersection. The latter three features are either a direct result of, or influenced by, intersection geometry.

Results. The results of applying the SSI method include multiple measures of effectiveness (MOEs) and a proposed set of SSI scores. The MOEs include the exposure through different conflict point types, the average *P(FSI)* for different conflict point types, and the average complexity for movements passing through different conflict point types. The SSI scores are derived based on the combined concepts of conflict points, conflict point severity, exposure, and complexity, and are a means to characterize the extent to which an intersection alternative in a given context aligns with the principles of a Safe System. The score for an intersection control alternative ranges from zero to 100, with higher scores representing higher levels of Safe System performance (i.e., lower chances of fatalities and serious injuries).

The Safe System concepts of kinetic energy transfer and management are grounded in science and represent a mechanistic approach to predicting crash injury outcomes. In order to explore the relationship of this SSI method to crash-based studies and models, results of the SSI analysis were qualitatively compared to results of crash-based predictive methods, particularly crash-based results applicable to fatal and injury (i.e., F&I or KABC) crashes. Given the current focus of the SSI method on a Stage 1 ICE application, the qualitative "litmus-test" comparisons highlighted general similarities and differences in the relative positions of intersection alternatives compared to an existing or future no-build condition. Chapter 4 includes such comparisons for three example project scenarios.

Beyond these qualitative comparisons, it was concluded that a conventional validation of the SSI score to crash-based predictive models is not yet possible. Notably, current intersection crash predictive methods are generally insensitive to intersection characteristics that are key to Safe System principles, such as size (in terms of cross sections of the approaching roadways and crossing distances), turning volumes, nonmotorized user volumes, and speeds. In addition, crash-based predictive methods are based on data from crash reports. Relationships between injuries reported as suspected serious injuries (A) on crash reports and serious injuries as defined by medical professionals on the MAIS scale may vary from location to location depending on crash reporting practices. Crash costs in the USDOT's Benefit-Cost Analysis Guidance for Discretionary Grant Programs suggest that, on average, only a percentage of reported crashes coded as suspected serious injuries (A) on crash reports are serious injuries as defined by medical professionals on the MAIS scale (USDOT, 2020).

Continued advancements in crash reporting, injury surveillance (including crash report and hospital record linkages), and more widespread availability of vehicle movement and speed data will allow more empirical linkages to be made between SSI scores and fatal and serious injury crash data. Chapter 5 contains future considerations for linking SSI scores to fatal and serious injury crash experience.

Potential Use. The Safe System performance of an intersection, represented by the SSI MOEs and the SSI scores, can serve as additional safety metrics to inform the process of screening alternatives and identifying an optimal solution for an intersection. A Stage I ICE safety analysis provides a basis to characterize safety performance of various alternatives. Performance analyses that occur during a Stage I ICE may rely on both qualitative and quantitative methods. Depending on the project intent, the Stage I safety analysis is generally meant to determine one of the following:

- If improving safety is the primary need for a project, does the intersection alternative address the safety need by enhancing safety performance?
- If improving safety is not the primary need for a project, does the intersection alternative maintain or enhance safety performance?

The SSI MOEs and SSI scores can complement crash-based metrics that come from predictive approaches like those in the *Highway Safety Manual* (HSM) and Safety Performance for Intersection Control Evaluation (SPICE) by:

- Focusing on fatalities and serious injuries defined on the MAIS scale and the key mechanisms that lead to these injuries (e.g., speeds, collision angles).
- Providing a metric for the safety of nonmotorized users while robust crash-based metrics are still in development.
- Communicating tradeoffs between vehicle-vehicle conflict SSI scores and vehicle-nonmotorized conflict SSI scores across different intersection alternatives.

The SSI MOEs and SSI scores can also provide metrics that consider safety in the absence of an HSM or SPICE analysis. This may be valuable in cases where it is not possible to conduct crash-based analyses on one or more alternatives, such as for atypical or emerging intersection concepts that are not-addressed by crash-based methods. With these uses in mind, along with the complementary nature of Safe System metrics and crash-based metrics, stakeholders guiding the development of future versions of resources such as the HSM may find it beneficial to incorporate the SSI method and other types of Safe System assessments.

3.3 DATA NEEDS

The required and optional traffic and geometric data inputs for implementing the SSI method are listed in table 3. The SSI method was developed with typically-available project data in mind in order to make it readily useable: speed (specifically, posted speed limit (PSL)), average annual daily traffic (AADT) volumes, and the number of through lanes on the intersecting roads. There are also several other inputs that, if available, will make the analysis more project-specific. Some of these optional inputs (e.g., vehicle speeds for different intersection movements and volumes of nonmotorized users) are central to Safe System principles but have not historically been as utilized or explored by the research and practitioner communities. The SSI method in this chapter offers assumptions and default values for their use, but agency-prescribed or project-specific values could also be used.

Table 3. SSI method data inputs.

Required Operational and Geometric Inputs	Other Operational and Geometric Inputs
• Posted speed limit • AADT volumes • Number of through lanes in one direction on each approach	• Through, right-turning, left-turning, and U-turning movement speeds • Roundabout entering, circulating, and exiting movement speeds • Nonmotorized AADT volumes • Directional split • Turning movement proportions (or turning movement AADT volumes) • Left-turn traffic signal phasing (protected, protected/permitted, or permitted) • Collision angles between conflicting movements (may vary from default due to intersection skew)

3.4 CONFLICT POINT INDENTIFICATION AND CLASSIFICATION

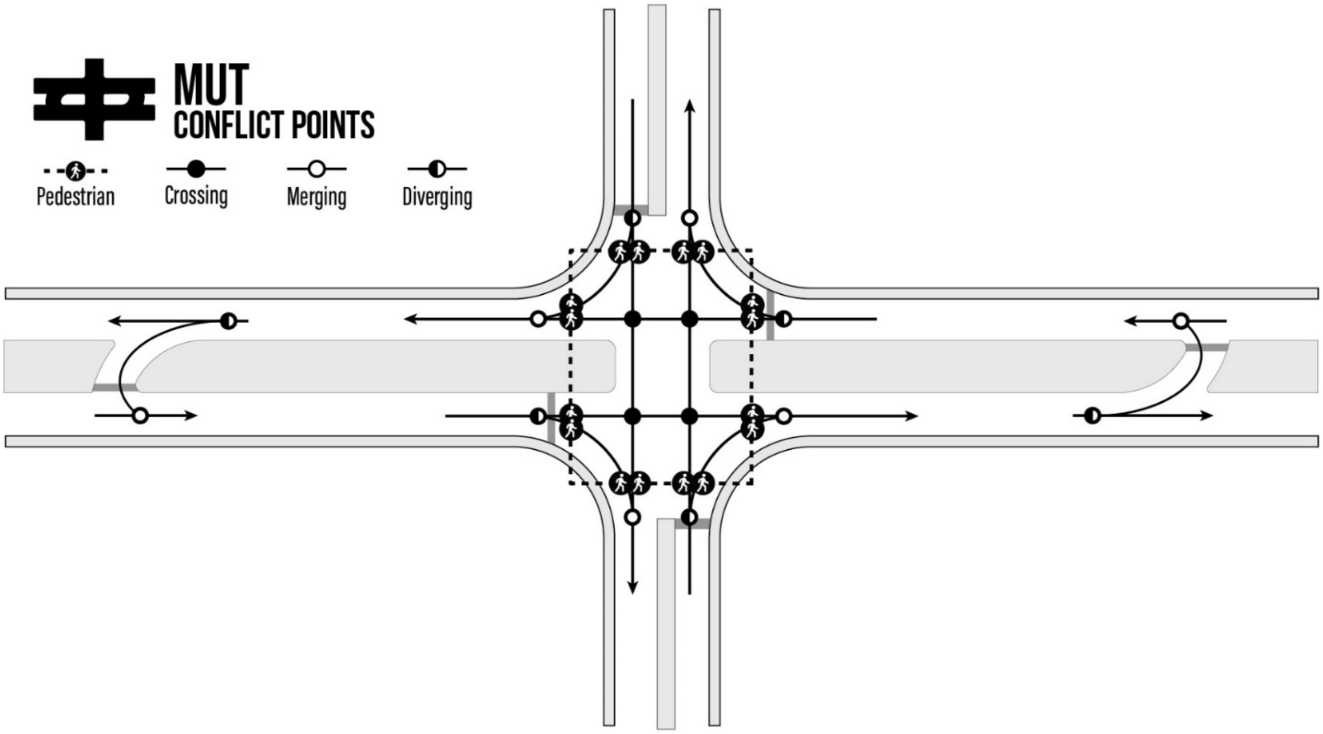
A conflict point is any location where the paths of road users coincide (FHWA, 2019). A traffic conflict is any traffic event involving the interaction of two users where one or both users may have to take evasive action to avoid a collision (Glauz & Migletz, 1980). Conflict points are the locations on the roadway where traffic conflicts are most likely to occur based upon the typical travel paths of road users. By their nature as planned points of conflict, intersections represent concentrated groupings of conflict points.

The SSI method categorizes conflict points as either crossing, merging, diverging, or nonmotorized conflict points, and adapts ideas from Gustafson (2018) with some modifications:

- Crossing conflict point—a location where vehicle paths come from different traffic streams, intersect, and then proceed as two separate traffic streams (i.e., two input traffic streams and two output traffic streams).
- Merging conflict point—a location where vehicle paths come from different traffic streams and converge into the same traffic stream (i.e., two input traffic streams and one output traffic stream).
- Diverging conflict point—a location where vehicle paths diverge from a single traffic stream into two separate traffic streams (i.e., one input traffic stream and two output traffic streams).
- Nonmotorized conflict point—a location where a vehicle path crosses a pedestrian/cyclist path.

The SSI method currently assumes that bicyclists follow the same paths as pedestrians through intersections. Future enhancements to the method could incorporate additional layers of vehicle-bicycle conflict points that depend on the selection of bicycle accommodation through the intersection, as outlined in the *Bikeway Selection Guide* (Schultheiss et al., 2019). Additional discussion of these enhancements is contained in section 3.8 and chapter 5. The SSI method also does not consider rear-end conflicts that result from speed differentials that arise from traffic congestion or deceleration and stopping due to traffic control devices (i.e., yield signs, stop signs, and traffic signals). It does consider rear-end conflicts that result from speed differentials at diverging conflict points where vehicles making different movements have different speeds.

Conflict points can be identified on a movement basis or on a lane-by-lane basis. Since this initial SSI method is intended for use in project scoping, and exact lane arrangements may not be known at this project development stage, the SSI method identifies conflict points on a movement basis. Figure 4 shows an example of the movement-based conflict points for a Median U-Turn (MUT) intersection. Movement-based conflict points are not dependent on the number of lanes or presence of auxiliary lanes for an alternative; rather, they are disaggregated by each movement combination. For example, there are two different nonmotorized conflict points associated with a nonmotorized road user crossing the receiving lanes of a minor road approach in figure 4: one associated with right-turning vehicles from the major road, and one associated with through-moving vehicles on the minor road. Appendix A illustrates movement-based conflict points for various intersection alternatives that State agencies with ICE policies commonly consider as part of a Stage I ICE.



Source: FHWA.

Figure 4. Graphic. Conflict points at a MUT intersection.

3.5 EXPOSURE

The likelihood of a crash at a given conflict point is related to the number of conflicting movements that pass through that conflict point. The SSI method accounts for this concept of exposure through an exposure index, which is estimated for each conflict point. The SSI method adopts an exposure index definition from Hakkert & Mahalel (1978). The exposure index at conflict point *c*, I_c, is simply the product of vehicle or nonmotorized user daily volumes through that conflict point ($Q_{1,c}$ and $Q_{2,c}$), illustrated in figure 5.

$$I_c = Q_{1,c} * Q_{2,c}$$

Figure 5. Equation. Exposure of index for conflict point c.

The values for $Q_{1,c}$ and $Q_{2,c}$ are determined using the daily volumes, turning movements, and intersection geometry.

The individual conflict point exposure indices can be summed across all conflict points of a certain type at an intersection to compute the total exposure for each conflict point type (e.g., total exposure through all crossing conflict points, total exposure through all merging conflict points, etc.). Appendix B provides example exposure index calculations.

3.6 CONFLICT POINT SEVERITY

The SSI method defines conflict point severity as the estimated probability of at least one fatal or serious injury, *P(FSI)*, as a result of a crash between conflicting road users making the typical movements that define the conflict point. The SSI method defines injury severity on the abbreviated injury scale (AIS), which is based on information provided by trained medical professionals following an assessment of a patient's injuries at the hospital (Burch et al., 2014). AIS classifications of injury severity may be more consistently coded within a State, across States, and over time than injury determinations made by police officers at the scenes of crashes. The ability to make a direct correlation to a person's probability of survival (shown in table 4) is another benefit of the AIS scale.

Table 4. AIS injury codes and corresponding probability of death (Harmon, et al., 2018).

AIS Code	Injury	Example Injury	Probability of Death (%)
0	None	No injury	0
1	Minor	Superficial laceration	0
2	Moderate	Fractured sternum	1 – 2
3	Serious	Open humerus fracture	8 – 10
4	Severe	Perforated trachea	5 – 50
5	Critical	Ruptured liver with tissue loss	5 – 50
6	Maximum	Total severance of aorta	100

AIS scores can characterize individual injuries on a person (e.g., an AIS score for different regions of the body injured in a crash). The MAIS is the most severe AIS across all body regions. Burch et al. noted that the trauma research community relies on AIS codes to analyze injury data and has accepted a serious injury definition as an AIS score of 3 or higher (Burch et al., 2014). The SSI method therefore defines fatal and serious injuries as injuries with MAIS scores of 3 or above.

The following sections detail the calculations used to estimate conflict point severity for the SSI method. The first section focuses on vehicle-vehicle conflict points (c_{veh}), which include crossing, merging, and diverging conflict points. The second section focuses on vehicle-nonmotorized conflict points (c_{ped}). The general approach outlined in these two sections follows the same general approach as in the Austroads Extended Kinetic Energy Management Model (X-KEMM-X) (Jurewicz et al., 2017), except for some differences in data sources and assumptions. Appendix B provides example conflict point severity calculations.

3.6.1 Vehicle-to-Vehicle Conflict Points

The SSI method estimates *P(FSI)* at crossing, merging, and diverging conflict points using an estimated speed for each conflicting movement and an estimated angle between conflicting movements. The SSI method assumes that the angle between conflicting movements is representative of the angle of collisions that would occur at the conflict point. This collision angle for conflict point c_{veh}, ϕ_{veh}, is defined as the angle at which two vehicles (U_1 and U_2) would collide at that conflict point, measured from the vehicle U_1's longitudinal axis (see figure 6). Using this convention, a collision angle of zero degrees is a rear-end collision; a collision angle of 180 degrees is a head-on collision; and collision angles of 90 degrees and 270 degrees are right-angle collisions.

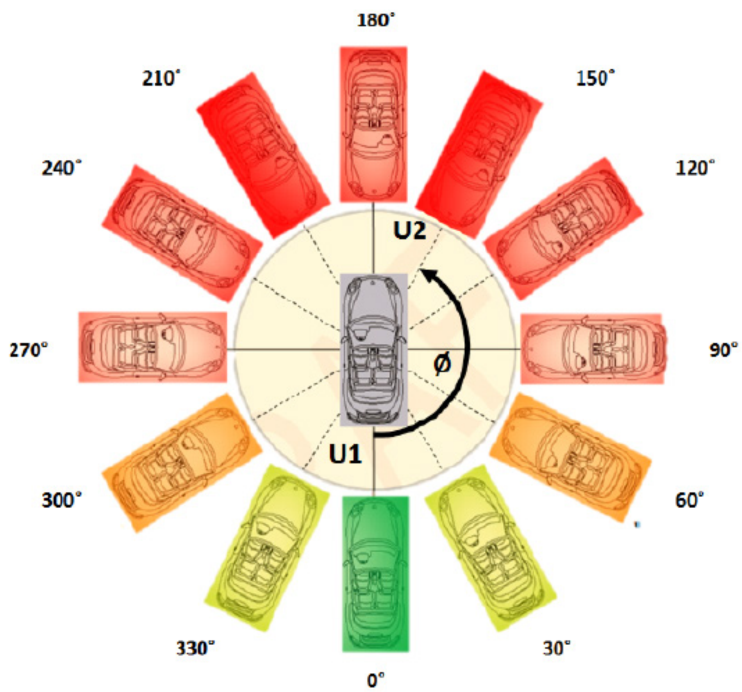


Figure 6. Graphic. Diagram illustrating various angles of collision.

The SSI method estimates *P(FSI)* at each vehicle-vehicle conflict point using a model developed by Joksch (1993) (as described in Evans, 1994). This model predicts *P(FSI)* for occupants of each individual vehicle (i.e., U_1 and U_2) involved in a vehicle-vehicle collision. The SSI method applies the model at each crossing, merging, and diverging conflict point. Figure 7 illustrates the application of the Joksch (1993) model to the SSI context.

$$P_{FSI,U_i,c_{veh}} = \left(\frac{\Delta V_{U_i,c_{veh}}}{\alpha}\right)^k$$

Figure 7. Equation. Probability of fatality or serious injury for one vehicle at crossing, merging, or diverging conflict point c_{veh}.

In this model, $\Delta V_{U\_i,c\_veh}$ represents the change in the velocity vector of vehicle U_i between a point in time just before the crash and a point in time just after the crash. The SSI method employs an approach to estimate $\Delta V_{U\_i,c\_veh}$ based on the speeds of vehicles U_1 and U_2 at each crossing, merging, and diverging conflict point (S_{U1,c_veh} and S_{U2,c_veh}) and ϕ_{c_veh}, shown in figure 8.

$$\Delta V_{U_i,c_{veh}} = \frac{\sqrt{S_{U1,c_{veh}}^2 + S_{U2,c_{veh}}^2 - 2S_{U1,c_{veh}}S_{U2,c_{veh}}\cos(\phi_{c_{veh}})}}{2}$$

Figure 8. Equation. Delta-V for vehicle U_i at conflict point c_{veh}.

This approach for estimating $\Delta V_{U\_i,c\_veh}$ assumes conservation of momentum and equal masses of both colliding vehicles. Under these assumptions, "delta-V" for both vehicles is the same (i.e. $\Delta V_{U\_1,c\_veh} = \Delta V_{U\_2,c\_veh}$). Evans (1994) estimated different values for α and k in figure 7 for different combinations of occupant restraint use and crash severity using 1982-1991 crash data from the National Automotive Sampling System (NASS). Evans (1994) only included crashes in his analysis where "delta-V" was estimated and coded through a structural analysis of the vehicle deformation produced by the crash; table 5 summarizes his results.

Table 5. Regression parameters as computed by Evans (1994).

	Fatality (unbelted)	Fatality (belted)	Fatality (frontal)	Fatality (all)	Serious Injury[1] (unbelted)	Serious Injury[1] (belted)
α	70.61	69.18	66.01	70.75	66.09	67.43
k	3.54	4.57	2.22	2.62	3.80	4.51
S.E. for *k*	0.18	0.25	0.11	0.17	0.17	0.32
[1]Evans (1994) uses the term "severe injuries," and notes that the term indicates injuries rated at 3 or greater on the AIS.						

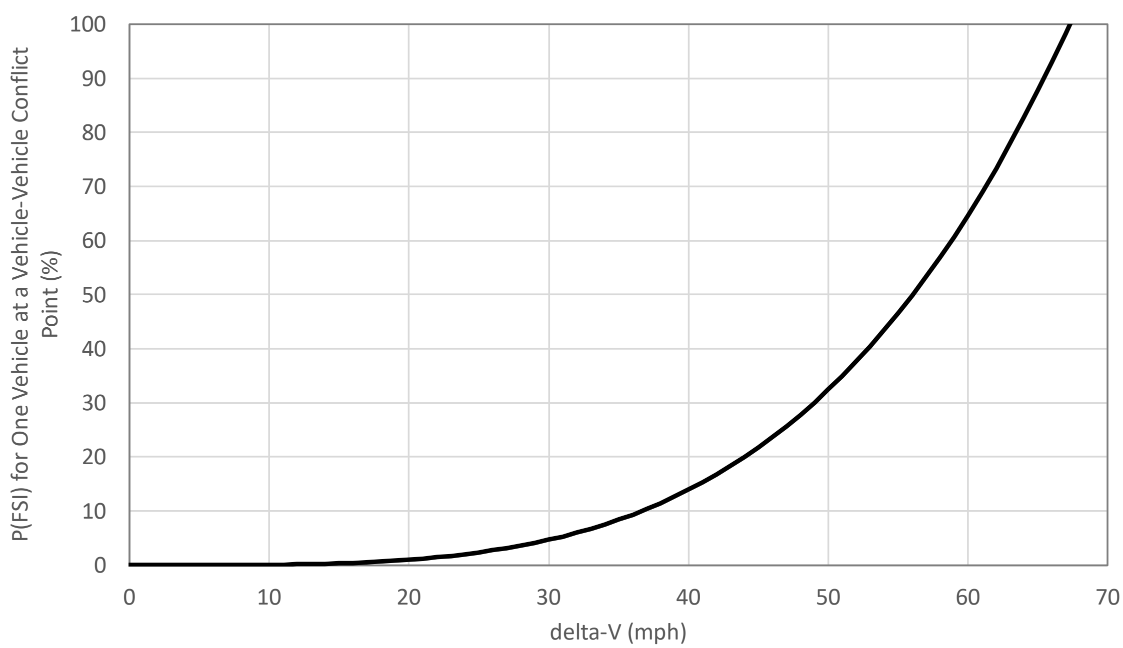
The SSI method requires this approach to be more general, without consideration of occupant restraint use, so its development comprised an estimation of weighted averages of the two regression parameters, α and k, to combine the different scenarios that Evans had considered. The process involved querying four years of crash data (2014 to 2017) from NHTSA's Fatality and Injury Reporting System Tool (FIRST). FIRST allows users to query several crash databases including the Fatality Analysis and Reporting System (FARS), which contains records of every fatal crash in the U.S., and the Crash Report Sampling System (CRSS), which contains data from nationally representative police reported crashes of all severities. FIRST also contains data elements that allow the user to filter based on the restraint use.

The next step created distributions based on crash severity and restraint use with the FIRST data, matching the scenarios Evans developed in table 5.

These crash distributions yielded estimates for:

- Percent of fatal and injury crashes that result in a fatality.
- Percent of fatal and injury crashes that result in no fatality.
- Percent of fatalities in which the person was belted.
- Percent of injuries in which the person was belted.

The final step used these four percentages to compute weighted averages of the values Evans calculated, which resulted in α = 67.29 and k = 3.79. Incorporating these values into figure 7 results in the *P(FSI)* relationship illustrated by figure 9.



Source: FHWA

Figure 9. Graphic. *P(FSI)* for occupants of one vehicle versus delta-V of that vehicle during a crash.

After estimating *P(FSI)* for each vehicle, the SSI method estimates *P(FSI)* at the crash-level (considering occupants of both vehicles) using figure 10.

$$P_{FSI,crash,c_{veh}} = P_{FSI,U_1,c_{veh}} + P_{FSI,U_2,c_{veh}} - P_{FSI,U_1,c_{veh}} \times P_{FSI,U_2,c_{veh}}$$

Figure 10. Equation. Probability of fatality or serious injury for both vehicles at conflict point c with weighted average regression parameters.

3.6.2 Nonmotorized Conflict Points

The SSI method estimates the severity of nonmotorized-vehicle conflict points based on the speed of vehicles traveling through the nonmotorized conflict point. The approach is based on a combination of data from Tefft (2013) and Chidester & Isenberg (2001). Tefft (2013) modeled the probability of pedestrian fatality or severe injury based on the estimated vehicle speed at impact using data from NHTSA's NASS Pedestrian Crash Data Study (PCDS). Tefft (2013) noted these data are the most recent U.S. data of pedestrian crashes where impact speed was estimated using crash reconstruction methods. The study did not directly present the model details but did present the results in tabular form, as shown in table 6.

Table 6. Estimated impact speeds at which risk of severe injury and death reach specified levels, adapted from Tefft (2013).

Risk (%)	Severe Injury[a]	
	Impact Speed (mph)	95% Confidence Interval
10	17.1	(14.4 – 20.0)
25	24.9	(22.4 – 27.6)
50	33.0	(29.9 – 37.2)
75	40.8	(36.5 – 47.3)
90	48.1	(42.4 – 57.1)

[a]Severe injury is defined as a MAIS score of 4 or greater and includes fatality.

Tefft's (2013) numbers can be represented by a logistic regression model, such as that shown in figure 11.

$$P_{FSI,Ped,c_{ped}}(V) = \frac{1}{1 + e^{-\beta_1 - \beta_2 * V}}$$

Figure 11. Equation. Logistic regression model form for nonmotorized road user fatality and severe injury based on Tefft (2013).

In this functional form, β_1 and β_2 are regression coefficients, and V is the estimated vehicle speed at impact in mph. Transforming the logistic regression model into a linear form allows least squares linear regression to determine the unknown coefficients that best fit the Tefft (2013) results. However, additional adjustments to the results are needed.

First, Tefft's model defined fatality and severe injury as a MAIS score of 4 and above. Therefore, to remain consistent with the definition of fatality and serious injury used in the vehicle-vehicle conflict point severity method detailed in the previous section, the model derived directly from Tefft's (2013) results had to be adjusted to account for MAIS scores of 3 and above. This modification was informed by a general distribution of MAIS data for pedestrian crashes in the U.S., in addition to data from the NHTSA PCDS (Chidester & Isenberg, 2001).The distribution of MAIS scores presented in Chidester & Isenberg (2001) shows that the percentage of pedestrian crashes with MAIS 3 and above is 15 percentage points higher than the percentage of pedestrian crashes with MAIS 4 and above.

Since Chidester & Isenburg (2001) did not present the MAIS percentages as a function of speed, the 15 percentage-point increase had to be distributed across the speeds in table 6, thereby increasing the corresponding risk at each speed. The distribution was determined using a table in the Tefft (2013) study that grouped the number and percentage of crashes by ranges of impact speeds (see table 7). The percentages from table 7 were applied to the overall 15 percentage-point increase for each respective row in table 6 to arrive at a risk adjustment. Table 8 provides the calculations and results.

Table 7. Percentage of crashes by impact speed from Tefft (2013).

Impact Speed (mph)	Percentage of Crashes (%)
< 15.0	52%
15.0-24.9	25%
25.0-34.9	12%
35.0+	11%

Table 8. MAIS4+ to MAIS3+ risk adjustments and results.

Risk of MAIS 4+ (%)	Impact Speed (mph) Table 7	Risk Adjustment	Estimated Risk of MAIS 3+ (%)
10	17.1	15% * 52% = 7.8%	17.8
25	24.9	15% * 25% = 3.8%	28.8
50	33	15% * 12% = 1.8%	51.8
75	40.8	15% * 7.3% = 1.1%[1]	76.1
90	48.1	15% * 3.7% = 0.6%[1]	90.6

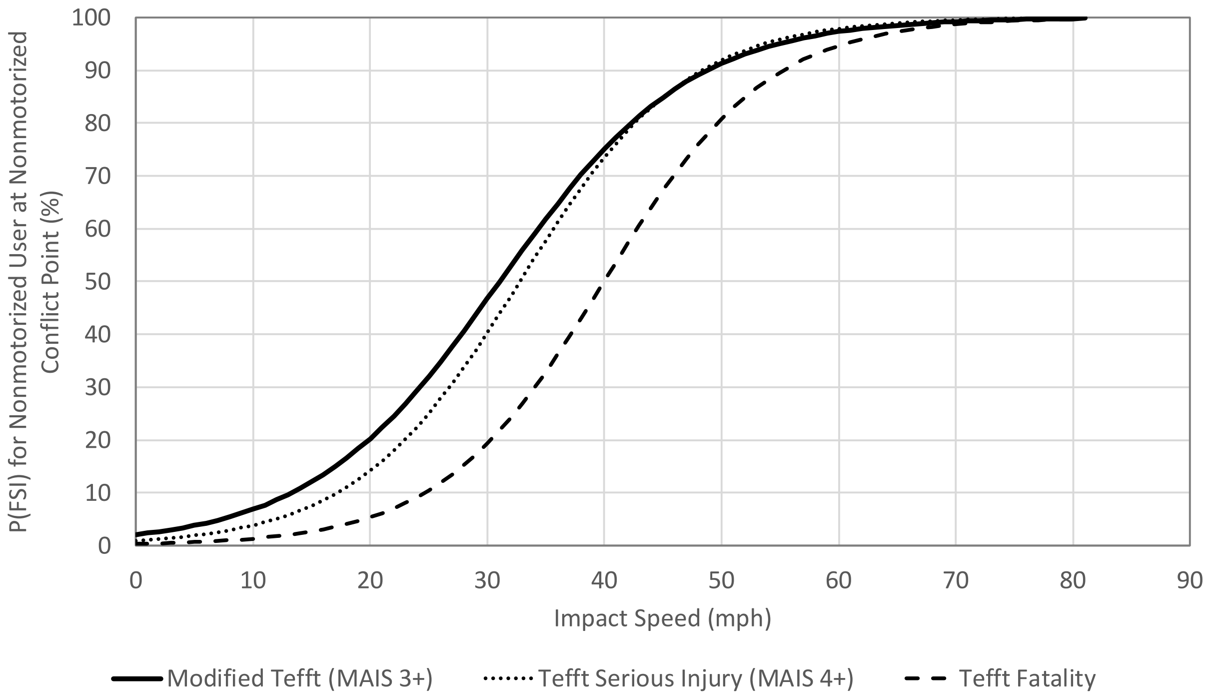
[1]Two-thirds of the 11% of crashes at 35 mph+ impacts speeds are applied to the 40.8 mph row; one-third to the 48.1 mph row.

The adjusted risk percentages and the impact speeds were used to determine the unknown coefficients in the logistic regression model in figure 11. Figure 12 represents the final model used by the SSI method for estimating *P(FSI)* at nonmotorized conflict points.

$$P_{FSI,Ped,c_{ped}} = \frac{1}{1 + e^{3.8432 - 0.1237V}}$$

Figure 12. Equation. Probability of fatality or serious injury for nonmotorized collision point c.

The lines in figure 13 represent the different nonmotorized risk curves discussed in this section. The solid line denotes the modified Tefft model developed for use in the SSI method. It generally predicts a higher risk of nonmotorized fatality or serious injury than the other curves, except at high speed values. This result is intuitive, as these higher-speed crashes are likely to result in injuries above MAIS 4, and therefore adding the MAIS 3 category does not alter the curve at higher speeds.



Source: FHWA

Figure 13. Graphic. Comparison of pedestrian risk curves.

While both the Tefft (2013) and Chidester & Isenberg (2001) studies focused on pedestrian crashes, the SSI method applies the severity curve here to both pedestrians and cyclists as part of the previously highlighted SSI assumption that bicyclists follow the same paths as pedestrians through intersections.

3.6.3 Speed and Angle Assumptions

Application of the *P(FSI)* models to determine conflict point severity requires estimates of vehicle speeds through each conflict point and – for vehicle-to-vehicle conflicts – an estimate of the collision angle between the vehicles.

Vehicle Speeds. There is little existing research into speed prediction at intersections, especially in differentiating speeds of different movements and maneuvers at different points throughout the vehicle path. The research that does exist (mostly for right-turning movements) requires geometric inputs that are generally not available during a project scoping stage. For this reason, the SSI method adopts a simplified set of speed assumptions to cover the different vehicle maneuvers at intersections. These assumptions can be adjusted based on local knowledge or any data that become available in the future.

First, each vehicle movement at a conflict point is assigned to a speed category. Table 9 illustrates the assignment of speed categories for the movements at eight of the different intersection configurations included in the SSI library of intersection types in appendix A: 1) signalized traditional, 2) minor road stop control (MRSC) traditional, 3) all-way stop control (AWSC) traditional, 4) signalized restricted crossing U-turn (RCUT), 5) unsignalized RCUT, 6) median U-turn (MUT), 7) jughandle, and 8) quadrant roadway (QR). The speed category assignment is based on a combination of factors including the intersection type, traffic control type, and movement. Movements that are not controlled by traffic signals or stop signs (typically uncontrolled major road movements) are assigned the speed category that corresponds to that movement. For example, the major road through movement at a MRSC intersection would be assigned the "major through" speed category. If the movement in question originates on an approach operating under stop or signal control, the movement is assigned to that respective speed category. For example, the left turn movement from the minor road at a signalized traditional intersection (i.e., minor left movement in the first column of table 9) is assigned to the signal control speed category. The exceptions are movements from the major road at a signalized intersection. The SSI method makes a simplifying assumption of assigning these movements to the uncontrolled category. For example, a through movement on the major road at a signalized traditional intersection (i.e., major through) will be assigned to the "major through" speed category, based on the assumption that most vehicles on the major road arrive during a green signal indication and are not making different movements from a stopped position. However, this assumption could be adjusted to reflect different conditions.

Table 9. Speed category assignments for different intersection types.

Movement	Traffic Control Type							
	Signalized Traditional	MRSC Traditional	AWSC Traditional	Signalized RCUT	Unsignalized RCUT	MUT	Jughandle	Quadrant Roadway
Major through	Major through	Major through	Stop	Major through	Major through	Major through	Major through	Major through
Major left turn (LT)	Major left	Major left	Stop	Major left	Major left	Major left	Major left	--
Major right turn (RT)	Major right	Major right	Stop	Major right	Major right	Major right	Major right	Major right
Minor through	Signal	Stop	Stop	--	--	Signal	Signal	Signal
Minor left	Signal	Stop	Stop	--	--	--	Signal	--
Minor right	Signal	Stop	Stop	Signal	Stop	Signal	Signal	Signal
Major U-turn	--	--	--	Signal	Stop	Signal	--	--
Jughandle left	--	--	--	--	--	--	Signal	--
Jughandle right	--	--	--	--	--	--	Signal	--
Minor through at jughandle	--	--	--	--	--	--	Minor through	--
Minor through at QR	--	--	--	--	--	--	--	Minor through
Minor LT into QR	--	--	--	--	--	--	--	Minor left
Minor RT into QR	--	--	--	--	--	--	--	Minor right
Major LT into QR	--	--	--	--	--	--	--	Major left
Major RT into QR	--	--	--	--	--	--	--	Major right
Left turns from QR	--	--	--	--	--	--	--	Signal
Right turns from QR	--	--	--	--	--	--	--	Signal

Next, each speed category is matched to the corresponding speed values in table 10. There are two speed values that apply to movements governed by stop control and therefore assigned to the stop control speed category: stop near-side and stop far-side. The stop control near-side speed value in table 10 is applied to movements made from stop control at conflict points on the side of the intersection near the stop bar from which the vehicle has accelerated. The stop control far-side speed value in table 10 is applied to movements made from stop control at conflict points on the side of the intersection opposite the stop bar, where the vehicle has had more opportunity to accelerate.

There are two similar speed values for the signal control speed category: signal control near-side and signal control far-side. These speed values are only applied to minor road approaches at signalized intersections. This assumes that minor road traffic will typically arrive on a red signal indication, accelerating from a stop when the signal changes to green.

Finally, there are three specific speed values for roundabouts – entering, circulating, and exiting – due to their unique geometric characteristics and inherent effects on vehicle speed, as well as their distinct arrangement of vehicle movements.

Agencies are encouraged to assess the speed value ranges in table 10 and adjust them based on local knowledge or available intersection speed data.

Table 10. Assumed speed values for SSI methodology.

Speed Category	Speed (mph)	
	Low End	High End
Major through	0.9 * Major PSL	1.1 * Major PSL
Major left	10	30
Major right	10	20
Minor through	0.7 * Minor PSL	Minor PSL
Minor left	10	30
Minor right	10	20
Stop control near-side	10	20
Stop control far-side	20	30
Signal control near-side	10	20
Signal control far-side	20	30
Roundabout entering	10	20
Roundabout circulating	15	25
Roundabout exiting	20	30

For vehicle-nonmotorized conflict points, the SSI method only requires the vehicle speed at the conflict point to compute *P(FSI)*. This speed is assigned as described above based on the vehicle movement involved at the conflict point.

This approach to determining vehicle speeds may not apply perfectly to every potential traffic control situation or vehicle maneuver at a given intersection. Users of the method are encouraged to adjust the speeds as they see fit to better reflect the conditions of the intersection being analyzed. Additionally, ongoing and future research may inform improvements to these speed assumptions, such as through increased understanding of the effects of different traffic control types, traffic volumes, and approach geometry on vehicle speeds. Chapter 5 contains additional discussion of speed data and modeling needs to support future SSI enhancements.

Collision Angles. The collision angle used to compute conflict point severity in the SSI method is based on the convention established in Jurewicz et al. (2017) (see figure 6). To facilitate efficient application to a variety of intersections, the SSI method uses five categories of potential collision types with assumed collision angles, as shown in table 11.

Table 11. Collision angle assumptions for SSI methodology.

Collision Type	Typical Collision Angle Range (deg)
Crossing – Broadside	80 – 100 (or 260 – 280)
Crossing – Left Turn	220 – 240
Crossing – Roundabout	45 – 75
Merging	30 – 60 (or 300 – 330)
Diverging	0 – 20 (or 340 – 360)

These collision angles are based on typical movement arrangements at intersections. They do not account for intersection skew or other context-specific geometrics but could be adjusted if that information is available.

3.7 MOVEMENT COMPLEXITY, USER WORKLOAD, AND THE SSI SCORE

The information provided in sections 3.4 to 3.6 and appendix A present steps to identify and classify conflict points for different intersection alternatives, determine user exposure at different conflict point types, and quantify conflict point severity. Measures derived from these steps can begin to give intersection planners and designers a general idea of how an intersection alternative aligns with Safe System principles. Possible MOEs to this point include the level of exposure for each conflict point type combined with the average *P(FSI)* for those same conflict point types.

Concepts that consider user behavior and performance, along with the workload imposed (or mitigated) by the design and operation of the intersection will also affect the crash risk per given level of exposure (Layer 4 of the KEMM). The SSI method therefore considers intersection features that represent the overall intersection form and size and that could affect the task complexity for users making specific movements (i.e., passing through specific conflict points) at an intersection. Section 3.7 presents a series of concepts intended to represent the level of complexity for different movements through an intersection. The SSI method assumes that intersection attributes associated with lower levels of complexity for all users brings an intersection into closer alignment with a Safe System.

Factors representing movement complexity are combined with the concepts of exposure and severity through an SSI score. The SSI score has a range of zero to 100, with 100 representing combinations of project contexts and intersection alternatives that are closest to a Safe System for the users considered by this method. The method produces an SSI score for each conflict point type (i.e., crossing, merging, diverging, nonmotorized) as well as for the intersection.

The first step in determining the SSI score is to compute the sum of the exposure-severity-complexity products for all individual conflict points of a specific type, E_t (see figure 14). This is done for all four conflict point types to create $E_{crossing}$, $E_{merging}$, $E_{diverging}$, and $E_{nonmotorized}$.

$$E_t = \sum_{i=1}^{n_t} \left[I_{i,t} * \mathrm{P(FSI)}_{i,t} * L_{1,i,t} * L_{2,i,t} \right]$$

Figure 14. Equation. Sum of exposure-severity-complexity products for all conflict points of type *t*.

L_1 and L_2 are complexity factors that are described in sections 3.7.2 and 3.7.3 of this chapter.

The second step is to estimate the SSI scores for the combined conflict points of type *t*, SSI_t.

$$SSI_t = 100 \times \exp\left(-\frac{1}{z} \times E_t\right)$$

Figure 15. Equation. SSI score for all conflict points of type *t*.

The parameter z, within the structure of figure 15, is a constant that scales the sum of exposure-severity-complexity products to the SSI score that falls between zero and 100. It is a feature of the method and is based on the distribution of values for the sum of exposure-severity-complexity products across a wide range of different intersection alternatives and project contexts. If the process and assumptions in this report are followed to develop the exposure-severity-complexity products for an intersection, the value for z is 1.37×10^7. The value would not be calibrated or adjusted to local conditions in this case.

The third and final step is to estimate the SSI score for the intersection, SSI_{int}, considering all conflict points combined. This step is performed using the equation in figure 16.

$$SSI_{int} = 100 \times \exp\left[-\frac{1}{z} \times \left(E_{crossing} + E_{merging} + E_{diverging} + E_{nonmotorized}\right)/4\right]$$

Figure 16. Equation. Intersection SSI score (all conflict points combined).

The following sections discuss the two complexity factors, L_1 and L_2, that are part of the exposure-severity-complexity product. L_1 addresses complexity added by the characteristics of conflicting traffic, which can be moderated by the type of traffic control. L_2 addresses additional complexity specific to nonmotorized movements through the intersection.

3.7.1 Conflict Point Application of the Complexity Factors

The complexity concepts in this section are applicable to a movement level (e.g., left turn from major road, through movement on minor road, etc.). However, the notation in figure 14 shows that the two complexity factors, L_1 and L_2, are applied at the individual conflict point level *i*. This is done by applying the complexity factor for a movement to the applicable conflict points along that same movement. The following sections will illustrate this movement-level analysis and corresponding conflict point application. Appendix B provides example calculations and applications of the two complexity factors.

3.7.2 Conflicting Traffic Complexity Factor

The first intersection complexity factor, L_1, captures complexity added by the characteristics of conflicting traffic, while accounting for how much of that complexity is moderated by the type of traffic control. L_1 applies to both vehicle and nonmotorized movements through an intersection and therefore to the vehicle-vehicle and vehicle-nonmotorized conflict points along those movements.

For each possible movement, L_1 is computed as the product of three parameters that represent the characteristics of the traffic control and conflicting traffic for that movement (shown in figure 17).

$$L_1 = a_{traffic\ control} * a_{conflicting\ \ lanes} * a_{conflicting\ \ speed}$$

Figure 17. Equation. Conflicting traffic complexity factor, L_1.

In figure 17, the three parameters on the right side of the equation represent the increased or decreased complexity due to the type of traffic control, the number of conflicting lanes, and the speed of conflicting traffic for different movements through the intersection. The remainder of section 3.7.2 describes each of these parameters in detail.

Traffic Control. The first parameter included in the conflicting traffic complexity factor, L_1, is the traffic control parameter, $a_{traffic\ control}$. This parameter accounts for the reduction in complexity that occurs when certain movements are separated in time due to the type of traffic control. As an example, the left-turning movement from the minor road could be a complex movement depending on the number of lanes and speed of conflicting traffic on the major road approaches. However, if the intersection is signal controlled, the minor and major road movements will not operate simultaneously, significantly decreasing the complexity of making the left-turn movement from the minor road. The traffic control parameter in this case will be a value less than one, reducing the conflicting traffic complexity factor for the left-turning movement from the minor road.

The traffic control parameter takes the form in figure 18, with *BTCAV* representing the base traffic control adjustment value and *f* representing a weight given to the use of traffic control devices, and user compliance to those traffic control devices, to separate conflicts.

$$a_{traffic\ control} = BTCAV + (1 - f) * (1 - BTCAV)$$

Figure 18. Equation. Traffic control parameter, $a_{traffic\ control}$.

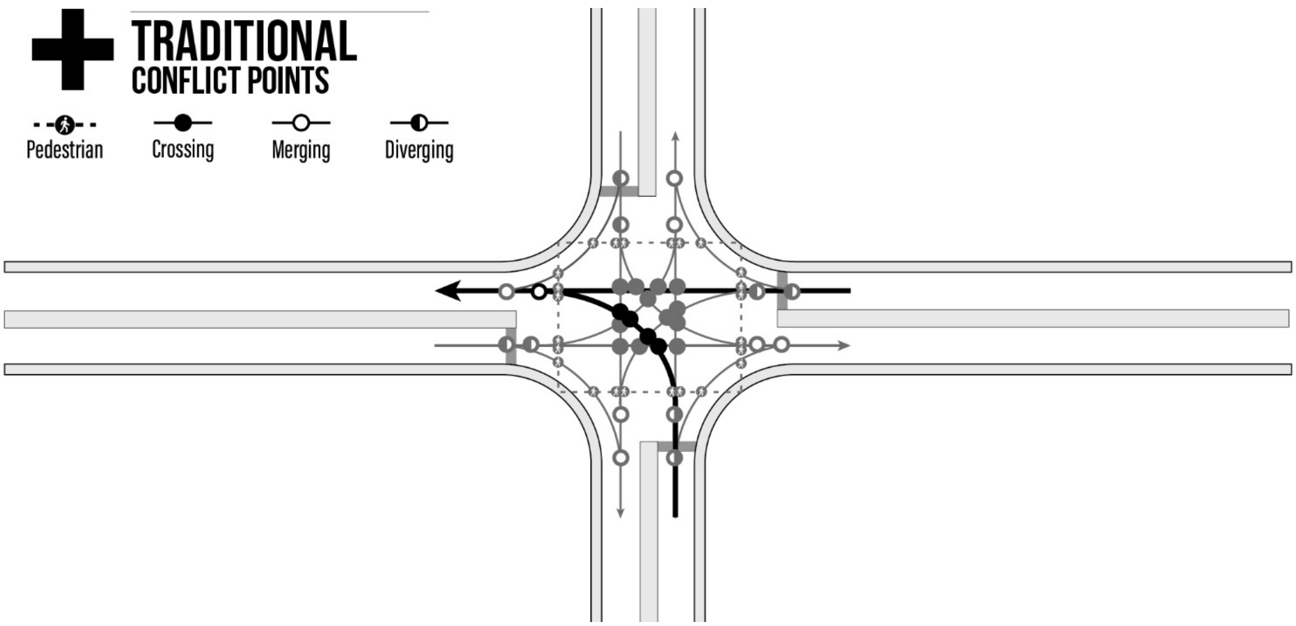
In the SSI method, potential values for *BTCAV* are informed by Crash Modification Factor (CMF) values for stop control, protected, and protected/permitted traffic signal control operations. The traffic control categories and corresponding *BTCAV* assumed ranges are:

- Permitted or yield control: 1.0.
- Protected/Permitted: 0.6-0.9 (based on CMF Clearinghouse ID 4270).
- Protected: 0.005-0.015 (based on CMF ID 333).
- Stop-Control: 0.4-0.5 (based on CMF ID 309, inverse).

The type of control for each movement and the corresponding *BTCAV* applied to each conflict point along a movement is determined based on the type of conflict separation achieved by the traffic control. For example, figure 19 shows a left turn movement from the minor road of a traditional, four-leg intersection. For illustration purposes, the discussion will consider this left-turn movement if the intersection operated as MRSC or if the intersection was signalized. There are eight conflict points along this left turn movement from the minor road:

- One diverging conflict point between the left-turn and through movement from the same minor road approach.
  - Since the SSI method does not currently incorporate effects of traffic control devices on rear-end conflicts, the value for $a_{traffic\ control} = BTCAV = 1$ for this diverging conflict point, regardless of whether the intersection is MRSC or signalized.
- Two nonmotorized conflict points: one between the left-turn and nonmotorized road users crossing the same minor road approach and one between the left-turn and nonmotorized road users crossing the major road.
  - For MRSC, since the minor road left turn of interest is coming from a stop-controlled approach, both nonmotorized conflict points are assigned to the stop control category.
  - For signalized operation, the conflict point between the minor road left turn and nonmotorized road users crossing the minor road approach is assigned to the protected category, since the signal control will separate these two movements in time. The conflict point between the minor road left turn and nonmotorized road users crossing the major road approach will be assigned to either the permitted, protected/permitted, or protected category, depending on the type of phasing for the left turn movement.
- Four crossing conflict points: one each with the through movement and the left turn from the near-side major road approach, one with the left turn from the far-side major road approach, and one with the opposing through movement on the minor road.
  - For MRSC, all four crossing conflict points are assigned to the stop control category.
  - For signalized operation, the three crossing conflict points between the minor road left turn and the through and left turn movements from the major road are assigned to the protected category, since the signal control will separate these movements in time. The crossing conflict point between the minor road left turn and the opposing minor road through will be assigned to either the permitted, protected/permitted, or protected category, depending on the type of phasing for the left turn movement.

- One merging conflict point with the far-side major road through movement.
    - For MRSC, the merging conflict point is assigned to the stop control category.
    - For signalized operation, the merging conflict point is assigned to the protected category, since the signal control will separate these movements in time.



Source: FHWA

Figure 19. Graphic. Minor road left turn to illustrate the SSI traffic control parameter.

Based on the foundational Safe System principles in chapter 2, the SSI method provides the option of reducing the *BTCAV* using a weight, *f*, less than one. This would mean that the traffic control parameter would not reduce movement complexity by the full value of the *BTCAV*. The traffic control parameter is dependent on user compliance with traffic control devices. The Safe System literature in chapter 2 suggests that traffic control devices would receive a "lower weight" as part of a Safe System analysis. For example, Jurewicz et al. (2015) conclude that separating movements by signalization provides only low to moderate levels of alignment with a Safe System at an intersection. Johansson (2009) asserts that separation in a Safe System is physical separation of conflicting movements and is not a temporal one, such as with traffic signal timing. Example calculations in this document use a traffic control parameter weight, f, of 0.5. Agencies can adjust values for *BTCAV* and *f* based on local conditions and experience.

As one example calculation, when the two movements that define a given conflict point are controlled by protected-permitted signal control (e.g., left-turns from the major road and opposing through movements), the corresponding *BTCAV* is 0.6-0.9 (assume 0.85 for this example). The traffic control parameter for this conflict point is computed using figure 18. The example calculation that incorporates a weight of 0.5 is shown in figure 20.

$$a_{traffic\ \ control} = 0.85 + (1 - 0.5) * (1 - 0.85) = 0.925$$

Figure 20. Equation. Example traffic control parameter calculation.

Conflicting Lanes. The conflicting lanes parameter, $a_{conflicting\ lanes}$, of the conflicting traffic complexity factor considers the overall intersection size and the potential workload on road users as they make specific movements through the intersection. The parameter is based on the number of lanes that carry conflicting traffic movements for a selected movement of interest. For any selected movement in the following "list of movements", conflicting traffic movements are those that cross or merge with the selected movement of interest and are also listed above the selected movement on the list:

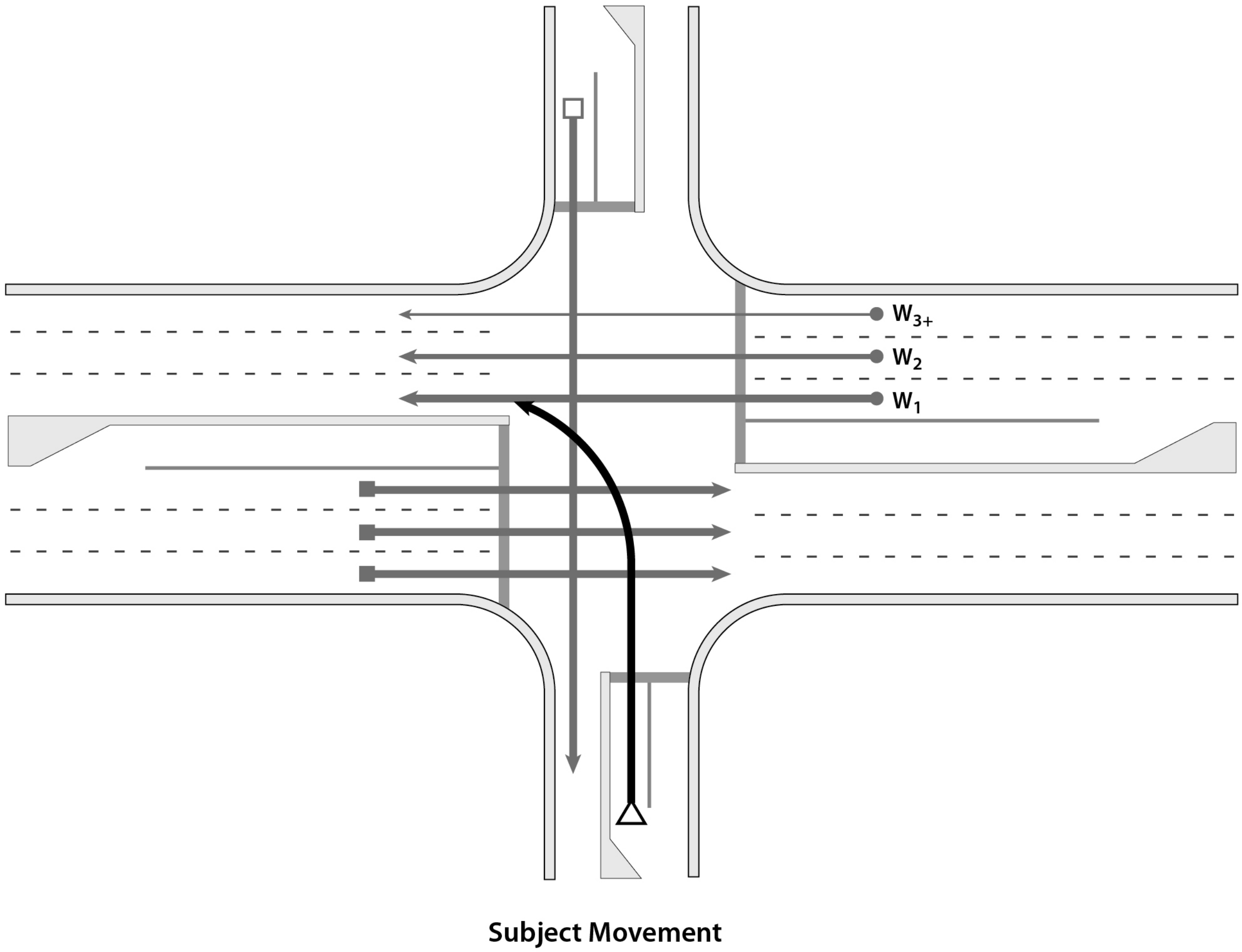
1. Major through and right turn.
2. Major left turn.
3. Minor through and right turn.
4. Minor left turn.
5. Nonmotorized.

Placing nonmotorized movements at the bottom of this list prioritizes nonmotorized movements in the SSI analysis when characterizing the complexity of an intersection. Although nonmotorized road users typically have higher priority from a regulatory or traffic control perspective, their vulnerability in a crash, along with uncertainty about driver awareness of their presence at any given time, may require nonmotorized road users to be aware of conflicting traffic movements that are lower-priority from a regulatory or traffic control perspective.

In the SSI method, the complexity of each movement at an intersection is scored based on how many conflicting major and minor approaching traffic streams the movement crosses and/or merges with and the number of through lanes on those approaches (i.e., excluding turn lanes, whose presence may or may not be known during a Stage I ICE). To illustrate this concept, there are three through lanes on the eastbound approach in figure 21, three through lanes on the westbound approach, and one through lane each on the north and southbound approaches. Subsequent paragraphs detail the steps of calculating the conflicting lanes parameter, first for vehicle-vehicle conflict points and then for nonmotorized-vehicle conflict points, and continue to reference the illustrative example in figure 21.

Beginning with vehicle-vehicle conflict points, the first step in computing the conflicting lanes parameter for each movement is to determine the movement's cross score. A movement's cross score is the maximum sum of through lanes (i.e., 1, 2, 3…) carrying conflicting traffic on the intersection approaches that a movement crosses without refuge during the movement.

Using the example of the left-turning movement from the minor road in figure 21, this movement crosses the approaching traffic stream on the near-side of the major road—three lanes in this case—plus the opposing through traffic stream—one lane in this case—on the minor road. A median is not present to provide refuge to the left-turning vehicle and allow a two-stage movement. Thus, the resulting cross score for the left turn from the minor road is 4. If there was a median wide enough to allow a two-stage movement, the cross score for this movement would be 3. Median details may not be available during a Stage 1 ICE, but medians are an inherent part of some intersection alternatives. Appendix A provides default median assumptions contained within the intersection diagrams and Stage 1 calculations of this report.



Source: FHWA

Figure 21. Graphic. Example crossing and merging for left-turn movement from the minor road.

The second step in computing the conflicting lanes parameter for each vehicular movement is to determine the movement's merge score. The merge score considers the number of lanes on the intersection approach that the subject movement is merging with, N_M. Table 12 contains the equations for computing the merge score for different values of N_M.

Table 12. Merge score for conflicting lanes parameter.

Number of Through Lanes on Merge Approach (N_M)	Merge Score
1	M
2	$M(1 + W_2)$
3+	$M[1 + W_2 + W_{3+}(N_M - 2)]$

In table 12, *M* represents a binary indicator variable capturing whether or not the merge score applies to the subject movement. The value for *M* will be 1 for any of the following movements:

- A turning movement merging with a through movement that is higher than the turning movement on the list of movements (e.g., a right turn from the minor road merging with a through movement on the major road).
- A movement entering the circulatory roadway of a roundabout and merging with traffic that is in already in the circulatory roadway and continuing around the circulatory roadway.
- A movement that approaches a roundabout and turns right merging with traffic that is exiting the roundabout in that same direction.

The value for *M* will be 0 otherwise. W_2 and W_{3+} represent the merging weights for Lane 2 (the lane adjacent to the lane the driver is merging into) and Lane 3+ (any lanes beyond Lane 2). These weights represent the relative level of attention needed from the driver for selecting a gap. The default values for W_2 and W_{3+} are 0.75 and 0.5, respectively. Lane 1 (the lane the driver is merging into) has a merging weight of 1 because the driver would generally be paying full attention to traffic in the lane they are merging into.

Building on the example in figure 21, the left-turning movement from the minor road is merging with traffic from a major road approach having three through traffic lanes. The merge score in this case is shown in figure 22.

$$Merge\ score_{veh} = M\big(1 + W_2 + W_{3+}(N_M - 2)\big) = 1\big(1 + 0.75 + 0.5(3 - 2)\big) = 2.25$$

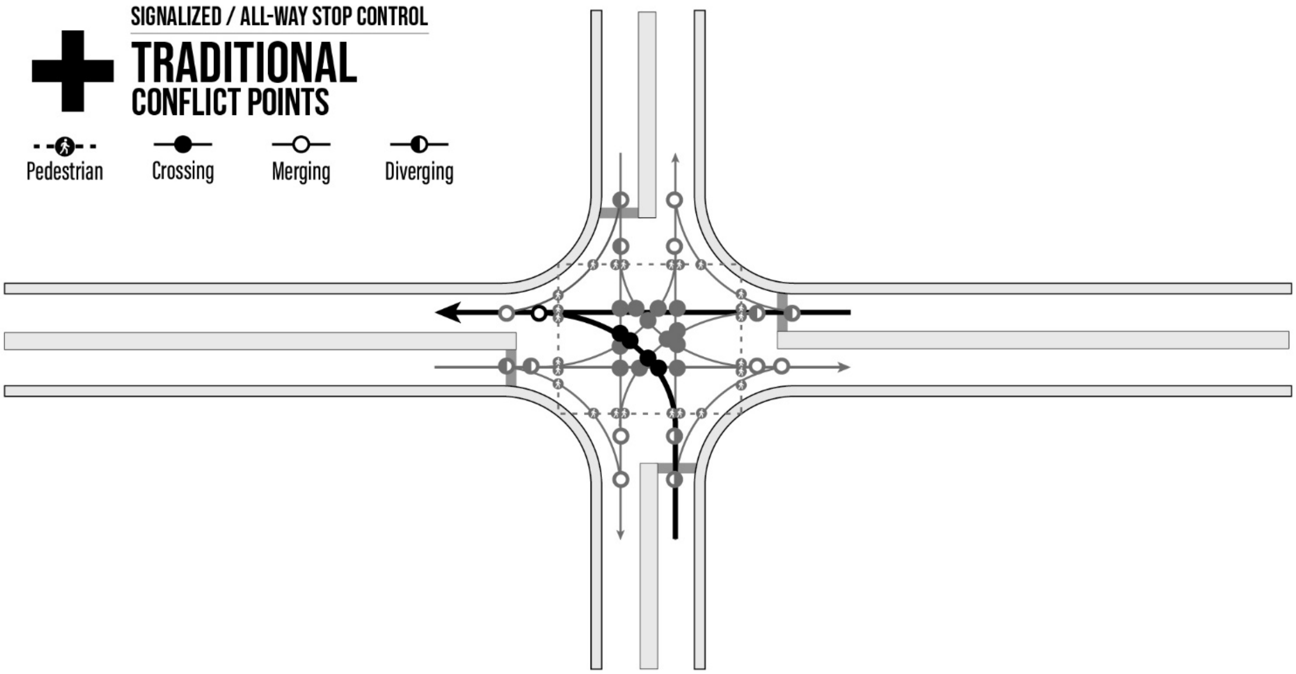
Figure 22. Equation. Example merge score calculation.

The merge score is added to the cross score to determine the overall conflicting lanes parameter, $a_{conflicting\ lanes}$(see figure 23).

$$a_{conflicting\ \ lanes,veh} = Cross\ Score_{veh} + Merge\ Score_{veh}$$

Figure 23. Equation. Conflicting lanes parameter – vehicles.

In this vehicle-vehicle conflict point example, the conflicting lanes parameter for the left-turning movement from the minor road in figure 21 is 6.25. The number 6.25 is $a_{conflicting\ lanes}$ when computing the conflicting traffic complexity factor for the individual crossing and merging conflict points along this left-turn movement and where the left-turn movement is the lower movement on the list of movements. These five conflict points for the left-turning movement from the minor road in figure 21 are identified with darker linework in figure 24.



Source: FHWA

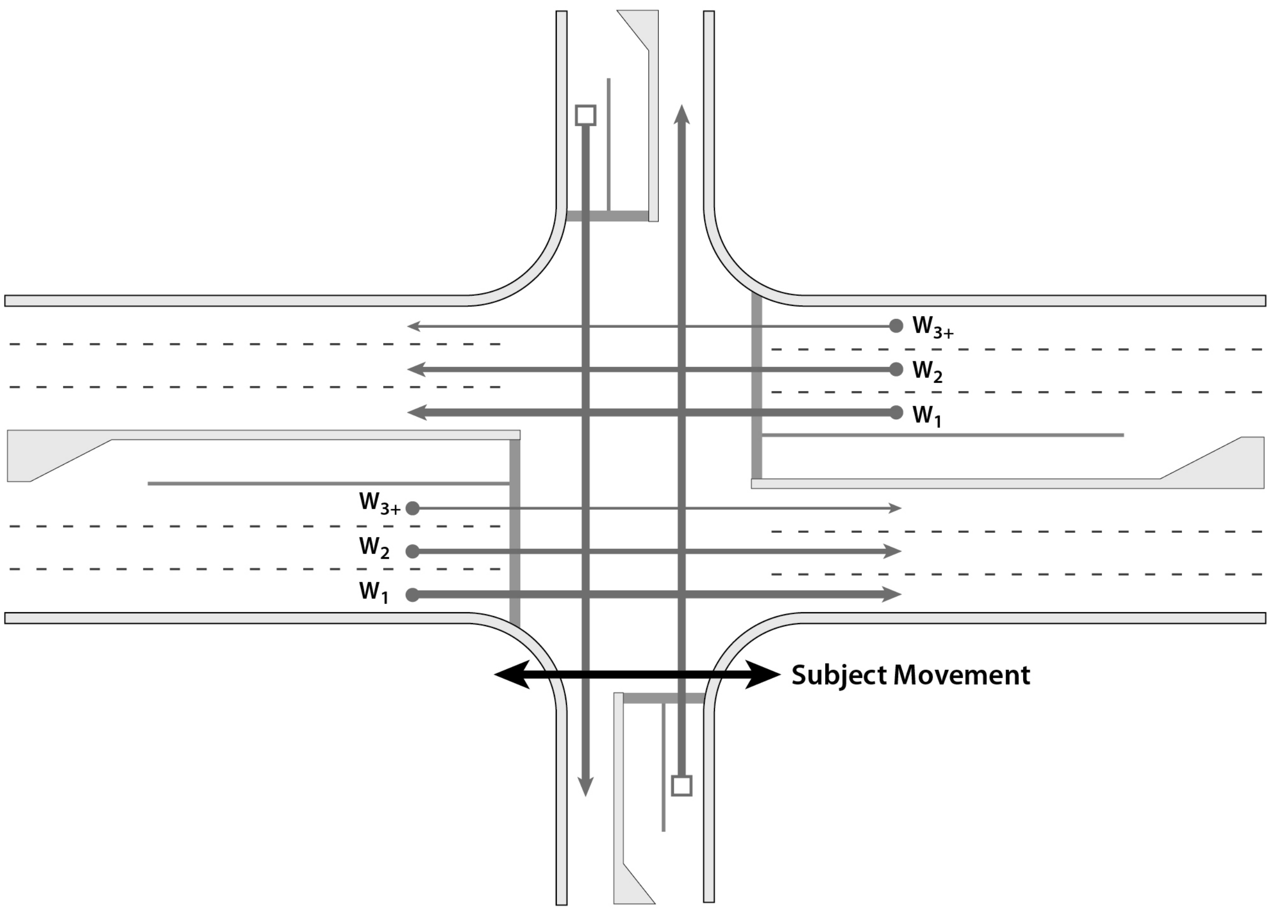
Figure 24. Graphic. Four crossing and one merging conflict points that receive the conflicting lanes complexity parameter associated with the left-turn movement from the minor road.

The conflicting lanes parameter for each nonmotorized movement is based on similar concepts, but with some differences in the details. The conflicting lanes parameter for a nonmotorized movement is the nonmotorized movement's cross score plus a total nonmotorized turn score, as shown in figure 25.

$$a_{conflicting\ lanes,nonmotorized} = cross\ score_{nonmotorized} + total\ turn\ score_{nonmotorized}$$

Figure 25. Equation. Conflicting lanes parameter – nonmotorized road users.

A nonmotorized movement's cross score is the maximum number of through lanes that the nonmotorized movement must cross without refuge. The total nonmotorized turn score considers complexity added by pedestrians or cyclists checking for oncoming vehicles from approaches parallel to their movement. In the case of the traditional intersection example shown in figure 26, a nonmotorized road user crossing the south leg of the intersection must cross the northbound through lane and the southbound through lane (turn lanes are not considered in the current SSI method). There is no refuge island. This results in a value of 2 for this nonmotorized movement's cross score. The nonmotorized road user is also monitoring the eastbound and westbound approaches to determine if any vehicles may be turning from those approaches into the nonmotorized road user's path (i.e., a right turn from the eastbound approach or a left turn from the westbound approach).



Source: FHWA

Figure 26. Graphic. Example for nonmotorized movement crossing the minor road.

To account for the complexity added by approaching traffic on the parallel approaches, table 13 presents a series of equations for computing the approach nonmotorized turn score for each approach that is parallel to the subject nonmotorized movement. The equations are similar to the merge score equations in table 12, and utilize the same assumed weight values, where W_2 is 0.75 and W_{3+} is 0.5. In the case of potential left turns from the westbound approach in figure 26, the pedestrian or cyclist would be mostly focused on identifying potential left-turning vehicles in the leftmost lane (Lane 1), but may also be monitoring the subsequent lanes (Lane 2 and Lane 3) to lesser degrees for vehicles that may be changing lanes as they approach the intersection to turn.

Table 13. Nonmotorized turn score for conflicting lanes complexity parameter.

Number of Through Lanes on Parallel Approach (N_P)	Approach Nonmotorized Turn Score
1	1
2	$1 + W_2$
3+	$1 + W_2 + W_{3+}(N_P - 2)$

In table 13, N_P represents the number of through lanes on the subject approach parallel to the nonmotorized movement in question. An approach nonmotorized turn score should be computed for each parallel approach separately, in case there are different numbers of through lanes on the approaches. The total nonmotorized turn score is the sum of the individual approach nonmotorized turn scores.

Continuing with the example of a pedestrian or cyclist crossing the south approach in figure 26, the nonmotorized road user is surveying the eastbound and westbound approaches, which have three through lanes each (N_P = 3). The approach nonmotorized turn score associated with the eastbound approach is computed as shown in figure 27. Because the westbound approach has the same number of through lanes in this example, the approach nonmotorized turn score calculation associated with the westbound approach is the same. Therefore, the total nonmotorized turn score is 2.25 + 2.25 = 4.5.

$$Approach\ Pedestrian\ Turn\ Score = 1 + W_2 + W_{3+}(N_P - 2) = 1 + 0.75 + 0.5(3 - 2) = 2.25$$

Figure 27. Equation. Example nonmotorized turn score calculation – eastbound approach.

It follows that the nonmotorized conflicting lanes parameter for the subject nonmotorized movement is computed as shown in figure 28. This value of 6.5 would be applied to the nonmotorized conflict points along the subject nonmotorized movement in figure 26.

$$a_{conflicting\ \ lanes\ ,ped} = cross\ score_{ped} + total\ turn\ score_{ped} = 2 + 4.5 = 6.5$$

Figure 28. Equation. Example nonmotorized conflicting lanes parameter calculation.

If a nonmotorized road user refuge area separated the northbound minor road approach lane from the southbound receiving lane (enough for a two-stage crossing), the nonmotorized movement's cross score would be one and the conflicting lanes parameter would be 5.5.

Speed of Conflicting Traffic. The third parameter that is part of the conflicting traffic complexity factor is the conflicting speed parameter, $a_{conflcting\ speed}$, which also considers an aspect of road user workload. When a road user is attempting to navigate an intersection, the user must judge the speeds of conflicting traffic at the intersection when searching for a gap. Higher speeds of conflicting traffic increase the complexity of this task.

The conflicting vehicle speed for any movement is the highest speed of all the conflicting traffic streams, with conflicting traffic streams being those that cross or merge with the subject movement and are higher on the list of movements. Using the example of the left-turning movement from the minor road in figure 21, the conflicting vehicle speed, V_c, is the highest of the speeds of the traffic streams from the near-side major roadway (through and left-turn movements), far-side major roadway (through and left-turn movements), and opposing minor road approach (through movement). Using the speed assumptions in table 10, the highest conflicting vehicle speed is the speed of the through movement on the major road, which is somewhere between 90 to 110 percent of the major road posted speed limit. This rule applies to nonmotorized-vehicle conflict points as well as vehicle-vehicle conflict points. For the subject nonmotorized movement in figure 26, the conflicting vehicle speed, V_c, is the highest of the speeds of the traffic streams from the near-side major roadway (right-turn movements), far-side major roadway (left-turn movements), northbound minor road approach (through, left-turn, and right-turn movements), and southbound minor road approach (through movement).

Research shows that a 10-percent reduction in vehicle speed is associated with a 15-percent reduction in crash likelihood (Campbell, et al., 2012). Since this is a relative adjustment, arbitrarily setting the speed of 60 mph as a conflicting speed parameter of 1 and applying that relationship results in figure 29 for the conflicting speed parameter, $a_{conflicting\ speed}$, where V_c is the conflicting vehicle speed. This value of $a_{conflicting\ speed}$ is applied when computing the conflicting traffic complexity factor for individual crossing, merging, or nonmotorized conflict points.

$$a_{conflicting\ \ speed} = 1 - \left(\frac{60 - V_C}{60} * \frac{0.10}{0.15} \right)$$

Figure 29. Equation. Conflicting speed parameter.

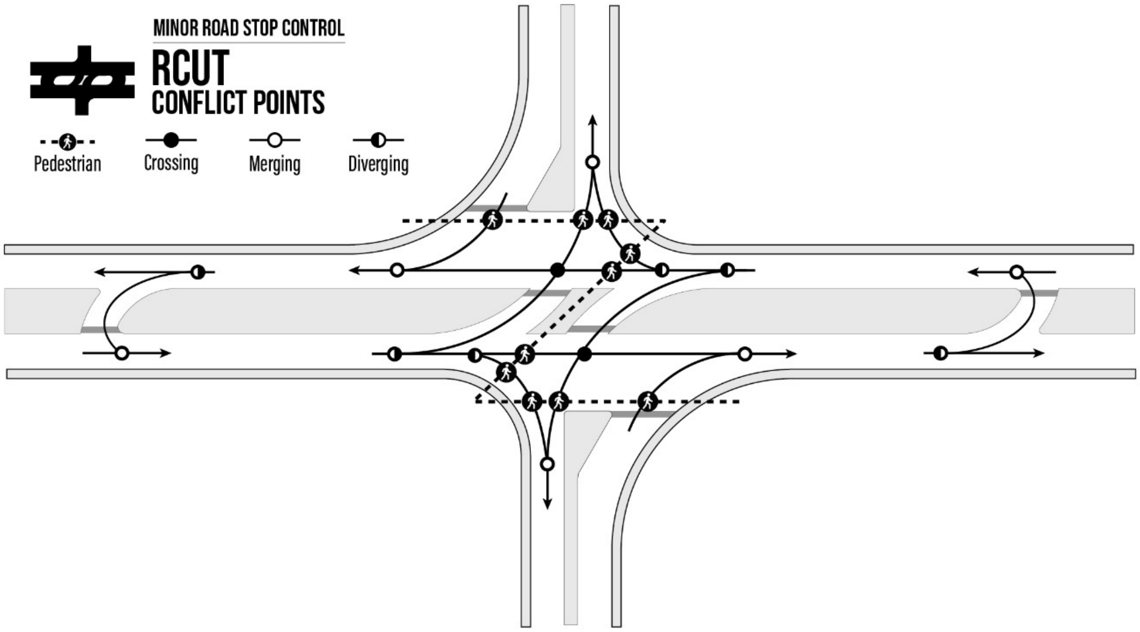
3.7.3 Nonmotorized Movement Complexity Factor

The second complexity factor is the nonmotorized complexity factor, L_2. This factor accounts for indirect and nonintuitive movements at an intersection that may present additional complexity for pedestrians and cyclists. The nonmotorized movement complexity factor takes a value of either 1, 2, or 3 based on two different indicators: an indirect paths indicator, $i_{indirect}$, and a nonintuitive motor vehicle movements indicator, $i_{nonintuitive}$. If neither indicator applies to a given nonmotorized movement, then the value of the nonmotorized movement complexity factor is 1 for that movement and its corresponding conflict points. If one indicator applies, the value is 2, and if both indicators apply, the value is 3. The nonmotorized movement complexity factor is therefore computed according to figure 30.

$$L_2 = 1 + i_{indirect} + i_{nonintuitive}$$

Figure 30. Equation. Nonmotorized movement complexity factor.

The indirect paths indicator applies to any nonmotorized movement where the pedestrian or cyclist is required to traverse a path other than their intended direction of travel (i.e., an indirect path). As an example, consider a nonmotorized movement from the bottom right quadrant to the top right quadrant of the RCUT shown in figure 31; because the typical Z-type crossing here requires a nonmotorized road user to travel outside of their desired direction, the indirect paths indicator applies.



Source: FHWA

Figure 31. Graphic. Example indirect nonmotorized path at an RCUT.

The nonintuitive motor vehicle movements indicator, $i_{nonintuitive}$, is applied to any nonmotorized movements that cross nonintuitive motor vehicle movements. An example of when the nonintuitive motor vehicle movements indicator is equal to one would be the nonmotorized movements on some or all approaches of a displaced left turn intersection, where motor vehicle traffic could alternate direction several times over the course of the nonmotorized road user crossing.

3.8 EXPANDING THE SSI LIBRARY OF INTERSECTION CONCEPTS

Appendix A contains various intersection alternatives that State agencies with ICE policies commonly consider as part of a Stage I ICE. The library could be expanded to include other intersection alternatives of interest, including at-grade crossroad ramp terminals, and then the same Stage I ICE SSI methodology could be applied to those new alternatives.

The alternatives in appendix A currently assume typical nonmotorized paths and assume that bicyclists follow the same paths as pedestrians. Given the significant impact of pedestrian and bicyclist considerations in a Safe System approach, future efforts should focus on how to incorporate more detailed analyses of pedestrians and bicyclists into a Stage I ICE. One promising approach is to develop multiple alternatives for a single intersection type that differ by pedestrian and bicycle accommodation. Instead of one

RCUT, the library could contain, for example, RCUT with sidewalk and on-street bike lanes, RCUT with shared use paths, RCUT with sidewalks and separated bike lanes and a protected intersection, etc. Such concepts would not only support a more informative pedestrian and bicycle SSI analysis, but would advance intersection planning and design practice in general with earlier consideration and pedestrian and bicyclist alternatives.

The *Bikeway Selection Guide* is one resource for informing the development of new intersection alternatives within each intersection type that are distinguished by pedestrian and bicycle facilities (Schultheiss et al., 2019). National Cooperative Highway Research Program (NCHRP) Research Report 926, *Guidance to Improve Pedestrian and Bicyclist Safety at Intersections*, is one example of a group of recently published and ongoing research efforts contributing to the development of these concepts (Sanders et al., 2020).

3.9 SSI EXTENSIONS TO STAGE 2 ICE – ALTERNATIVE SELECTION

A Stage 2 ICE is intended to differentiate among the intersection alternatives brought forward from the Stage I analysis that is the focus of this report. Stage 2 ICE is conducted as part of preliminary engineering and includes the estimating of environmental, utility, and right-of-way impacts. Analyses that occur in a Stage 2 ICE are at a level of detail that allows objective comparisons of alternatives to each other.

The concepts in this chapter can be extended for a Stage 2 ICE. In addition to the features that are part of the SSI Stage 1 analysis, the following present practical extensions of the SSI method for Stage 2 ICE:

- Incorporating the presence, number, and type of turn lanes, which would be expected to have the following impacts:
    - Decreasing the speed differences between through and turning vehicles at the diverging conflict points on intersection approaches.
    - Increasing crossing scores that are part of the conflicting traffic complexity factor.
    - Possibly changing turning speed and traffic control assumptions, depending on the type of turning lanes (e.g., separate free-flow right turning roadway at a signalized intersection).
- Incorporating additional detail that becomes available with respect to signal operation (e.g., left-turn operation, right-turn-on-red restrictions, leading pedestrian intervals).

- Incorporating additional detail on the presence and size of medians and pedestrian and bicyclist refuge at the intersection, which could impact:
  - Pedestrian refuge during crossing movement.
  - Vehicle refuge and the introduction of multi-stage vehicle movements through the intersection.
- Representing any potential impacts of intersection skew on the collision angles in table 11.

The section 3.7 recommendation to consider different intersection alternatives within each intersection type that are distinguished by pedestrian and bicycle facilities also applies to a Stage 2 ICE.

CHAPTER 4: EXAMPLE PROJECT APPLICATIONS

This chapter presents three example applications of the SSI method to individual intersections that are part of realistic project scenarios. The three project scenarios represent different area types, traffic volumes, lane configurations, traffic control types, and nonmotorized user volumes:

- Scenario 1—a suburban signalized intersection of two medium-volume roads with moderate use by nonmotorized users.
- Scenario 2—a rural unsignalized intersection of two-lane roads with few nonmotorized users.
- Scenario 3—an urban signalized intersection of two high-volume roads with heavy use by nonmotorized users.

Chapter 3 presented typical ranges for two inputs to the SSI method: vehicle speeds and collision angles. The examples laid out in the remainder of this chapter assume specific values from within these ranges, displayed in table 14 and table 15.

Table 14. Speed values used in SSI method examples.

Speed Category	Speed (mph)
Major through	Major PSL
Major left	20
Major right	15
Minor through	0.85 * Minor PSL
Minor left	20
Minor right	15
Stop control near-side	15
Stop control far-side	25
Signal control near-side	15
Signal control far-side	25
Roundabout entering	20
Roundabout circulating	25
Roundabout exiting	30

Table 15. Collision angle values used in SSI method examples.

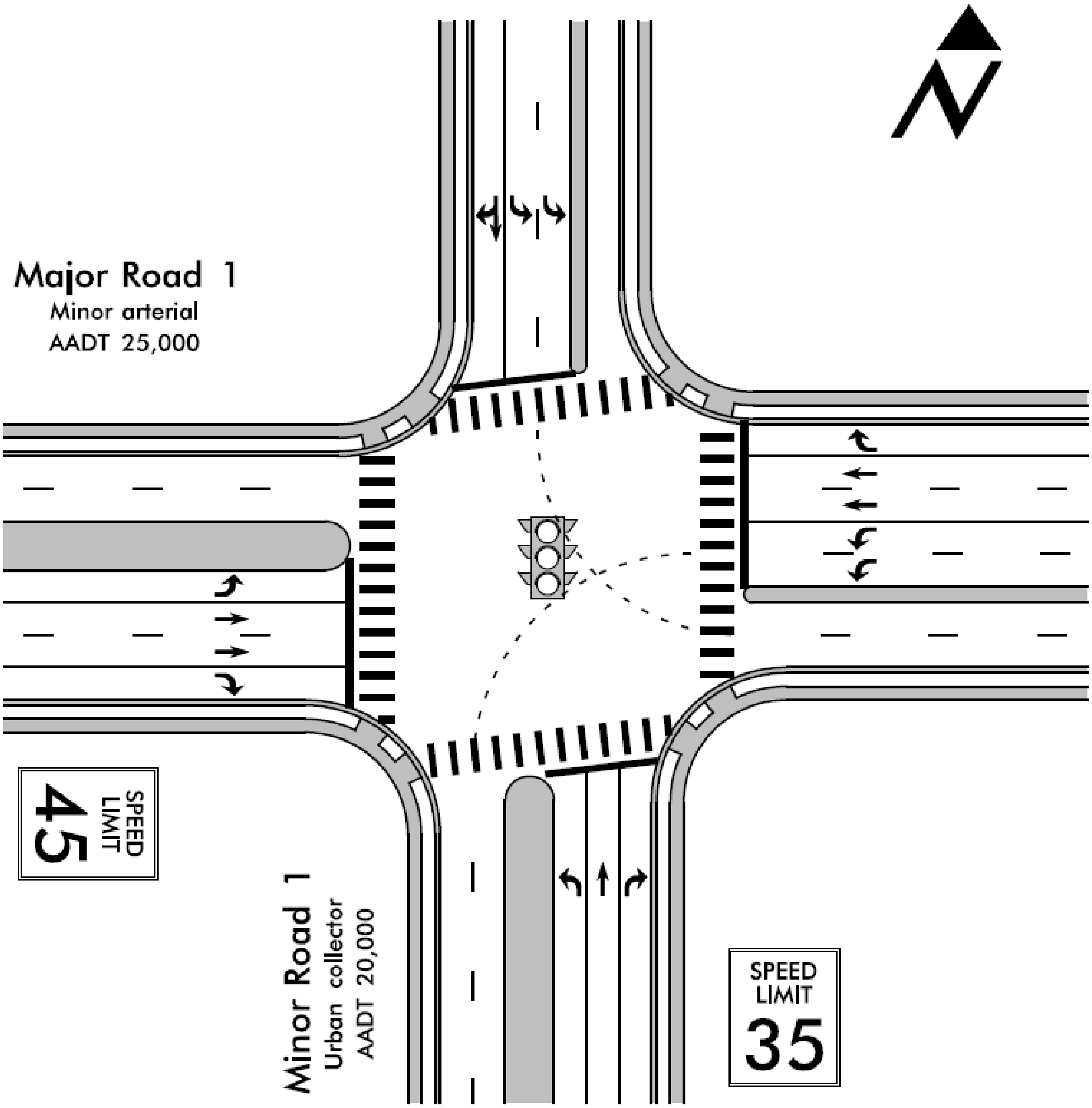
Collision Type	Collision Angle (deg)
Crossing – Broadside	90 (or 270)
Crossing – Left Turn	230
Crossing – Roundabout	60
Merging	45 (or 315)
Diverging	10 (or 350)

Following a basic description of the conditions at each intersection, the examples discuss Stage 1 ICE alternatives screening based on capacity, crash-based safety performance assessments, and SSI results.

4.1 SCENARIO 1

4.1.1 Intersection Conditions

Scenario 1 is a suburban signalized intersection of a four-lane arterial and a two-lane collector and is depicted in figure 32. The intersection is being studied as part of a broader corridor planning effort. Design year traffic volumes are estimated at 25,000 and 20,000 vehicles per day, respectively, on the major and minor roads. The posted speed limits are 45 mph on the major road and 35 mph on the minor. There are sidewalk facilities along all approaches, and the intersection serves a moderate number of nonmotorized users.



Source: FHWA

Figure 32. Illustration of intersection conditions for Scenario 1.

The information in table 16 summarizes the key intersection attributes.

Table 16. Intersection attributes for Scenario 1.

Item	Input Value
Area type	Suburban
Functional classification – major	Minor arterial
Functional classification – minor	Collector
Design year AADT – major	25,000
Design year AADT – minor	20,000
Number of thru lanes – major	4
Number of thru lanes – minor	2
Traffic control type	Signalized
Posted speed limit – major	45
Posted speed limit – minor	35
Nonmotorized average daily traffic (ADT)	2,400

A Stage 1 ICE analysis of this intersection occurred as part of the corridor planning study. The following sections summarize the capacity, crash-based safety performance, and SSI analysis results. Note that the results of these analyses are presented using the intersection type names from the SSI library of intersections (contained in appendix A). In some cases, the analysis results come from other tools that may use slightly different naming conventions.

4.1.2 Capacity-Based Feasibility Review

The Stage 1 ICE alternatives screening used the Capacity Analysis for Planning of Junctions (CAP-X) tool. CAP-X is a spreadsheet-based tool for determining the operational performance of different intersection types. It primarily assesses intersection types by computing the volume-to-capacity (V/C) ratio given vehicle volume inputs and intersection lane arrangements. Table 17 summarizes the CAP-X results and provides the overall V/C ratio and V/C ranking. Based on these results and the general lane arrangements of the corridor, the minor road stop control (MRSC) traditional, all-way stop control (AWSC) traditional, and 1x1 roundabout are dropped from further consideration.

Table 17. CAP-X results for Scenario 1.

Type of Intersection	Overall V/C Ratio	V/C Ranking
Quadrant Roadway	0.25	1
Full Displaced Left Turn (FDLT)	0.27	2
Median U-Turn (MUT)	0.31	T3
2x2 Roundabout	0.31	T3
Partial Displaced Left Turn (PDLT)	0.32	5
Bowtie	0.40	6
Signalized Traditional (existing)	**0.44**	**7**
Signalized Restricted Crossing U-Turn (RCUT)	0.48	8
2x1 Roundabout	0.53	9
1x1 Roundabout	0.63	10
Unsignalized Restricted Crossing U-Turn (RCUT)	0.85	11
All-Way Stop Control (AWSC) Traditional	1.36	12
Minor Road Stop Control (MRSC) Traditional	1.38	13
Jughandle*	--	--

* The Jughandle intersection is not included in CAP-X, but it has the capacity to handle high intersection volumes.

4.1.3 Crash-Based Safety Performance Review

The Stage 1 ICE alternatives screening also used the SPICE tool. SPICE is a spreadsheet-based tool for determining the safety performance of different intersection types using crash-based predictive analysis.

The information in table 18 summarizes the SPICE results for Scenario 1. The SPICE output contains the predicted number of crashes for the design year for both total crashes (i.e., all types and severities) and fatal and injury crashes unless there is not an appropriate safety performance function (SPF) available, as in the case of the 2x2 roundabout. The results show that all the intersection types for which there are predictive methods available have fewer total and fewer fatal and injury crashes than the signalized traditional intersection that is the no-build condition. Based on these SPICE results, no additional intersections are dropped from consideration.

Table 18. SPICE results for Scenario 1.

Control Strategy	Predicted Crashes in Design Year (crashes/year)	
	Fatal & Injury	Total
Unsignalized RCUT	0.53	1.69
MUT	1.24	4.08
Jughandle	1.31	3.55
Signalized RCUT	1.38	4.08
FDLT	1.55	4.22
Signalized Traditional (existing)	**1.77**	**4.80**
2x2 Roundabout	No SPF	2.29
2x1 Roundabout*	--	--
Quadrant Roadway*	--	--
PDLT*	--	--
Bowtie*	--	--

* These intersection types are not included in SPICE but are included in the SSI library of intersections.

4.1.4 SSI Methodology and Results

This section presents the results of applying the SSI method in chapter 3 to the Scenario 1 example. Table 19 summarizes the SSI scores for the feasible intersection alternatives from appendix A. The list of intersection alternatives is ordered based on the overall Intersection SSI Score, showing that the 2x1 roundabout has the highest (i.e., best) SSI score. There are seven intersection design alternatives that indicate an improved SSI score compared to the existing, signalized traditional intersection: 2x1 roundabout, MUT, 2x2 roundabout, signalized RCUT, bowtie, quadrant roadway, and jughandle.

The four rightmost columns in table 19 contain the SSI scores for individual conflict point types. The seven alternatives listed above have improved SSI scores for the nonmotorized conflict points compared to the signalized traditional intersection (which is the existing/no-build condition). There are eight options that have improved crossing conflict SSI scores compared to the no-build alternative: 2x1 roundabout, MUT, 2x2 roundabout, signalized RCUT, bowtie, unsignalized RCUT, FDLT, and PDLT. These designs reroute one or more movements at the intersection, removing crossing conflict points, reducing vehicle speeds and angles at crossing conflict points, or both. As expected, the range of nonmotorized and crossing Conflict Type SSI Scores is lower than the merging and diverging scores, indicating that nonmotorized and crossing conflicts are more likely to lead to fatalities and serious injuries than merging and diverging conflicts. The zero SSI scores for nonmotorized conflict points at several of the alternatives reflect the relatively higher probability of a nonmotorized road user fatality or serious injury if there was a nonmotorized-vehicle crash at this intersection under the speed assumptions of the SSI method.

Table 19. SSI score results for Scenario 1.

Intersection Type	Intersection SSI Score	Conflict Type SSI Scores			
		Nonmotorized	Crossing	Merging	Diverging
2x1 Roundabout	52	8	93	98	100
MUT	44	10	52	83	88
2x2 Roundabout	42	4	90	98	100
Signalized RCUT	40	5	74	77	86
Bowtie	31	4	23	94	96
Quadrant Roadway	30	6	14	93	94
Jughandle	27	3	18	93	97
Signalized Traditional (existing)	**24**	**2**	**19**	**93**	**100**
Unsignalized RCUT	19	0	65	69	86
FDLT	10	0	32	91	97
PDLT	9	0	26	91	97

The information in table 20 provides additional context to help interpret the SSI scores. The intersection alternatives are listed in the same order as in table 19. The left portion of the table displays the exposure for each conflict point type relative to the existing/no-build alternative (where “NM” stands for nonmotorized). In other words, the exposure for the existing intersection design (in this case, the signalized traditional intersection) is set to one and the exposure for the other intersection types is shown relative to it. Values greater than one represent higher exposure at those conflict point types while values less than one represent lower exposure.

The middle portion of the table shows the average *P(FSI)* for each conflict point type. Together, these two metrics provide insights to the contributions of exposure and severity to the SSI scores in table 19. Note, for example, that while the signalized RCUT has a slightly higher average *P(FSI)* for crossing conflict points than the signalized traditional (0.09 versus 0.04)[4], exposure at crossing conflict points is 81 percent lower for the signalized RCUT compared to the signalized traditional. Other intersection alternatives with a similar pattern include the MUT, PDLT, and FDLT. The roundabout alternatives have equal exposure at crossing conflict points to the traditional intersection but much lower chance of fatality or serious injury for these crossing conflict points due to the lower speeds and shallower angles of the crossing conflicts.

The rightmost portion of the table shows the average complexity adjustment for each conflict point type. This is computed by summing the products of the complexity factors (L_1 and L_2) for each conflict point of a certain type and then dividing that sum of products by the number of conflict points of that particular type. It shows that most of the intersection types have less user complexity for nonmotorized and crossing conflict points than the existing signalized traditional intersection. The additional complexity of the PDLT and FDLT intersections for pedestrians and cyclists result in these intersection alternatives receiving a lower SSI score given the projected nonmotorized volumes crossing at-grade at this intersection.

[4] The movement-based conflict point diagrams in appendix A show that the average *P(FSI)* for the RCUT is based on its two crossing conflict points. Both are defined by left-turning and through moving vehicles on the major road. The signalized traditional intersection has more crossing conflict points (16 versus 2), with some occurring at lower speeds. This lowers the average *P(FSI)* across all crossing conflict points.

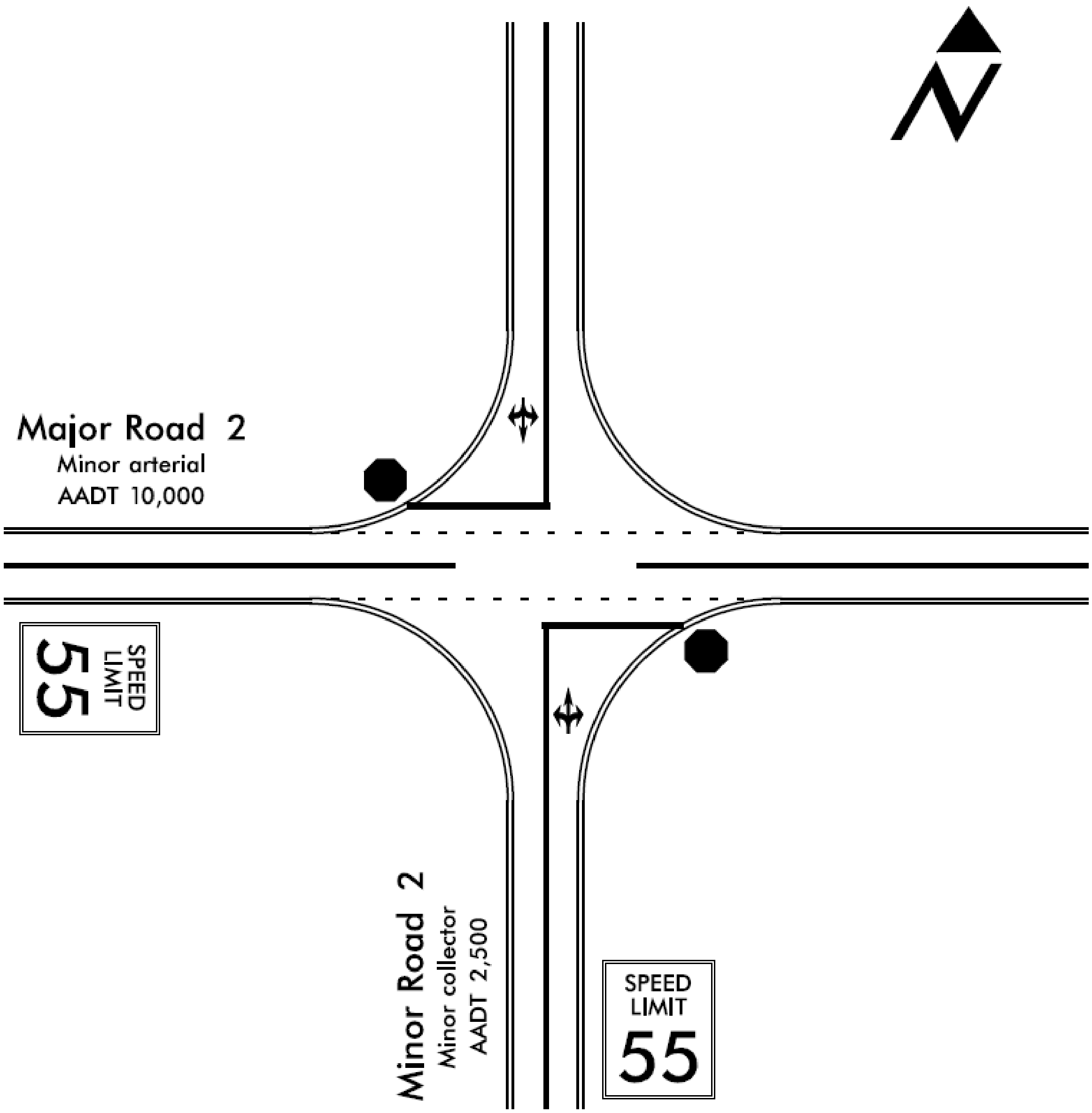
Table 20. Relative exposure, average *P(FSI)*, and average complexity adjustment results for Scenario 1.

Intersection Type	Relative Exposure (Relative to Existing)				Average *P(FSI)*				Average Complexity Adjustment			
	NM	Cross	Merge	Diverge	NM	Cross	Merge	Diverge	NM	Cross	Merge	Diverge
2x1 Roundabout	1.00	1.00	1.51	1.49	0.33	0.00	0.00	0.00	1.83	0.92	0.99	1.00
MUT	1.25	0.84	2.58	2.88	0.33	0.04	0.01	0.00	1.04	0.84	0.77	1.00
2x2 Roundabout	1.00	1.00	1.51	1.49	0.33	0.00	0.00	0.00	2.44	1.22	1.15	1.00
Signalized RCUT	1.22	0.19	3.31	3.25	0.28	0.09	0.01	0.00	1.73	0.84	0.77	1.00
Bowtie	1.25	0.94	2.46	2.43	0.34	0.04	0.01	0.00	1.84	1.68	1.01	1.00
Quadrant Roadway	1.00	1.34	1.57	1.77	0.27	0.04	0.01	0.00	1.84	1.34	0.96	1.00
Jughandle	1.07	1.11	1.28	1.20	0.29	0.04	0.01	0.00	2.08	2.00	1.23	1.00
Signalized Traditional (existing)	**1.00**	**1.00**	**1.00**	**1.00**	**0.29**	**0.04**	**0.01**	**0.00**	**3.15**	**2.03**	**1.53**	**1.00**
Unsignalized RCUT	1.22	0.19	3.31	3.25	0.31	0.09	0.01	0.00	3.06	1.21	1.11	1.00
FDLT	1.00	0.89	1.00	1.00	0.32	0.04	0.01	0.00	4.37	1.30	2.01	1.00
PDLT	1.00	0.96	1.00	1.00	0.32	0.04	0.01	0.00	4.74	1.70	2.12	1.00

4.2 SCENARIO 2

4.2.1 Intersection Conditions

Scenario 2 is a rural unsignalized intersection of a two-lane minor arterial and a two-lane minor collector and is depicted in figure 33. The minor road is under stop control, while the major road is uncontrolled. The intersection was included in a list of locations considered for safety improvement based on the last three years of observed crash data compared to expected crash counts at this site. Design year traffic volumes are estimated at 10,000 and 2,500 vehicles per day, respectively, on the major and minor roads. The posted speed limit on both roadways is 55 mph. The intersection serves a low number of nonmotorized users.



Source: FHWA

Figure 33. Graphic. Illustration of intersection conditions for Scenario 2.

The information in table 21 summarizes the key intersection attributes.

Table 21. Intersection attributes for Scenario 2.

Item	Input Value
Area type	Rural
Functional classification – major	Minor arterial
Functional classification – minor	Minor collector
Design year AADT – major	10,000
Design year AADT – minor	2,500
Number of thru lanes – major	2
Number of thru lanes – minor	2
Traffic control type	Minor road STOP
Posted speed limit – major	55
Posted speed limit – minor	55
Nonmotorized ADT	100

A Stage 1 ICE analysis of this intersection occurred as part of the safety improvement study. The following sections summarize the capacity, crash-based safety performance, and SSI analysis results.

4.2.2 Capacity-Based Feasibility Review

The information in table 22 summarizes the CAP-X results and provides the overall V/C ratio and V/C ranking. Based on life cycle costs and Manual on Uniform Traffic Control Devices (MUTCD) traffic signal warrants, the low volumes at the intersection do not justify signal control. As such, all the signalized intersection types are dropped from further consideration.

Table 22. CAP-X results for Scenario 2.

Type of Intersection	Overall V/C Ratio	V/C Ranking
Unsignalized RCUT	0.06	1
FDLT	0.08	T2
2x1 Roundabout	0.08	T2
2x1 Roundabout	0.08	T2
Quadrant Roadway	0.09	T5
PDLT	0.09	T5
MRSC Traditional (existing)	**0.11**	**7**
Signalized RCUT	0.15	T8
MUT	0.15	T8
1x1 Roundabout	0.16	T10
Signalized Traditional	0.16	T10
Bowtie	0.18	12
AWSC Traditional	0.41	13
Jughandle*	--	--

* The Jughandle intersection is not included in CAP-X but it has the capacity to handle high intersection volumes.

4.2.3 Crash-Based Safety Performance Review

The information in table 23 summarizes the SPICE results for Scenario 2. The results show that all the intersection types for which there are predictive methods available have fewer predicted total and fewer predicted fatal and injury crashes than the MRSC traditional intersection (which is the existing condition). Based on the SPICE results, no additional intersections are dropped from consideration.

Table 23. SPICE results for Scenario 2.

Control Strategy	Predicted Crashes in Design Year (crashes/year)	
	Fatal & Injury	Total
1x1 Roundabout	0.25	1.59
Unsignalized RCUT	0.53	1.69
MRSC Traditional (existing)	**1.15**	**2.61**
2x2 Roundabout	No SPF	2.29
2x1 Roundabout*	--	--
AWSC Traditional*	--	--

* These intersection types are not included in SPICE but are included in the SSI library of intersections.

4.2.4 SSI Methodology and Results

The information in table 24 summarizes the SSI scores for the remaining intersection alternatives under consideration for Scenario 2 from the library of SSI intersection alternatives in appendix A. It shows there are 5 intersection design alternatives under consideration that indicate improved Safe System performance compared to the existing MRSC traditional intersection design: the 1x1, 2x1, and 2x2 roundabouts, along with the AWSC traditional and unsignalized RCUT intersections.

The individual conflict type SSI scores in table 24 illustrate the Safe System performance of the intersection design in more detail. All the considered alternatives perform better from an SSI score perspective than the existing design for nonmotorized and crossing conflict points. The unsignalized RCUT scores worse than the existing MRSC traditional intersection for merging and diverging conflict points. This is because the unsignalized RCUT intersection design results in additional merging and diverging conflict points and exposure at those conflict points due to the way that turning movements are routed at the intersection. Overall, the merging and diverging conflict type SSI scores are high across all intersection designs, indicating lower probabilities of fatalities and serious injuries from these conflict types.

The range of intersection SSI scores across the alternatives is on the high end (i.e., closer to 100) when compared to the results from Scenario 1. This is because the volumes at the intersection (both motorized and nonmotorized) are significantly lower in this scenario, decreasing the exposure. The low levels of exposure combine with lower levels of complexity to result in lower levels of crash likelihood, even though the higher speeds may lead to higher probabilities of fatalities or serious injuries if a nonmotorized crash occurs or if a crash occurs between vehicles at crossing conflict points.

Table 24. SSI score results for Scenario 2.

Intersection Type	Intersection SSI Score	Conflict Type SSI Scores			
		Nonmotorized	Crossing	Merging	Diverging
1x1 Roundabout	99	98	100	100	100
2x1 Roundabout	99	97	100	100	100
AWSC Traditional	99	98	98	100	100
2x2 Roundabout	99	96	99	100	100
Unsignalized RCUT	96	95	95	97	97
MRSC Traditional (existing)	**94**	**92**	**86**	**99**	**98**

The information in table 25 provides an additional level of detail for exploring the SSI results pertaining specifically to conflict point exposure, average *P(FSI)*, and average complexity adjustments. It shows that the unsignalized RCUT alternative shows a significant decrease in exposure at crossing conflict points. The existing MRSC traditional intersection as well as the AWSC traditional alternative exhibit the lowest exposure at merging and diverging conflict points.

The roundabout alternatives and the AWSC traditional design show improvements over the existing design in terms of average *P(FSI)* at crossing, merging, and diverging conflict points. The average *P(FSI)* at crossing conflict points for the unsignalized RCUT and MRSC traditional are 0.16 and 0.06, respectively[5]. All the intersection types under consideration have lower average complexity adjustments than the existing condition for nonmotorized and crossing conflict point types.

[5] The Scenario 1 discussion addressed the reason for the higher average *P(FSI)* at RCUT crossing conflict points.

Implementing effective speed management strategies at locations such as Scenario 2 has proven challenging in the U.S. but would offer SSI score benefits, if effective. For example, if speed management strategies were able to reduce speeds on the major and minor road intersection approaches to 40 mph, the SSI score for the MRSC traditional intersection in table 25 would increase from 94 to 97. The average *P(FSI)* at the MRSC traditional crossing conflicts in table 25 would decrease from 0.06 to 0.03. The average complexity adjustment at the MRSC traditional crossing conflicts in table 25 would decrease from 1.66 to 1.37. Such hypothetical examples show that while the SSI method in chapter 3 was presented in the context of project scoping, it could also begin to inform multidisciplinary safety stakeholders and the traveling public about the SSI effects of speed management strategies that span the different elements of a Safe System (e.g., "safe speeds," "safe road users," "safe vehicles").

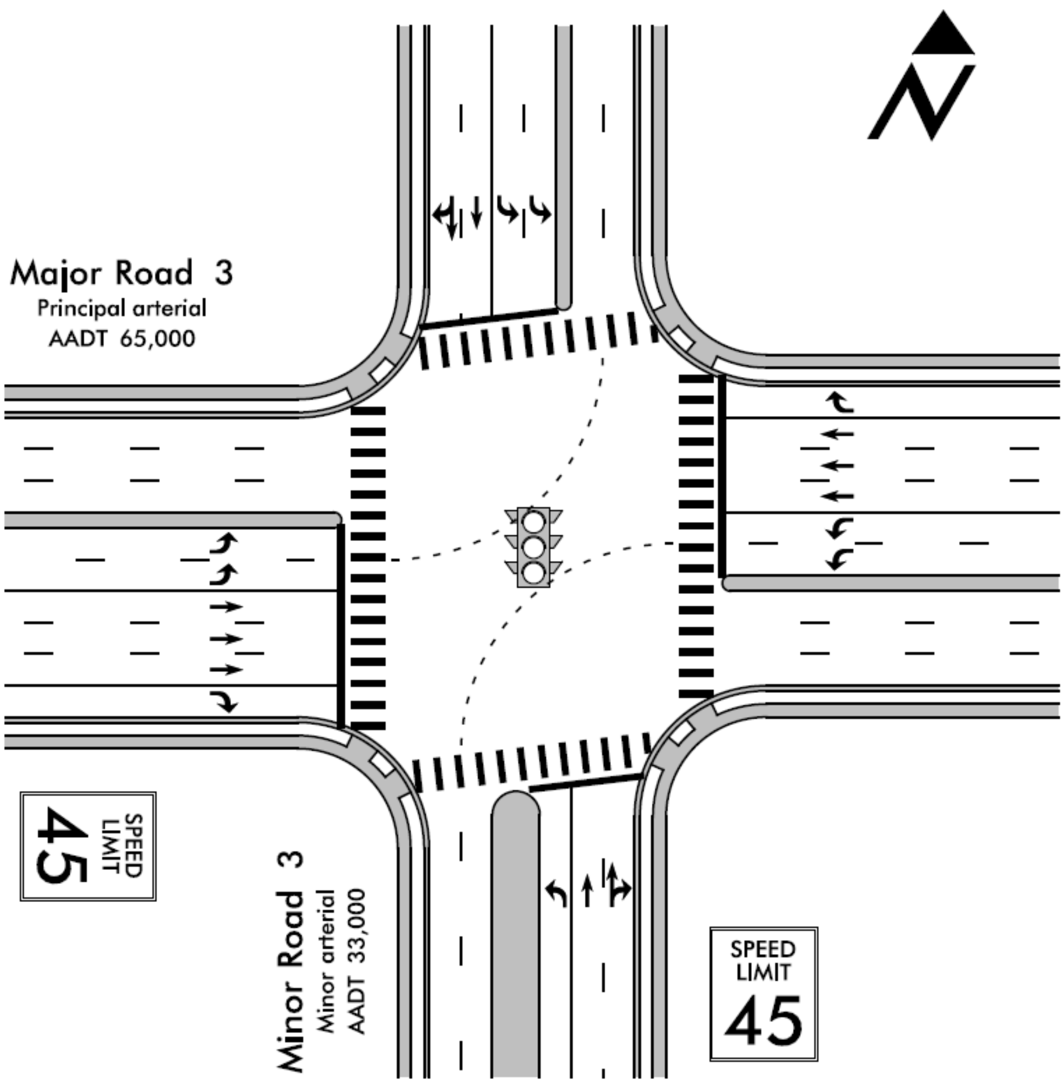
Table 25. Relative exposure, average *P(FSI)*, and average complexity adjustment results for Scenario 2.

Intersection Type	Exposure (Relative to Existing)				Average *P(FSI)*				Average Complexity Adjustment			
	NM	Cross	Merge	Diverge	NM	Cross	Merge	Diverge	NM	Cross	Merge	Diverge
1x1 Roundabout	1.00	1.10	1.78	1.37	0.33	0.00	0.00	0.00	1.22	0.61	0.61	1.00
2x1 Roundabout	1.00	1.10	1.78	1.37	0.33	0.00	0.00	0.00	1.83	0.92	0.99	1.00
AWSC Traditional	1.00	1.00	1.00	1.00	0.19	0.01	0.00	0.00	2.74	1.63	1.37	1.00
2x2 Roundabout	1.00	1.10	1.78	1.37	0.33	0.00	0.00	0.00	2.44	1.22	1.15	1.00
Unsignalized RCUT	1.10	0.40	3.38	2.12	0.33	0.16	0.02	0.02	2.10	0.68	0.68	1.00
MRSC Traditional (existing)	**1.00**	**1.00**	**1.00**	**1.00**	**0.31**	**0.06**	**0.01**	**0.01**	**3.26**	**1.66**	**1.37**	**1.00**

4.3 SCENARIO 3

4.3.1 Intersection Conditions

Scenario 3 is an urban signalized intersection of a six-lane arterial and a four-lane arterial and is depicted in figure 34. The intersection is being studied as part of a congestion mitigation project. Design year traffic volumes are estimated at 65,000 and 33,000 vehicles per day, respectively, on the major and minor roads. The posted speed limit on both roadways is 45 mph. There are sidewalk facilities along all approaches, and the intersection serves large numbers of nonmotorized users.



Source: FHWA

Figure 34. Graphic. Illustration of intersection conditions for Scenario 3.

The information in table 26 summarizes the key intersection attributes.

Table 26. Intersection attributes for Scenario 3.

Item	Input Value
Area type	Urban
Functional classification – major	Principal arterial
Functional classification – minor	Minor arterial
Design year AADT – major	65,000
Design year AADT – minor	33,000
Number of thru lanes – major	6
Number of thru lanes – minor	4
Traffic control type	Signalized
Posted speed limit – major	45
Posted speed limit – minor	45
Nonmotorized ADT	4,000

A Stage 1 ICE analysis of this intersection occurred as part of the congestion mitigation study. The following sections summarize the capacity, crash-based safety performance, and SSI analysis results.

4.3.2 Capacity-Based Feasibility Review

The information in table 27 summarizes the CAP-X results and provides the overall V/C ratio and V/C ranking. Based on these results and the general lane arrangements of the intersection, the unsignalized and roundabout intersection types are dropped from further consideration.

Table 27. CAP-X results for Scenario 3.

Type of Intersection	Overall V/C Ratio	V/C Ranking
FDLT	0.42	1
PDLT	0.56	2
MUT	0.58	3
Quadrant Roadway	0.62	4
Signalized Traditional (existing)	**0.67**	**5**
Bowtie	0.75	6
Signalized RCUT	0.84	7
2x2 Roundabout	1.01	8
2x1 Roundabout	1.84	9
1x1 Roundabout	2.46	10
AWSC Traditional	2.51	11
Unsignalized RCUT	7.60	12
MRSC Traditional	30.23	13
Jughandle*	--	--

* The Jughandle intersection is not included in CAP-X but it has the capacity to handle high intersection volumes.

4.3.3 Crash-Based Safety Performance Review

The information in table 28 summarizes the SPICE results for Scenario 3. The results show that all the intersection types for which there are predictive information available have fewer predicted total and fewer predicted fatal and injury crashes than the signalized traditional intersection (which is the existing condition). Based on the SPICE results, no additional intersections are dropped from consideration.

Table 28. SPICE results for Scenario 3.

Control Strategy	Predicted Crashes in Design Year (crashes/year)	
	Fatal & Injury	Total
MUT	3.38	10.52
Jughandle	3.58	9.16
Signalized RCUT	3.77	10.52
FDLT	4.25	10.89
Signalized Traditional (existing)	**4.83**	**12.38**
Quadrant Roadway*	--	--
PDLT*	--	--
Bowtie*	--	--

* These intersection types are not included in SPICE but are included in the SSI library of intersections.

4.3.4 SSI Methodology and Results

The information in table 29 summarizes the SSI scores for the remaining intersection alternatives still under consideration in Scenario 3 from the library of SSI intersection alternatives in appendix A. It shows that all the feasible intersection design options for this scenario result in an Intersection SSI Score of zero, except for the MUT and signalized RCUT which have a score of one. This means that none of the feasible designs would align well with Safe System principles due to the combinations of user volumes and vehicle speeds at the intersection. In this case, the alternatives are listed from the lowest to highest average exposure-severity-complexity products [i.e., ($E_{crossing}$ + $E_{merging}$ + $E_{diverging}$ + $E_{nonmotorized}$)/4]. Using this measure, the MUT, signalized RCUT, bowtie, quadrant roadway, and jughandle have improved SSI performance compared to the signalized traditional alternative that represents the no-build condition.

The individual conflict type SSI score results in table 29 illustrate the overall Safe System performance of the intersection design in more detail. While all the feasible options have an Intersection SSI Score of zero, some of the intersection types have SSI scoring differences when considering specific conflict point types. For example, the signalized RCUT performs better than other alternatives for crossing conflict points, while the traditional signalized and several others perform better for merging conflict points.

Table 29. SSI score results for Scenario 3.

Intersection Type	Intersection SSI Score	Conflict Type SSI Scores			
		Nonmotorized	Crossing	Merging	Diverging
MUT	1	0	2	30	53
Signalized RCUT	1	0	6	25	52
Bowtie	0	0	0	67	76
Quadrant Roadway	0	0	0	61	68
Jughandle	0	0	0	58	79
Signalized Traditional (existing)	**0**	**0**	**0**	**64**	**100**
FDLT	0	0	0	46	81
PDLT	0	0	0	56	81

The information in table 30 provides an additional level of detail for exploring the SSI score results pertaining specifically to conflict point exposure, average P(FSI), and average complexity adjustment. The MUT, signalized RCUT, FDLT, and PDLT have lower exposure at crossing conflict points than other alternatives. Most of the intersection types have lower average complexity adjustments than the signalized traditional intersection for nonmotorized and crossing conflict point types. The exceptions are the FDLT and PDLT, which have higher levels of nonmotorized complexity due to the indirect nonmotorized paths and nonintuitive motor vehicle movements at these intersection types.

The average *P(FSI)* values are highest for nonmotorized and crossing conflict points. The average *P(FSI)* for nonmotorized conflict points range from 0.27 to 0.33 under the speed assumptions of the SSI method. The average *P(FSI)* for crossing conflict points range from 0.04 to 0.09. The top MUT and signalized RCUT ranking is a result of reduced crossing conflict point exposure and lower levels of complexity for crossing and nonmotorized movements. The jughandle, quadrant roadway, and bowtie achieve their improved SSI score over the traditional intersection almost solely from the lower levels of complexity for crossing and nonmotorized movements.

Scenario 3 shows that moving towards a Safe System at some locations is challenging to achieve based on the individual intersection design alternative alone. In some cases, solutions may be found by looking to the network and providing improved connectivity for both motorized and nonmotorized users and avoiding the high level of exposure at a single, large intersection.

Table 30. Relative exposure, average *P(FSI)*, and average complexity adjustment results for Scenario 3.

Intersection Type	Exposure (Relative to Existing)				Average *P(FSI)*				Average Complexity Adjustment			
	NM	Cross	Merge	Diverge	NM	Cross	Merge	Diverge	NM	Cross	Merge	Diverge
MUT	1.25	0.74	2.86	2.51	0.33	0.04	0.01	0.00	1.67	1.26	1.05	1.00
Signalized RCUT	1.17	0.26	3.25	2.82	0.28	0.09	0.01	0.00	2.60	1.26	1.05	1.00
Bowtie	1.25	1.05	2.50	2.21	0.34	0.04	0.01	0.00	2.95	2.53	1.51	1.00
Quadrant Roadway	1.00	1.38	1.65	1.78	0.27	0.05	0.01	0.00	3.04	1.94	1.43	1.00
Jughandle	1.08	1.18	1.37	1.20	0.29	0.04	0.01	0.00	2.99	2.59	1.89	1.00
Signalized Traditional (existing)	**1.00**	**1.00**	**1.00**	**1.00**	**0.29**	**0.04**	**0.01**	**0.00**	**4.41**	**2.63**	**2.26**	**1.00**
FDLT	1.00	0.89	1.00	1.00	0.32	0.05	0.01	0.00	7.12	1.97	2.90	1.00
PDLT	1.00	0.97	1.00	1.00	0.32	0.04	0.01	0.00	7.68	2.57	3.11	1.00

CHAPTER 5: FUTURE VISION FOR THE SSI METHOD

While U.S. intersection planning and design practices have incorporated Safe System principles to some extent over the last several decades, significant opportunities for advancing Safe System approaches remain. Where enough data are available, U.S. experiences with intersection alternatives that simplify road user decision-making and manage impact angles and speeds have shown safety performance benefits. These safety benefits are typically expressed in the form of CMFs derived from retrospective statistical analyses of crash data. The CMFs are usually applicable to the "intersection as a whole" and reflect overall changes or differences in the number of crashes at the intersection alternative of interest compared to another intersection alternative. In other words, intersection CMFs are often developed with and applicable to an aggregation of crashes resulting from different movements through the intersection, involving different intersection users, and resulting in a range of injury outcomes. For example, intersection CMFs for fatal and injury crashes are applicable to crashes of all types with injury outcomes ranging from fatal to possible injuries.

As a complement to more aggregate crash-based findings such as CMFs, the SSI method in chapter 3 provides an approach to characterize intersection alternatives with respect to the Safe System principles of simplified decision-making and management of impact angles and speeds, with the ultimate goal of reducing traffic fatalities and serious injuries. The method is applied at the conflict point level and incorporates the characteristics of different movements through the intersection for motorized and nonmotorized users. The SSI method is sensitive to volumes, vehicle speeds, potential collision angles, and geometry. The results of applying the SSI method comprise multiple MOEs and a corresponding set of SSI scores. The MOEs include exposure through different conflict point types, the average *P(FSI)* for different conflict point types, and the average complexity for movements passing through different conflict point types. The SSI scores are derived based on the combined concepts of conflict points, conflict point severity, exposure, and complexity and are a means to characterize the extent to which an intersection alternative in a given context aligns with the principles of a Safe System.

Chapter 3 concluded with ideas to expand the library of Stage I ICE intersection alternatives in appendix A to incorporate alternative pedestrian and bicycle facilities and to extend the method for Stage II ICE analyses. The remainder of this chapter builds on these ideas, outlining future enhancements and considerations for the SSI method. The ideas are organized into two categories: 1) SSI enhancements for common intersection planning and design applications and 2) SSI enhancements for broader Safe System implementation.

5.1 SSI ENHANCEMENTS FOR COMMON INTERSECTION PLANNING AND DESIGN APPLICATIONS

The SSI method in chapter 3 is intended for implementation by intersection planners and designers within the typical project development process. There are multiple enhancements to the method and supporting data that will improve its application in this typical project development context:

- Expand to other conflict types.
- Develop data and models to support intersection speed prediction.
- Link SSI MOEs and scores to FSI crash frequencies.

5.1.1 Expand to Other Conflict Types

Appendix A contains various intersection alternatives that State agencies with ICE policies commonly consider as part of a Stage I ICE. The alternatives in appendix A currently apply typical pedestrian paths and assume that bicyclists follow the same paths as pedestrians. Given the significant impact of pedestrian and bicyclist considerations in a Safe System approach, future efforts should focus on how to incorporate more refined identification and analysis of pedestrian and bicyclist conflict points. The conclusion of chapter 3 pointed out that one promising approach is to develop multiple alternatives for a single intersection type that differ by pedestrian and bicycle accommodation. Instead of one RCUT, the library could contain, for example, RCUT with sidewalk and on-street bike lanes, RCUT with shared use paths, RCUT with sidewalks and separated bike lanes and a protected intersection, and other variations. Each variation would illustrate the corresponding pedestrian and bicyclist conflict points as the starting point for applying the SSI method.

The SSI method does not currently consider rear-end conflicts that result from speed differentials that arise from traffic congestion or deceleration and stopping due to traffic control devices (i.e., yield signs, stop signs, and traffic signals). It also does not consider merge and diverge conflicts that may vary in their location along an intersection approach due to lane changing, including weaving movements. These rear-end and sideswipe additions would increase the overall completeness of the method but may not have a significant impact on the overall SSI results due to the shallower angles and lower speed differentials of these conflict types.

5.1.2 Develop Data and Models to Support Intersection Speed Prediction

Speed is central to the Safe System approach. As such, predicted operating speeds for vehicles approaching and navigating different intersection alternatives are inputs to the SSI method. Chapter 3 noted that there is little existing research into speed prediction at intersections, especially in differentiating speeds of different movements and maneuvers at different points throughout the vehicle path. For this reason, the current SSI method adopts a simplified set of speed assumptions to cover the different vehicle maneuvers at intersections. These assumptions can be adjusted based on local knowledge or any data that become available in the future.

Application of the SSI method would benefit from new research on estimating and predicting operating speeds through intersections. At a minimum, the research should provide insights to expected operating speeds by intersection type, type of traffic control, and movement. Ideally, the methods would also be sensitive to other characteristics of the intersection and intersection approaches that would influence speeds, particularly traffic volumes. This could support the development of the exposure-severity-complexity products in chapter 3 that are sensitive to speeds by time of day (e.g., peak, non-peak). The time-of-day exposure-severity-complexity products could then be aggregated to determine the overall SSI scores and other MOEs.

5.1.3 Link SSI MOEs and Scores to FSI Crash Frequencies

The exposure-severity-complexity products that lead to the SSI scores in chapter 3 contain the same general components as what would be expected in an intersection crash predictive method for fatal and serious injury crashes:

- Characterization of exposure.
- Movement complexity factors that, in addition to exposure, are expected to be associated with higher or lower crash likelihoods.
- The probability (or proportion) of crashes that occur resulting in a fatality or serious injury.

Future efforts to validate and calibrate the SSI method using crash data could take multiple approaches:

- One approach could seek to establish statistical associations between the SSI MOEs and SSI scores and the average number of intersection crashes.
- A second approach could try to maximize the statistical associations between the SSI MOEs and SSI scores and the average number of intersection crashes. This could include calibrating some of the parameters that are part of the exposure-severity-complexity product using observed crash data. These parameters include:
    - Coefficients (other than the currently assumed 1.0) applied to the volumes that make up the exposure indices.

- Values for the traffic control parameters that make up part of the conflicting traffic complexity factor, including the *BTCAV* and the weight applied to traffic control.
- Weights assigned to adjacent lanes that are part of the merge score and nonmotorized turn score in the conflicting traffic complexity factor.
- Parameters that could adjust the level of contribution of the conflicting traffic complexity factor and nonmotorized movement complexity factor to the exposure-severity-complexity product and overall SSI score (currently, both are given equal weight).

Such efforts could further enhance the complementary nature of Safe System metrics and crash-based metrics and support steps towards future versions of resources such as the HSM incorporating the SSI method and other types of Safe System assessments.

Ideally, efforts to validate and calibrate the SSI method with crash data would be based on fatal and serious injury crashes, with serious injuries determined on an AIS by trained medical professionals following an assessment of a patient's injuries at the hospital. Such an approach, however, would require a traffic injury surveillance system in the State where police-reported crashes are linked to hospital records, which is rare. In the absence of such a system, it is possible that validation and calibration could occur with "KA" crashes.

5.2 SSI ENHANCEMENTS FOR BROADER SAFE SYSTEM IMPLEMENTATION

In addition to use by intersection planners and designers within the typical project development process, the fundamental building blocks of the SSI method in chapter 3 would also allow it to incorporate impacts of broader system-level policies and characteristics on SSI MOEs and SSI scores. Such capabilities could help advance stakeholder knowledge of the Safe System approach to road safety management and support continued dialogue on steps to achieve a vision of zero fatalities and serious injuries in the U.S. The following sections offer ideas on how the SSI method could incorporate effects of system characteristics such as self-explaining roads and speed enforcement, vehicles, and users.

5.2.1 Self-Explaining Roads and Speed Enforcement

Speed management is central to achieving a Safe System. Tingvall & Haworth (1999) provided table 2 as speeds representing an "inherently safe system." Strategies to achieve such speeds in many cases span across "Safe System elements" and require political and societal will. Several countries that take a Safe System approach to road safety management have implemented or are implementing speed limit reductions along with high levels of enforcement to reduce speeds. For example, the Netherlands Sustainable Safety Start-up Program included the large-scale implementation of 30 km/hr (20 mph) zones in urban areas and 60 km/hr (40 mph) zones in rural areas, along with corresponding educational and enforcement activities.

New Zealand's Safer Journeys Action Plan 2011-2012 identified three areas of focus within their "Safe Speeds" element:

- Public campaigns to achieve acceptance of safe speeds.
- Create speed limits that reflect a Safe System.
- Increase the use of safety cameras.

In addition, the classification of roads based on their function and the design and the operation of those roads to be self-explaining of that function play key roles in achieving a Safe System. This is most notably the case with the Functionality and Predictability principles of Sustainable Safety in the Netherlands, and the corresponding design features of through roads, distributor roads, and access roads (Wegman et al., 2008).

The SSI method could be used to explore and communicate impacts of effective speed management and self-explaining roads policies at the intersection level. The effects of changing vehicle speeds in a significant way would be captured when quantifying conflict point severity (Section 3.6) and the movement complexity attributed to the speed of conflicting traffic (Section 3.7.2). The "Scenario 2" example in chapter 4 concluded with an exploration of effective speed management at a rural intersection using the SSI method that reduced approach speeds from 55mph to 40mph.

Effective implementation of self-enforcing roads and longer-term changes in driver behavior would be seen in the conflicting lanes parameter of the conflicting traffic complexity factor. The parameter in the current method is based on the number of lanes that carry conflicting traffic movements for a selected movement of interest. For any selected movement in the following list, conflicting traffic movements are those that cross or merge with the selected movement of interest and are also listed above the selected movement on the list:

1. Major through and right turn.
2. Major left turn.
3. Minor through and right turn.
4. Minor left turn.
5. Nonmotorized.

Chapter 3 noted that placing nonmotorized movements at the bottom of this list prioritizes nonmotorized movements in the SSI analysis when characterizing the complexity of an intersection. The current method noted that, although nonmotorized road users typically have higher priority from a regulatory or traffic control perspective, their speed and vulnerability in a crash, along with uncertainty about driver awareness of their presence at any given time, may require pedestrians and cyclists to be aware of conflicting traffic movements that are lower-priority from a regulatory or traffic control perspective. This adds complexity for non-motorized users. Complexity would be reduced as long-term driver behavior changed to more consistently reflect typical nonmotorized road user priority from a regulatory or traffic control perspective.

5.2.2 Vehicles

Vehicle design plays a key role in achieving a Safe System at an intersection. The SSI method could incorporate different aspects of vehicle design if corresponding data or assumptions are available. The following sections provide two examples.

Vehicle Size. When estimating *P(FSI)* for vehicle-vehicle conflict points, the current SSI method assumes the masses of both vehicles are the same. Differences in the sizes of two vehicles involved in a collision will impact the estimates of *P(FSI)* for the occupants of each vehicle. The SSI method could incorporate sensitivity to vehicle sizes through the following steps:

- Establish vehicle categories and corresponding representative sizes (e.g., compact car, SUV/pickup truck, bus, large truck).
- Develop a method that translates user inputs or default values for vehicle mix into probabilities of crashes at a conflict point involving each possible combination of vehicles. Based on ties between "delta V" and *P(FSI)*, the specifics of which vehicle is making which movement through different conflict points is an important detail. For example, the conflict point defining a left-turn from the major road, an opposing through on the major road, and a car-bus combination could have the bus turning left with the car as the opposing through vehicle or vice versa. Each of these two scenarios would have a different *P(FSI)*.
- Estimate *P(FSI)* curves as functions of speeds and angles for each vehicle combination.
- Use the probabilities of crashes at a conflict point involving each combination of vehicles and *P(FSI)* for each combination to compute an overall *P(FSI)*.

In a similar fashion, *P(FSI)* curves for pedestrian and bicyclist crashes can also be defined as a function of vehicle size and combined with the probability that a pedestrian or bicyclist crash involves each vehicle size to estimate an overall *P(FSI)*.

Vehicle Technologies. Automated driving system (ADS) technologies are quickly advancing and are expected to impact road safety in the coming years. Such technologies would be expected to impact intersection crash likelihood and severity for different crash types. Such impacts would likely differ by ADS technology and conflict point type. The existing structure of the SSI method could incorporate ADS effects in an average/aggregate way. Distributions of vehicles with different technologies could be applied to movement volumes, resulting in exposure indices for each combination of ADS technologies. Those combinations could have different *P(FSI)* curves if the technologies are expected to automate reductions in speeds and/or collision angles during last the final seconds pre-crash scenarios. Much like the traffic control parameter of the conflicting lanes complexity factor, ADS parameters could also reduce complexity significantly, resulting in lower values for some exposure-severity-complexity factors and improved SSI MOEs and scores.

5.2.3 Users

User characteristics such as fatigue, impairment, behavior (e.g., level of compliance, distraction), and performance capabilities can impact the likelihood of a crash as those users make different movements through an intersection. Similarly, a user's age, condition, and use of safety equipment (e.g., seatbelts, helmets) can have significant effects on their level of injury resulting from a crash. Such extensive sets of user characteristics can quickly complicate the SSI method, but they are a part of a systems analysis of intersection safety. The existing structure of SSI method could incorporate such user characteristics in an average/aggregate way. Distributions of key user characteristics could be applied to movement volumes, resulting in exposure indices for each combination of user characteristics. Those combinations of user characteristics could have different *P(FSI)* curves, and different user characteristic parameters applied to the complexity factors. This would lead to exposure-severity-complexity products for different combinations of user characteristics, which could then be summed for different conflict point types and for the intersection, leading to the SSI MOEs and scores.

At some point, the large number of user and vehicle type combinations could lend themselves to an analysis by a microscopic safety simulation, where distributions of user characteristics, vehicle characteristics, and user arrival distributions are inputs and the intersection is modeled in a stochastic way. Crash probabilities for users making different movements would vary based on these characteristics and other conditions at any given time. Similarly, *P(FSI)* would be a function of the vehicles and users involved in a crash that had a specific speed and angle. Such a model could be validated by whether the simulation, carried out over a year or multi-year time period, would simulate comparable numbers and severities of crashes as to what is observed. Research and supporting data to inform the development of such a microscopic safety simulation model would improve the ability of intersection planners and designers to gain a greater system-level understanding of the factors leading to fatalities and serious injuries and to manage intersection safety toward the goal of achieving zero fatalities and serious injuries.

APPENDIX A: SSI LIBRARY OF INTERSECTION TYPES

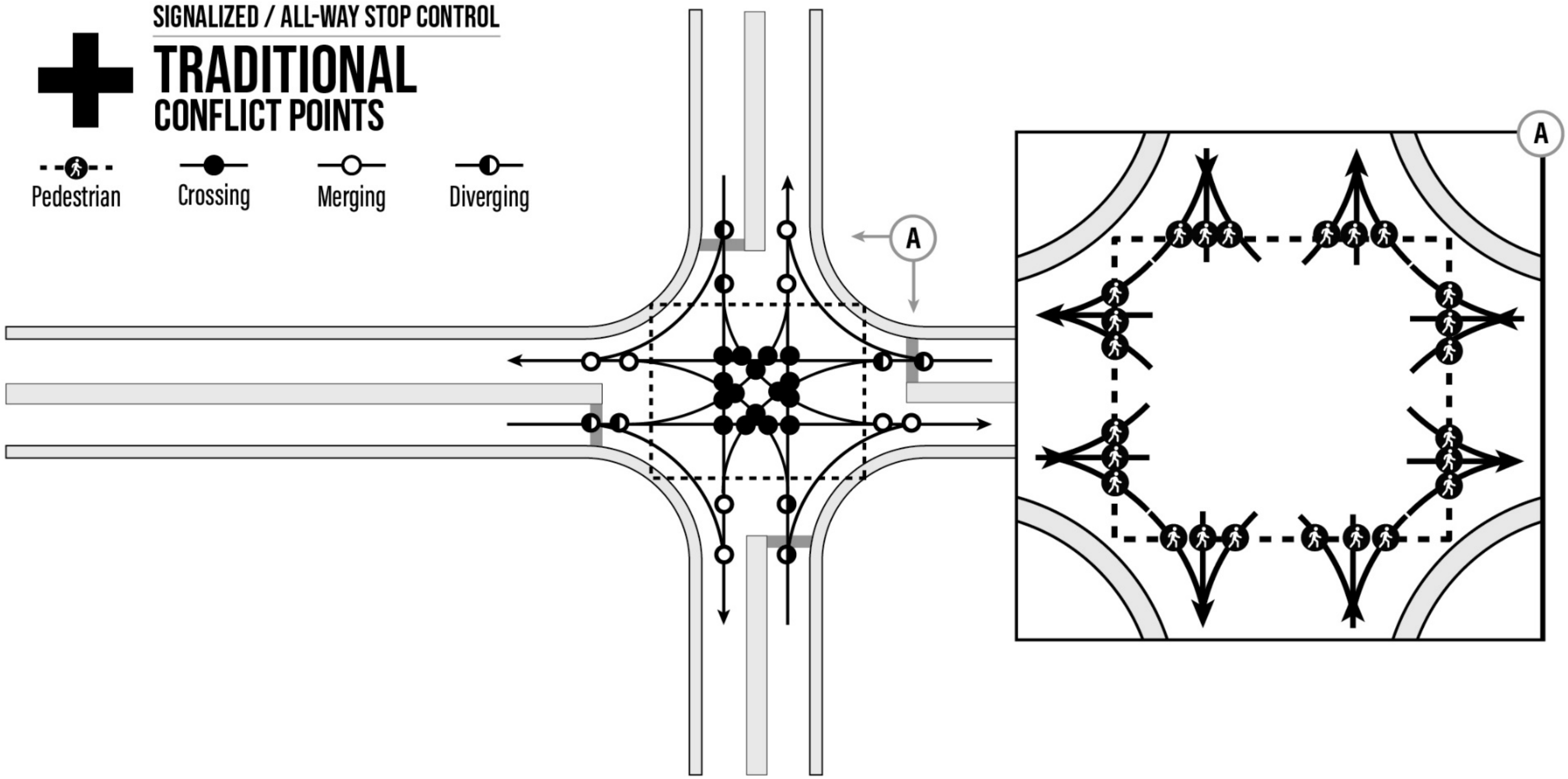
This appendix provides overviews of various intersection alternatives that transportation agencies could consider as part of Stage 1 ICE. For each intersection alternative, the appendix includes the following information:

- Intersection type (and aliases).
- Distinguishing features and other key considerations.
- Nonmotorized considerations.
- Assumptions in SSI method application for Stage 1 ICE.
    - These are "default" assumptions made in this report for demonstrating the application of the SSI method to Stage 1 ICE. However, the method can be generalized and applied to agency- and project-specific situations that differ from the assumptions (e.g., three intersecting legs, major road median providing refuge for minor road through and left-turning vehicles at traditional intersection).
- Conditions supporting consideration.
- Potential benefits.
- Traffic control characteristics.
- Counts and diagrams of movement-based conflict points.

TRADITIONAL

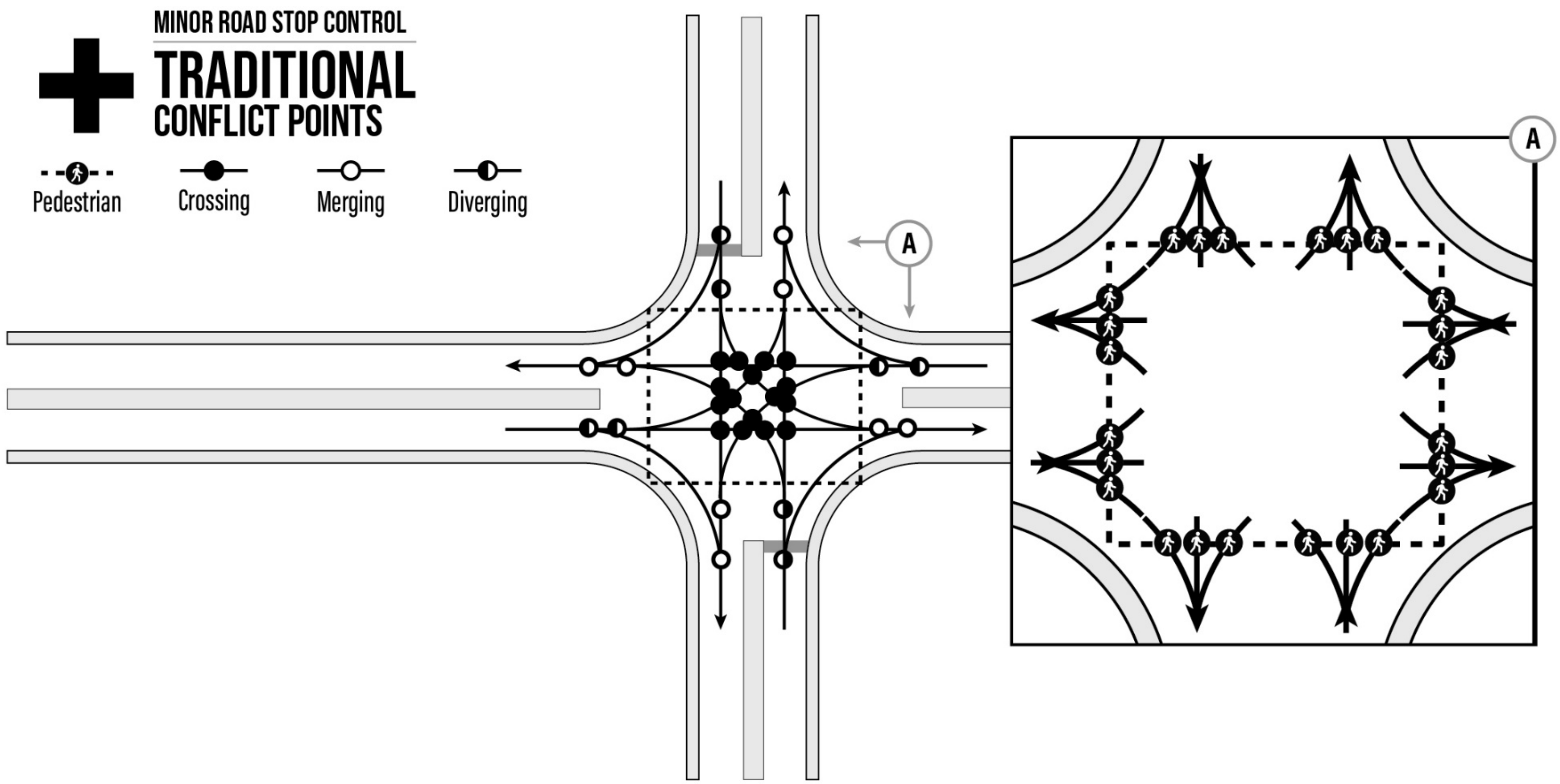
Table 31. Key characteristics and considerations related to the traditional intersection alternatives.

Intersection type	Traditional	
Aliases	Conventional; standard; default	
Distinguishing features/key considerations	• Allows direct movements (left, thru, right) on all approaches; State or local agencies may implement some movement restrictions with traffic control devices.	
Nonmotorized considerations	• One-stage or two-stage crossings depending on presence of refuge. • Long signal cycle lengths can limit crossing opportunities.	
Report assumptions in SSI method application for Stage 1 ICE	• Intersection has 4 legs. • 3 traffic control schemes (signal control, all-way stop control, minor road stop control) considered. • No medians on any legs.	
Conditions supporting consideration	• Generally considered across a wide range of contexts.	
Potential benefits	• Widespread familiarity and intuitive nature of movements.	
Traffic control characteristics	• Can operate under signal control, all-way stop control, or minor road stop control.	
Movement-based conflict points	Vehicle-vehicle – total	32
	Vehicle-vehicle – crossing	16
	Vehicle-vehicle – merging	8
	Vehicle-vehicle – diverging	8
	Nonmotorized-vehicle	24



Source: FHWA

Figure 35. Graphic. Diagram of movement-based conflict points for Traditional Signalized and All-Way Stop Control intersections.



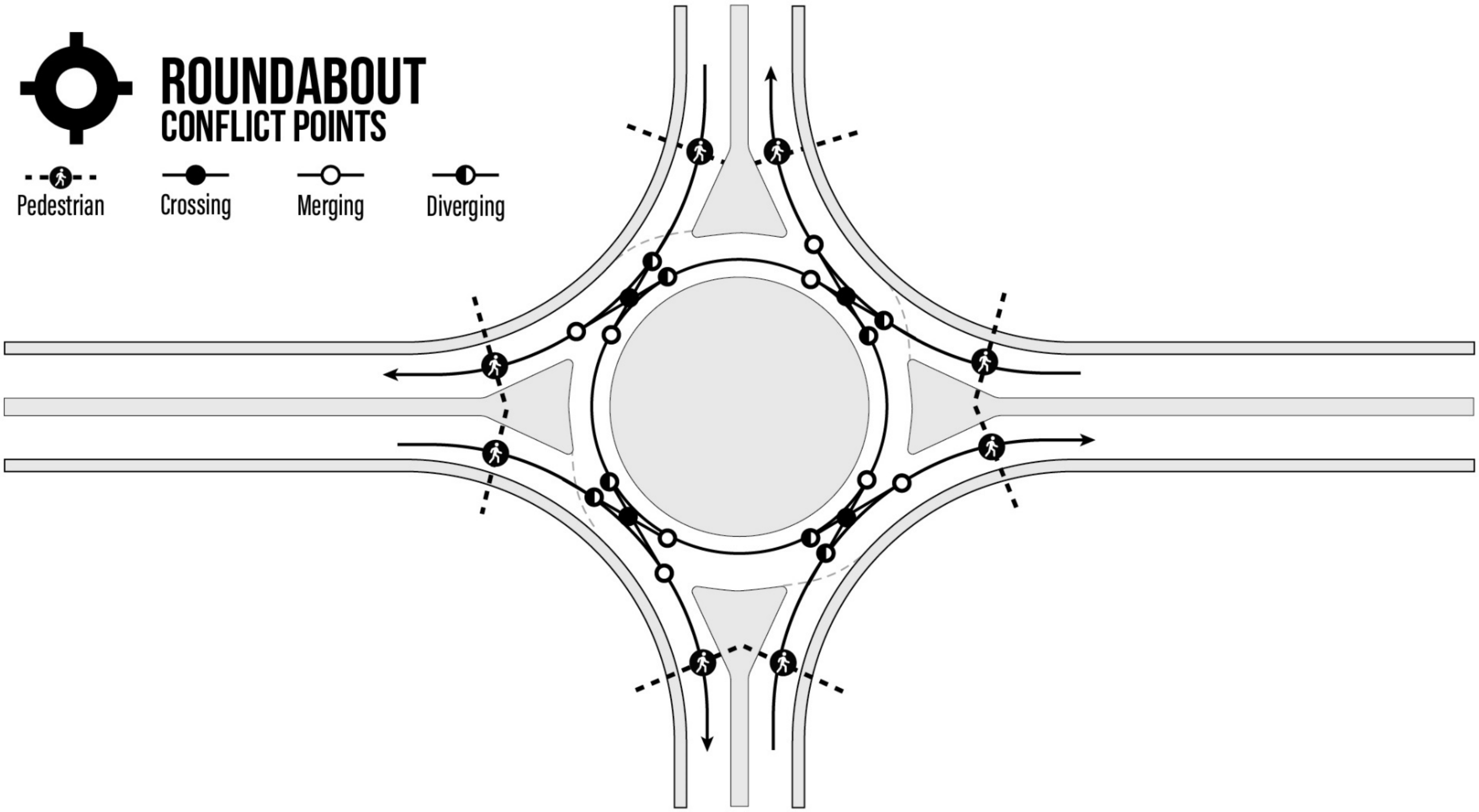
Source: FHWA

Figure 36. Graphic. Diagram of movement-based conflict points for Traditional Minor Road Stop Control intersections.

ROUNDABOUT

Table 32. Key characteristics and considerations related to the roundabout intersection alternatives.

Intersection type	Roundabout	
Aliases		
Distinguishing features/key considerations	• Removes direct left turns from all approaches and replaces them with yield-controlled approaches into a counter-clockwise circulatory lane. • Can be installed at individual intersections (provided they are located far enough from nearby signalized/stop-controlled intersections that queues do not extend into the roundabout) or in series along a corridor.	
Nonmotorized considerations	• Splitter islands provide refuge and allow for two stage crossings.	
Report assumptions in SSI method application for Stage 1 ICE	• All approaches have splitter islands/pedestrian refuge islands. • Three roundabout entry geometries considered: 1x1 Roundabout (1 lane in each direction on all approaches), 2x1 Roundabout (2 lanes in each direction on major road, which yield to one circulating lane; 1 lane in each direction on minor road, which yield to two circulating lanes), and 2x2 Roundabout (2 lanes in each direction on all approaches, yielding to two circulating lanes). • All approaches operate under yield control. • Indirect Paths adjustment applied to all nonmotorized movements due to footprint and placement of crosswalks.	
Conditions supporting consideration	• High frequency of left-turning or right-angle crashes. • Increased capacity or improved efficiency desired without adding lanes along the corridor. • Sufficient space available at the intersection (wide nodes, narrow roads concept).	
Potential benefits	• Reduction in crossing conflict points. • Roundabout geometry and yield control lead to reduced vehicle speeds. • Geometry deflects approaching vehicles and produces shallower collision angles (less severe). • Increased capacity and improved operational efficiency, as vehicles operate on a gap-acceptance model. • Simplified decision-making for road users as conflicting movements approach from one direction.	
Traffic control characteristics	• All approaches typically operate under yield control. Unexpected demand may result in signalized control of one or more entries, or signalized control of the circulating roadway.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	20 *(32)*
	Vehicle-vehicle – crossing	4 *(16)*
	Vehicle-vehicle – merging	8 *(8)*
	Vehicle-vehicle – diverging	8 *(8)*
	Nonmotorized-vehicle	8 *(24)*



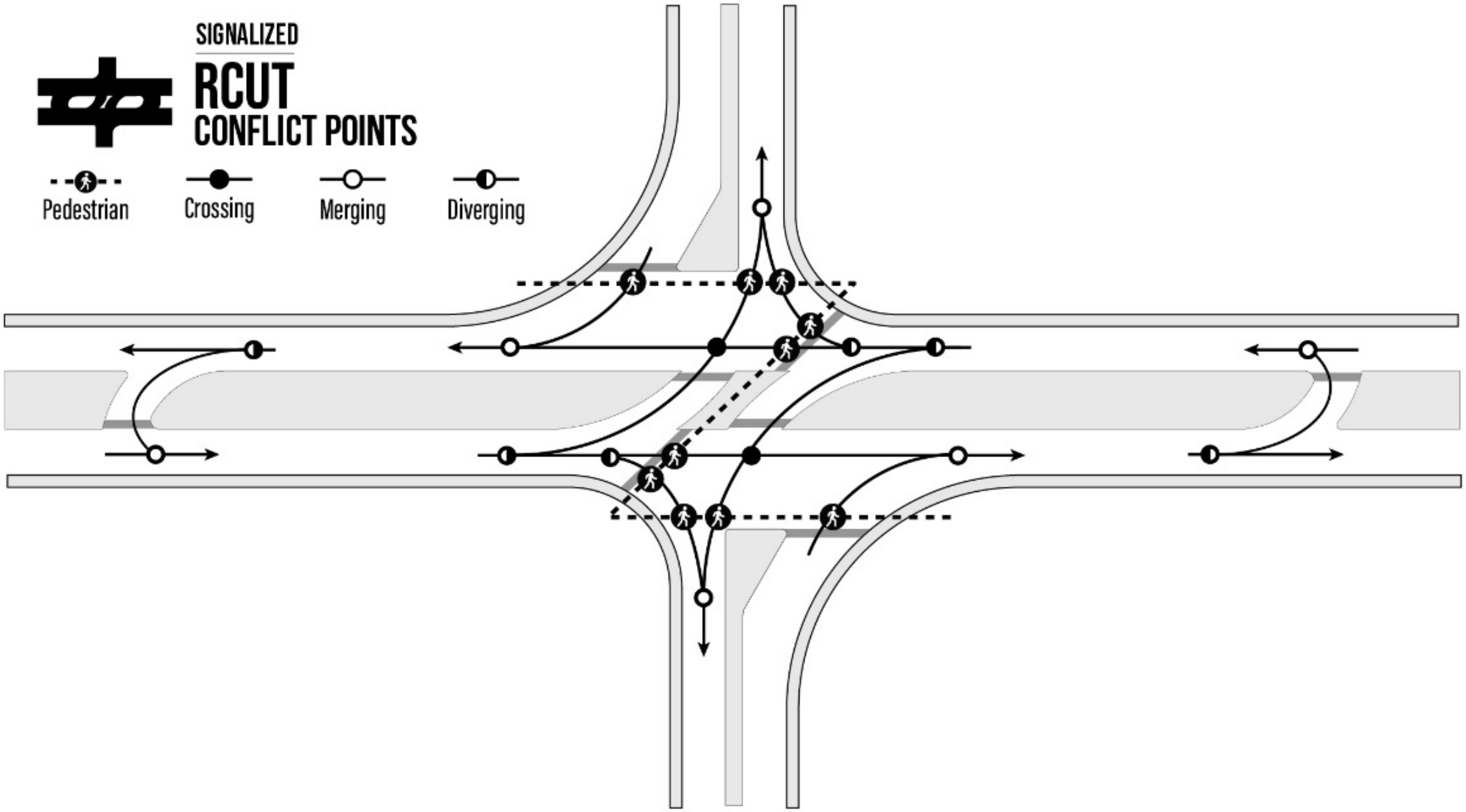
Source: FHWA

Figure 37. Graphic. Diagram of movement-based conflict points for Roundabout intersections.

RESTRICTED CROSSING U-TURN (RCUT)

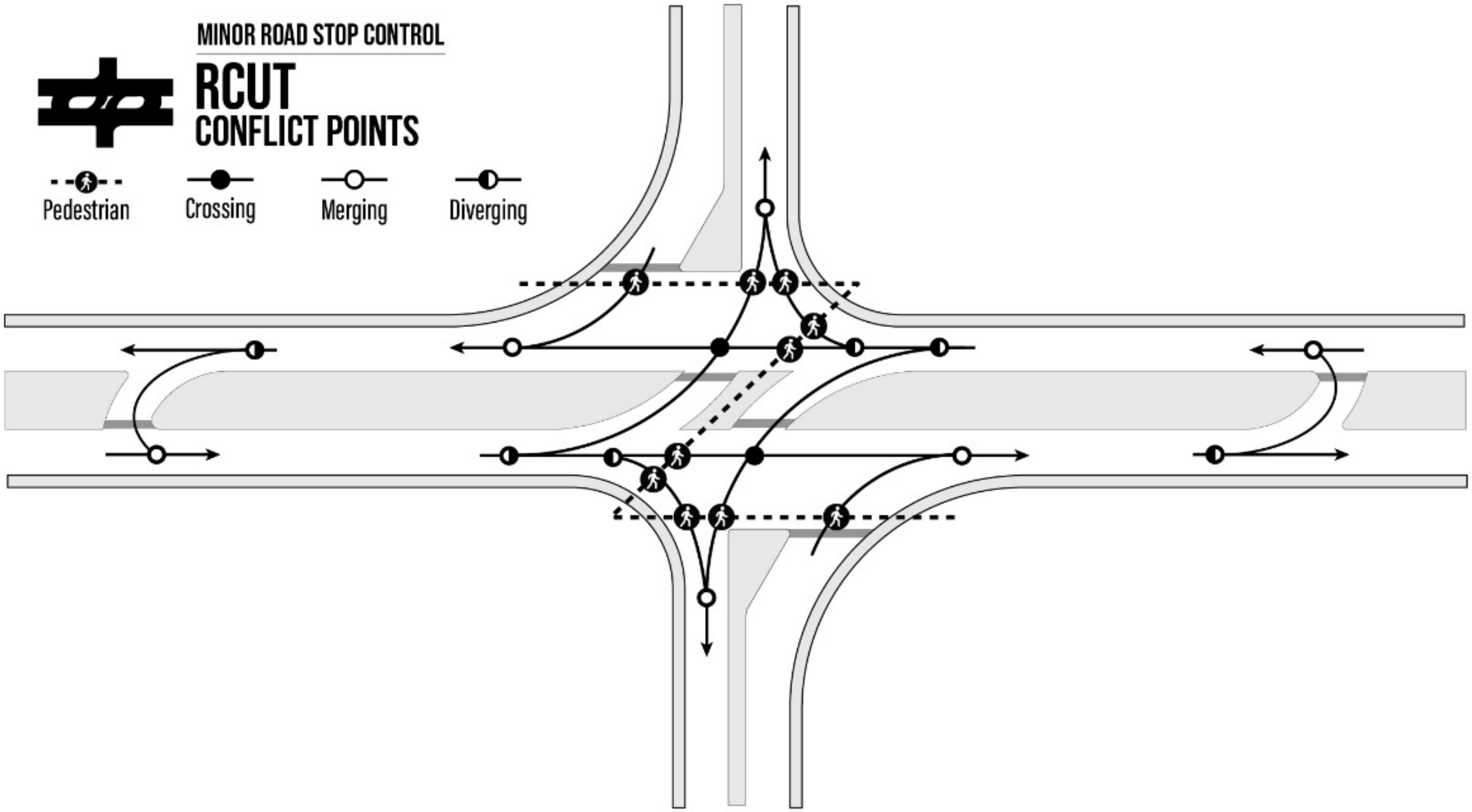
Table 33. Key characteristics and considerations related to the RCUT intersection alternatives.

Intersection type	Restricted crossing U-turn	
Aliases	J-turn; superstreet; synchronized street; reduced conflict intersection	
Distinguishing features/key considerations	• Removes direct left turns and through movements from minor road (minor road left turns made via right-turn/U-turn combination, minor road through movements made via right-turn/U-turn/right-turn combination). • Requires downstream U-turn accommodations along major road.	
Nonmotorized considerations	• Wider footprint lengthens crossings, but major road median provides refuge for multistage crossing. • Shorter signal cycle lengths yield more frequent crossing opportunities. • Z-crossing is most common pattern, resulting in some indirect nonmotorized movements.	
Report assumptions in SSI method application for Stage 1 ICE	• All approaches have medians/pedestrian refuge islands. • 2 traffic control schemes (signal control, minor road stop control) considered. • Z-type pedestrian crossing pattern is utilized, Indirect Paths adjustment applied to nonmotorized road users crossing major road.	
Conditions supporting consideration	• Lower left-turning and through volumes from minor road. • High frequency of right-angle crashes. • Sufficient median width, right-of-way (ROW), and intersection spacing for U-turn accommodations. • Accommodates wide range of major road volumes.	
Potential benefits	• Eliminates all but two crossing conflict points. • Provision of pedestrian refuge medians. • Simplified decision-making for road users as conflicting movements approach from one direction. • Increased capacity and improved operational efficiency. • Increased flexibility in signal timing, especially for accommodating unbalanced flows. • Fewer signal phases may yield improved coordination with adjacent signals.	
Traffic control characteristics	• Minor road stop control can be considered for low minor road volumes. • Usually signalized with moderate to high minor road volumes. • U-turns may operate under signal control, stop control, or yield control.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	14 *(32)*
	Vehicle-vehicle – crossing	2 *(16)*
	Vehicle-vehicle – merging	6 *(8)*
	Vehicle-vehicle – diverging	6 *(8)*
	Nonmotorized-vehicle	10 *(24)*



Source: FHWA

Figure 38. Graphic. Diagram of movement-based conflict points for Signalized RCUT intersections.



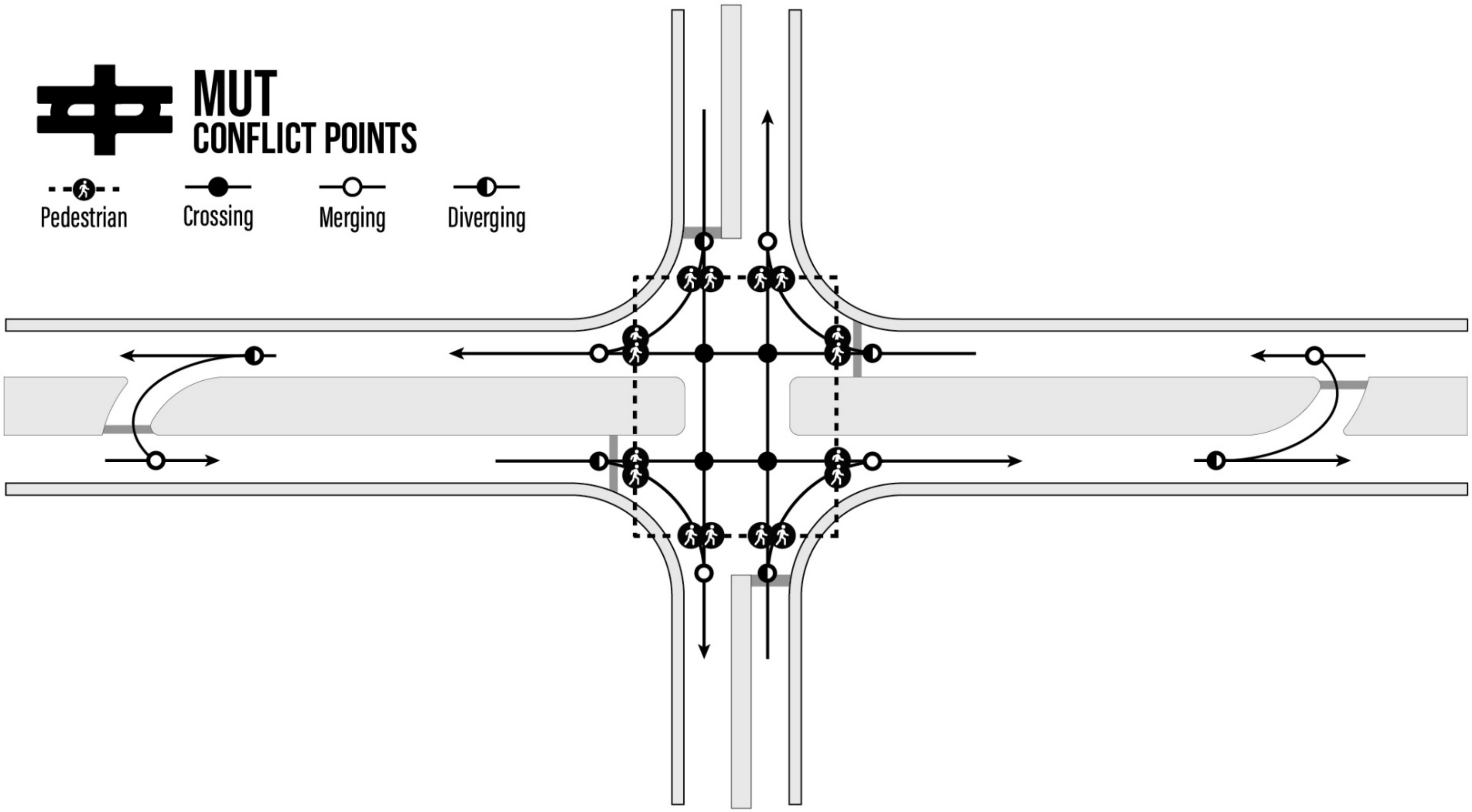
Source: FHWA

Figure 39. Graphic. Diagram of movement-based conflict points for Unsignalized RCUT intersections.

MEDIAN U-TURN (MUT)

Table 34. Key characteristics and considerations related to the MUT intersection alternative.

Intersection type	Median U-Turn (MUT)	
Aliases	ThrU-turn; indirect left; express left; Michigan left; Michigan loon	
Distinguishing features/key considerations	• Removes direct left turns from major and/or minor roads. • Requires downstream U-turn accommodations along major road or minor road. • Left turns made via right-turn/U-turn or U-turn/right-turn combination. • Can be installed at individual intersections or applied in series along a corridor.	
Nonmotorized considerations	• Wider footprint lengthens crossings, but major road median provides adequate refuge for multistage crossing. • Shorter signal cycle lengths yield more frequent crossing opportunities.	
Report assumptions in SSI method application for Stage 1 ICE	• All approaches have medians/pedestrian refuge islands. • All direct left turns are removed from intersection.	
Conditions supporting consideration	• Higher proportion of thru volumes to left-turning volumes. • Higher frequency of right-angle and rear-end crashes. • Sufficient median width, ROW, and intersection spacing for U-turn accommodations. • Can accommodate high intersection volumes.	
Potential benefits	• Reduction in crossing conflict points. • Simplified task of crossing for nonmotorized road users as there are no conflicting left turn movements at the main intersection. • Increased capacity and improved operational efficiency. • Increased capacity and improved operational efficiency. • Fewer signal phases may yield improved coordination with adjacent signals.	
Traffic control characteristics	• Main junction is signalized. • U-turns may operate under signal control, yield control, or no control.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	16 *(32)*
	Vehicle-vehicle – crossing	4 *(16)*
	Vehicle-vehicle – merging	6 *(8)*
	Vehicle-vehicle – diverging	6 *(8)*
	Nonmotorized-vehicle	16 *(24)*



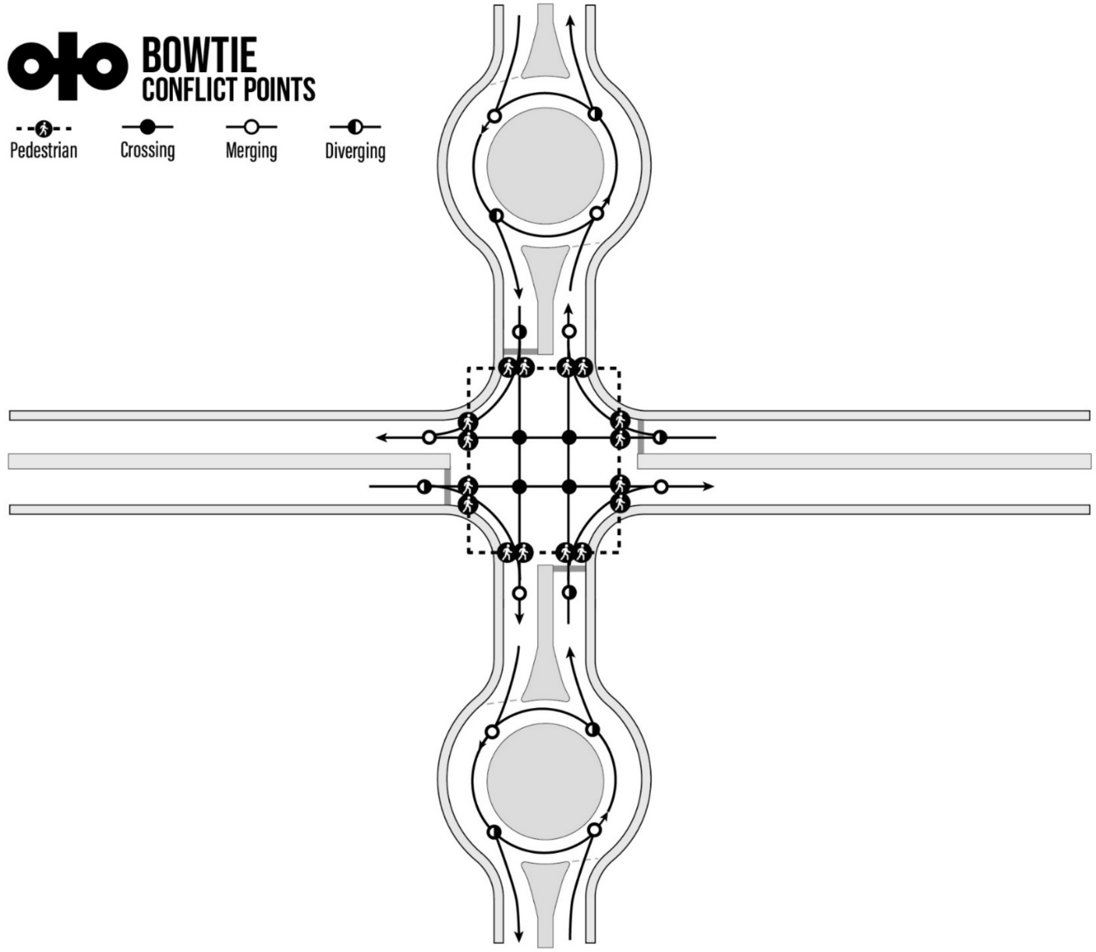
Source: FHWA

Figure 40. Graphic. Diagram of movement-based conflict points for MUT intersections.

BOWTIE

Table 35. Key characteristics and considerations related to the bowtie intersection alternative.

Intersection type	Bowtie	
Aliases		
Distinguishing features/key considerations	• Removes direct left turns from all approaches. • Roundabouts placed on the minor road on each side of the main intersection. • Left turn movements are accommodated by a combination of right turns, U-turns at a roundabout, and through movements through the main intersection.	
Nonmotorized considerations	• Crossings at main intersection similar to a traditional intersection. • Crossings at roundabouts are the same as roundabouts, i.e. splitter islands provide refuge and allow for two stage crossings.	
Report assumptions in SSI method application for Stage 1 ICE	• No left turn movements at the main intersection. • Secondary roundabouts do not provide a speed reduction benefit for vehicles entering the main intersection.	
Conditions supporting consideration	• Increased capacity required without sufficient ROW to add lanes along the corridor. • Sufficient ROW available up/downstream of main intersection for roundabouts. • Moderate-heavy major road through volumes and low-moderate left turn volumes.	
Potential benefits	• Eliminates all left turning crossing conflicts. • Conflicts at secondary roundabouts receive same benefits as standalone roundabout. • Simplified task of crossing for pedestrians as there are no conflicting left-turn movements at the main intersection. • Increased capacity and improved operational efficiency for the major through movements. • Fewer signal phases may yield improved coordination with adjacent signals.	
Traffic control characteristics	• Main intersection operates under signal control. • Roundabouts on minor road operate the same as standard roundabouts, i.e. yield control.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	20 *(32)*
	Vehicle-vehicle – crossing	4 *(16)*
	Vehicle-vehicle – merging	8 *(8)*
	Vehicle-vehicle – diverging	8 *(8)*
	Nonmotorized-vehicle	16 *(24)*



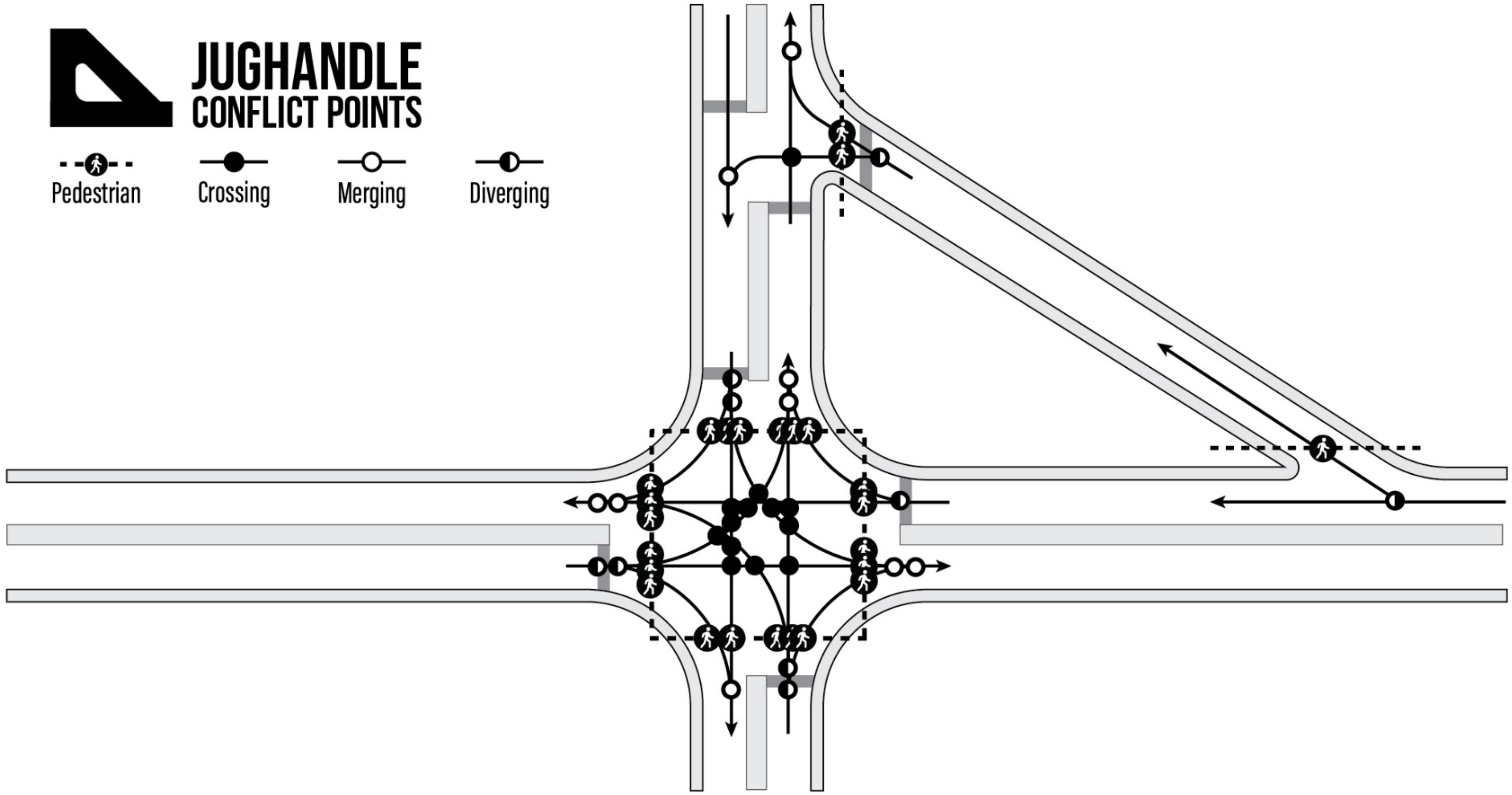
Source: FHWA

Figure 41. Graphic. Diagram of movement-based conflict points for Bowtie intersections.

JUGHANDLE

Table 36. Key characteristics and considerations related to the jughandle intersection alternative.

Intersection type	Jughandle	
Aliases	New Jersey Left	
Distinguishing features/key considerations	• Removes direct right and left turns from one approach. • Replaces these movements by directing them onto an at-grade roadway (the "jughandle"). • From the jughandle, vehicles can then turn left or right onto the intersecting road.	
Nonmotorized considerations	• Crossings at main intersection similar to a traditional intersection, though crossing widths may be reduced due to absence of turn lane(s). • Nonmotorized road users traveling in the same quadrant as the jughandle have additional crossing point(s).	
Report assumptions in SSI method application for Stage I ICE	• Though other configurations are possible, the most common type, the forward jughandle, is assumed.	
Conditions supporting consideration	• High frequency of right-angle crashes. • Sufficient ROW available in one quadrant for the jughandle. • Relatively low left turn volumes.	
Potential benefits	• Removes one left turn movement from main intersection, eliminating the crossing and nonmotorized conflict points associated with that left turn movement at the main intersection. • Increased capacity and improved operational efficiency due to removal of turns from one approach.	
Traffic control characteristics	• Main intersection operates under signal control. • Left turns off of the jughandle are stop-controlled. • Right turns off of the jughandle may be either stop-controlled or yield-controlled.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	31 *(32)*
	Vehicle-vehicle – crossing	13 *(16)*
	Vehicle-vehicle – merging	9 *(8)*
	Vehicle-vehicle – diverging	9 *(8)*
	Nonmotorized-vehicle	25 *(24)*



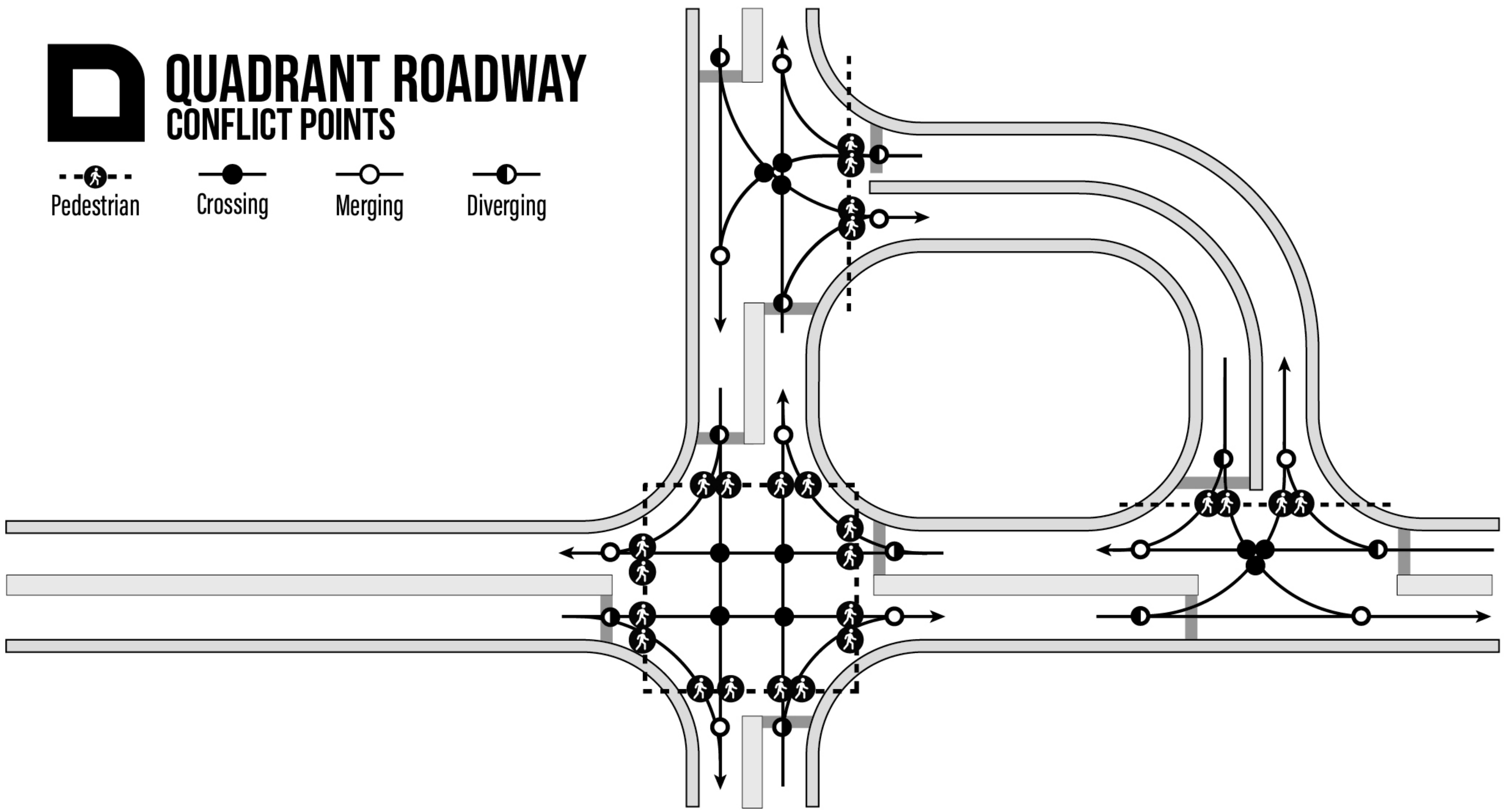
Source: FHWA

Figure 42. Graphic. Diagram of movement-based conflict points for Jughandle intersections.

QUADRANT ROADWAY

Table 37. Key characteristics and considerations related to the quadrant roadway intersection alternative.

Intersection type	Quadrant roadway	
Aliases		
Distinguishing features/key considerations	• Removes direct left turns from all approaches. • Two secondary intersections, one each on the major and minor roadways, are connected by a quadrant roadway. • Left turns are accommodated by performing right turns and through movements at the main intersections and left and right turns at each of the secondary intersections.	
Nonmotorized considerations	• Crossings at main intersection similar to a traditional intersection, though crossing widths may be reduced due to absence of turn lane(s). • Nonmotorized road users traveling in the same quadrant as the quadrant roadway have an additional crossing point(s).	
Report assumptions in SSI method application for Stage 1 ICE	• Though it is possible for other configurations, such as having quadrant roadways in two quadrants or having roundabouts serve as the secondary intersections, a single quadrant roadway with signalized T-intersections is assumed.	
Conditions supporting consideration	• High frequency of right-angle crashes. • Roadway in one quadrant already exists and can be utilized as the connecting roadway. • Heavy through and left turn volumes on both intersecting roads.	
Potential benefits	• Removes all left turn movements from main intersection, reducing crossing conflicts. • Simplified task of crossing for nonmotorized road users, as there are no left turn vehicles intersecting crosswalks at the main intersection. • Increased capacity and improved operational efficiency due to removal of all direct left turns from main intersection. • Fewer signal phases may yield improved coordination with adjacent signals.	
Traffic control characteristics	• Main intersection and secondary T-intersections are signalized. • The three signalized intersections can be synchronized to provide optimal efficiency for both roadways.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	30 *(32)*
	Vehicle-vehicle – crossing	10 *(16)*
	Vehicle-vehicle – merging	10 *(8)*
	Vehicle-vehicle – diverging	10 *(8)*
	Nonmotorized-vehicle	24 *(24)*



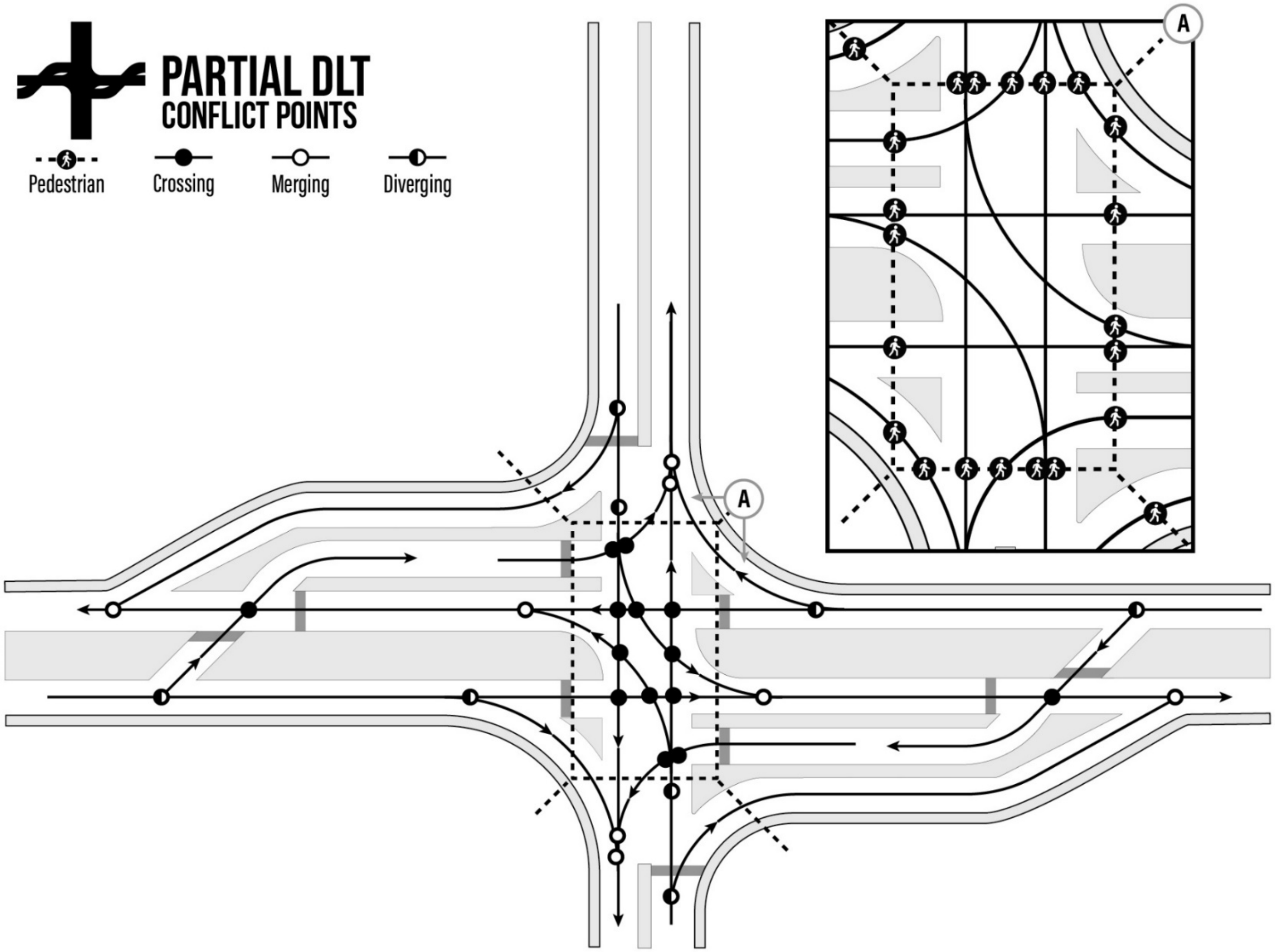
Source: FHWA

Figure 43. Graphic. Diagram of movement-based conflict points for Quadrant Roadway intersections.

PARTIAL DISPLACED LEFT TURN (PDLT)

Table 38. Key characteristics and considerations related to the PDLT intersection alternative.

Intersection type	Partial displaced left turn (PDLT)	
Aliases	Continuous flow intersection (CFI)	
Distinguishing features/key considerations	• Left-turning traffic along major or minor road crosses over to the left-hand side of the road at secondary intersections upstream of the main junction. • Enables left-turns and through movements to occur simultaneously at main intersection without conflicting with one another.	
Nonmotorized considerations	• Movements are more complex than at traditional intersection due to unique lane placement; traffic may approach from unexpected direction. • Wider footprint lengthens crossings, but islands provide refuge for multistage crossing. • Shorter signal cycle lengths yield more frequent crossing opportunities.	
Report assumptions in SSI method application for Stage 1 ICE	• Displaced left turns are applied to major road. • All approaches have medians/pedestrian refuge islands and right turns are all channelized. • Indirect Paths adjustment applied to all nonmotorized conflict points (due to channelized right turns); Non-Intuitive Motor Vehicle Movements adjustment applied to nonmotorized conflict points along nonmotorized movements that cross approaches with displaced left turns.	
Conditions supporting consideration	• Heavy thru and left-turning volumes. • Left-turn queues that exceed existing storage. • High frequency of crashes associated with left turns. • Can accommodate high intersection volumes.	
Potential benefits	• Reduction in crossing conflict points. • Increased capacity and improved operational efficiency. • Fewer signal phases may yield improved coordination with adjacent signals.	
Traffic control characteristics	• Main junction and crossovers are signalized.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	30 *(32)*
	Vehicle-vehicle – crossing	14 *(16)*
	Vehicle-vehicle – merging	8 *(8)*
	Vehicle-vehicle – diverging	8 *(8)*
	Nonmotorized-vehicle	22 *(24)*



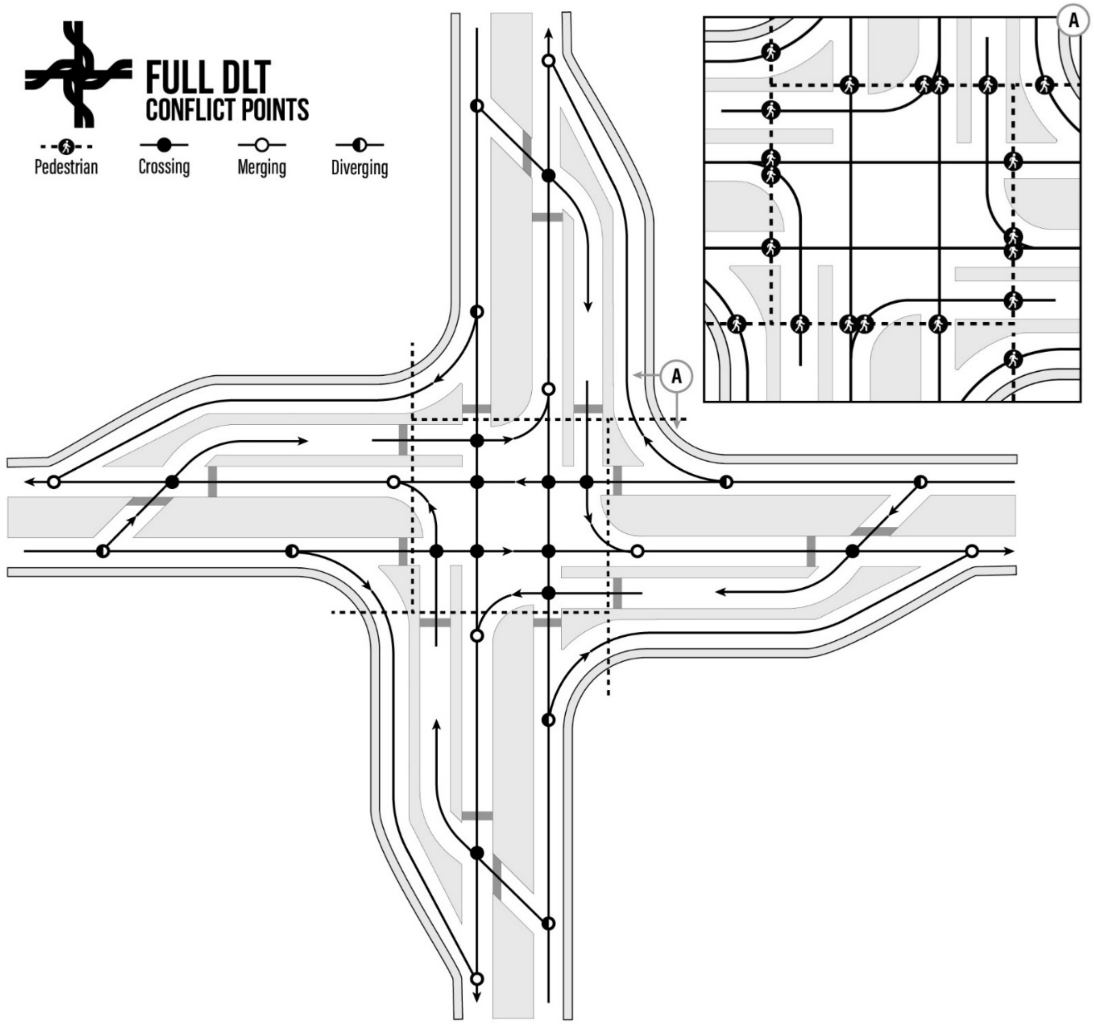
Source: FHWA

Figure 44. Graphic. Diagram of movement-based conflict points for Partial DLT intersections.

FULL DISPLACED LEFT TURN (FDLT)

Table 39. Key characteristics and considerations related to the FDLT intersection alternative.

Intersection type	Full displaced left turn (FDLT)	
Aliases	Continuous flow intersection (CFI)	
Distinguishing features/key considerations	• Left-turning traffic along major and minor road crosses over to the left-hand side of the road at secondary intersections upstream of the main junction. • Enables left-turns and through movements to occur simultaneously at main intersection without conflicting with one another.	
Nonmotorized considerations	• Movements are more complex than at traditional intersection due to unique lane placement; traffic may approach from unexpected direction. • Wider footprint lengthens crossings, but median islands provide refuge for multistage crossing. • Shorter signal cycle lengths yield more frequent crossing opportunities.	
Report assumptions in SSI method application for Stage 1 ICE	• All approaches have medians/pedestrian refuge islands and right turns are all channelized. • Indirect Paths adjustment applied to all nonmotorized conflict points (due to channelized right turns) and Non-Intuitive Motor Vehicle Movements adjustment applied to all nonmotorized conflict points.	
Conditions supporting consideration	• Heavy thru and left-turning volumes. • Left-turn queues that exceed existing storage. • High frequency of crashes associated with left turns. • Can accommodate high intersection volumes.	
Potential benefits	• Reduction in crossing conflict points. • Increased capacity and improved operational efficiency. • Fewer signal phases may yield improved coordination with adjacent signals.	
Traffic control characteristics	• Main junction and crossovers are signalized.	
Movement-based conflict points *(Compared to Traditional)*	Vehicle-vehicle – total	28 *(32)*
	Vehicle-vehicle – crossing	12 *(16)*
	Vehicle-vehicle – merging	8 *(8)*
	Vehicle-vehicle – diverging	8 *(8)*
	Nonmotorized-vehicle	20 *(24)*



Source: FHWA

Figure 45. Graphic. Diagram of movement-based conflict points for Full DLT intersections.

APPENDIX B: SSI METHOD EXAMPLE CALCULATIONS

This appendix presents example calculations of the SSI method for a selection of intersection types and conflict points. For each major step in the SSI method, the appendix illustrates calculations for several different conflict points at three different intersection alternatives: the traditional signalized intersection, the 2x1 roundabout, and the unsignalized RCUT intersection. The specific conflict points used were chosen to illustrate different aspects of the method.

The example calculations are based on the intersection conditions of Scenario 1 in chapter 4, a suburban intersection of a four-lane arterial and a two-lane collector that currently exists as a traditional signalized intersection as depicted in figure 32. Table 40 contains the data inputs as well as some assumptions used to perform the calculations. Note that some of these assumptions may not be necessary depending on an agency's available data. For instance, if an agency had access to turning movement counts (either peak hour counts or turning movement ADTs) it would not be necessary to assume a directional split or turning proportions.

Table 40. Example calculation core inputs.

Item	Input Value	Assumption
Design year AADT – major	25,000	50% directional split. Turning proportions: 25% left turn, 25% right turn.
Design year AADT – minor	20,000	50% directional split. Turning proportions: 25% left turn, 25% right turn.
Nonmotorized ADT	2,400	Nonmotorized volume is evenly distributed across the four crossings at the intersection.
Number of thru lanes – major	4	--
Number of thru lanes – minor	2	--
Traffic control type	Signalized	Left-turn signal phasing for both major and minor roads is protected-permitted.
Posted speed limit – major	45	--
Posted speed limit – minor	35	--

Furthermore, the movement speeds, collision angles, *P(FSI)* regression parameters, *BTCAV*'s, driver merging weights, and nonmotorized turn score merging weights are derived from the ranges presented in chapter 3. In most cases, Scenario 1 calculations use the midpoint of the ranges. Table 41 summarizes the input values for the example calculations in this appendix.

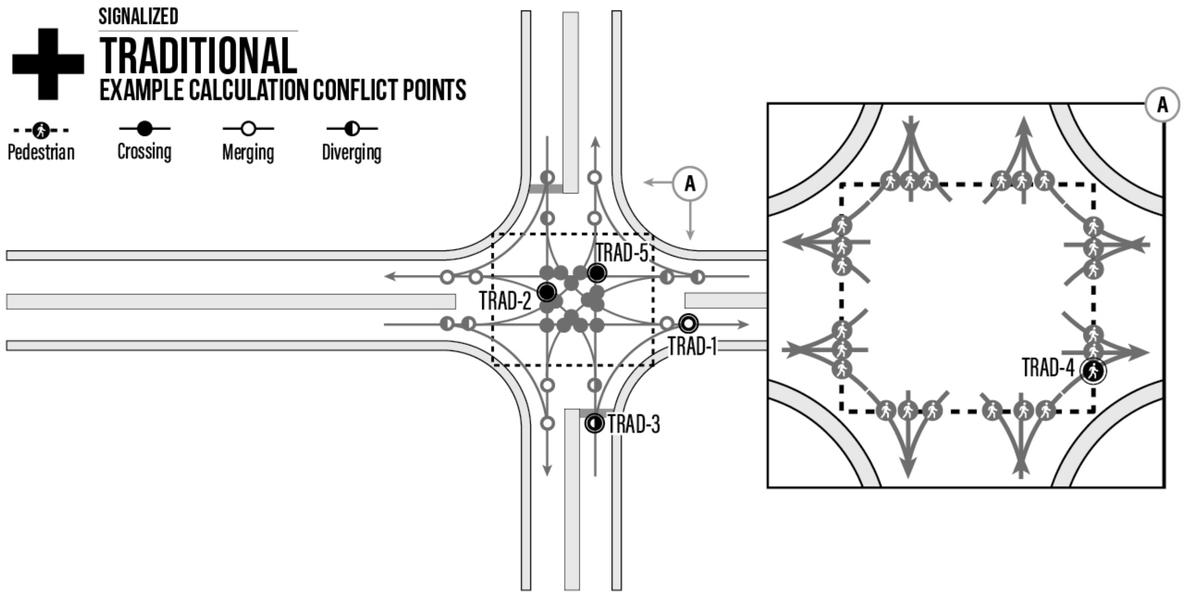
Table 41. Default input values used for example calculations.

Category	Item	Value	Units
Movement speeds	Major through	Major PSL	mph
	Major left	20	mph
	Major right	15	mph
	Minor through	0.85 * Minor PSL	mph
	Minor left	20	mph
	Minor right	15	mph
	Stop control near-side	15	mph
	Stop control far-side	25	mph
	Signal control near-side	15	mph
	Signal control far-side	25	mph
	Roundabout entering	20	mph
	Roundabout circulating	25	mph
	Roundabout exiting	30	mph
Collision angles	Crossing – Broadside	90	deg
	Crossing – Left Turn	230	deg
	Crossing – Roundabout	60	deg
	Merging	45	deg
	Diverging	10	deg
P(FSI) regression parameters	*alpha*	67.29	--
	k	3.79	--
Traffic control adjustments	*BTCAV*, permitted	1	--
	BTCAV, protected/permitted	0.85	--
	BTCAV, protected	0.01	--
	BTCAV, stop-controlled	0.45	--
	Weight, *f*	0.5	--
	Major left turn phasing	Protected/permitted	--
	Minor left turn phasing	Protected/permitted	--
Driver Merging and Nonmotorized Turn Score Weights	Lane 1 (W_1)	1	--
	Lane 2 (W_2)	0.75	--
	Lane 3+ (W_{3+})	0.5	--

Finally, table 42 lists the conflict points featured in this appendix to illustrate the SSI method example calculations. Some of these selected conflict points are used to illustrate each part of the SSI method (i.e., exposure, severity, and complexity calculations) while others were chosen to specifically highlight one specific part. The conflict point naming convention presented in the second column of table 42 is used throughout this appendix to simplify references to the different conflict points. Figure 46, figure 47, and figure 48 display the three intersection types with the conflict points featured in this appendix denoted by darker linework and labels corresponding to the conflict point names in table 42. It will be helpful for the reader to refer to these figures, as well as the intersection figures presented in appendix A, to better visualize the different conflict points used in these example calculations. Note that the cardinal directions used to describe the different movements, conflict points, and areas of intersections assume the convention that "north" is oriented "up" toward the top of the page when the page is correctly oriented for reading. In both chapter 4 and appendix A, the intersecting road positioned in the "up-down" (i.e., north-south) direction is the minor road. The intersecting road positioned in the "left-right" (i.e., east-west) direction is the minor road.

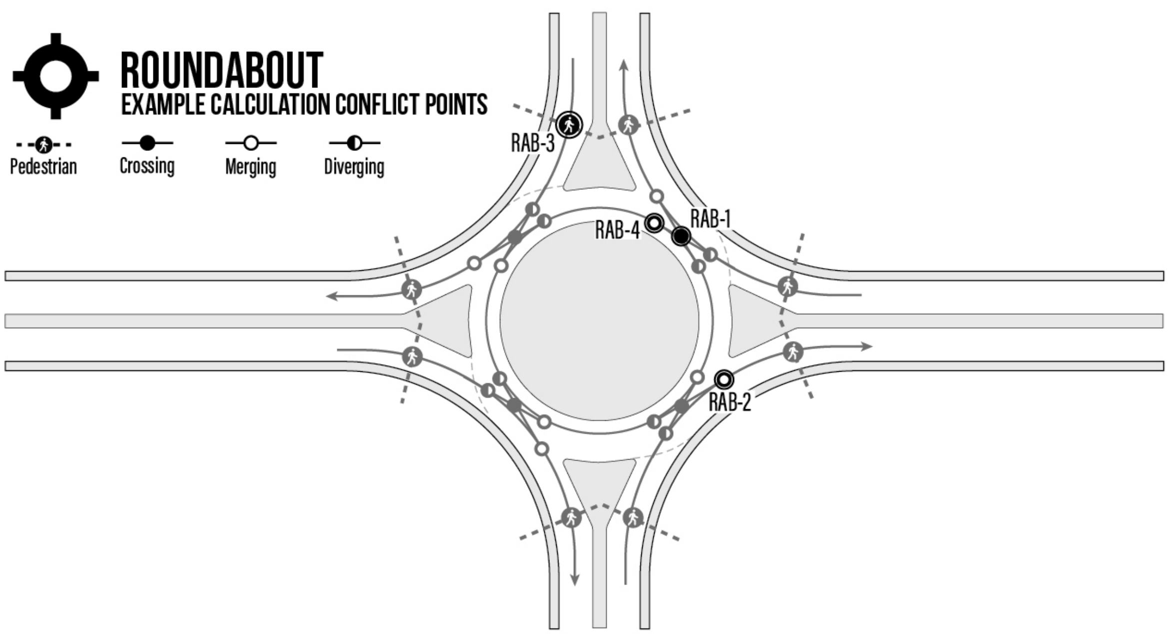
Table 42. Conflict points used for example calculations.

Intersection Type	Conflict Point Name	Conflict Point Type	Movement 1	Movement 2
Traditional Signalized (see figure 46)	Trad-1	Merging – Right Turn	Eastbound (EB) Thru	Northbound (NB) Right
	Trad-2	Crossing – Left Turn	Southbound (SB) Thru	NB Left
	Trad-3	Diverging	NB Thru	NB Right
	Trad-4	Nonmotorized	East Leg Nonmotorized (NM)	NB Right
	Trad-5	Crossing	NB Thru	WB Thru
Roundabout (see figure 47)	RAB-1	Crossing	NB Exiting	WB Entering
	RAB-2	Merging – Exiting	NB Entering	EB Exiting
	RAB-3	Nonmotorized	North Leg NM	SB Entering
	RAB-4	Merging - Circulating	WB Entering	Circulating
Unsignalized RCUT (see figure 48)	RCUT-1	Merging – Left Turn	WB Left	EB Right
	RCUT-2	Diverging	EB Thru	East U-Turn
	RCUT-3	Nonmotorized	Major NM	WB Thru
	RCUT-4	Merging – U-Turn	WB Thru	East U-Turn



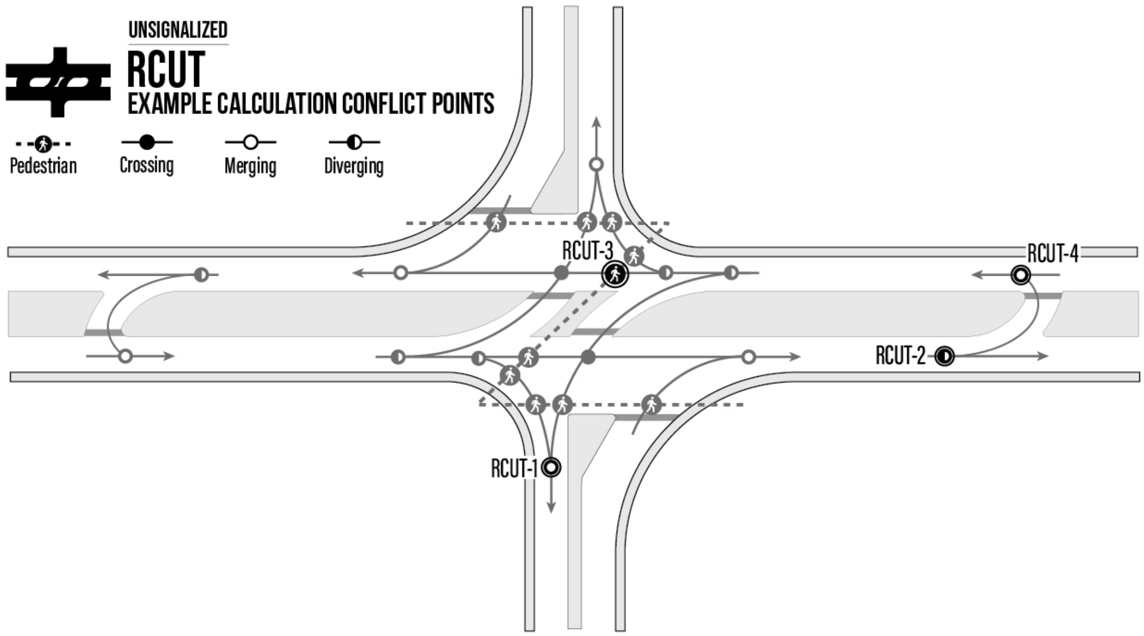
Source: FHWA

Figure 46. Graphic. Example calculation conflict points for Traditional Signalized intersection.



Source: FHWA

Figure 47. Graphic. Example calculation conflict points for Roundabout intersection.



Source: FHWA

Figure 48. Graphic. Example calculation conflict points for Unsignalized RCUT intersection.

EXPOSURE

This section presents example calculations for the exposure index of the SSI method. For background on this part of the method, refer to section 3.5 of this report.

Traditional Signalized

In the case of the traditional signalized intersection, consider merging conflict point Trad-1 where the eastbound through movement on the major road conflicts with the northbound right turn on the minor road. The daily vehicle volumes of these two movements are Q_1 = 6,250 and Q_2 = 2,500 vehicles per day, respectively. Therefore, the exposure index for this conflict point would be computed as shown in figure 49.

$$I = 6{,}250 * 2{,}500 = 15{,}625{,}000$$

Figure 49. Equation. Exposure index example for traditional signalized intersection merging conflict point Trad-1.

Similarly, consider crossing conflict point Trad-2 represented by the southbound through movement on the minor road and the northbound left turn from the opposing the minor road approach. The daily volumes for those movements are Q_1 = 5,000 and Q_2 = 2,500 vehicles per day, respectively. Therefore, the exposure index is computed as shown in figure 50.

$$I = 5{,}000 * 2{,}500 = 12{,}500{,}000$$

Figure 50. Equation. Exposure index example for traditional signalized intersection crossing conflict point Trad-2.

Roundabout

Consider a 2x1 roundabout intersection and examine crossing conflict point RAB-1 in the northeast quadrant of the intersection. Determining the daily turning movement counts of these two movements is different than at the traditional intersection because the two traffic streams at this conflict point involve more than two movements in a traditional sense. This example will refer to the two traffic streams as “circulating” and “entering.” The circulating traffic stream includes both the northbound through movement and the eastbound left movement. The daily vehicle volume for the circulating traffic stream is therefore Q_1 = 5,000 + 3,125 = 8,125. Similarly, the daily vehicle volume for the entering traffic stream applicable to the crossing conflict point is the sum of the westbound left and westbound through turning movement counts, or Q_2 = 3,125 + 6,250 = 9,375. Now that the daily volumes have been determined for the two traffic streams, the exposure index is computed as shown in figure 51.

$$I = 8{,}125 * 9{,}375 = 76{,}171{,}875$$

Figure 51. Equation. Exposure index example for roundabout intersection crossing conflict point RAB-1.

As another example of exposure index calculation at a 2x1 roundabout, consider merging conflict point RAB-2 in the southeast quadrant of the intersection represented by the circulating movement that is exiting the roundabout eastbound and the movement coming northbound and turning right to also exit the roundabout eastbound. The circulating/exiting movement is made up of vehicles traveling in the eastbound through movement as well as the southbound left movement. This means the total volume for this movement is Q_1 = 6,250 + 2,500 = 8,750 vehicles per day. The northbound right is simply the turning movement count of northbound right-turning vehicles, or Q_2 = 2,500 vehicles per day. The exposure index for this conflict point is computed as shown in figure 52.

$$I = 8{,}750 * 2{,}500 = 21{,}875{,}000$$

Figure 52. Equation. Exposure index example for roundabout intersection merging conflict point RAB-2.

The exposure index for nonmotorized conflict points is computed in much the same way. Consider conflict point RAB-3, represented by the nonmotorized movement crossing the north leg (i.e., the approach on the north side of the intersection) and the southbound entering traffic. The nonmotorized volume crossing this leg is Q_1 = 600 pedestrians/cyclists per day. The vehicle traffic will consist of all southbound movements: the southbound through, left, and right. This means the vehicle volume at this conflict point will be Q_2 = 5,000 + 2,500 + 2,500 = 10,000 vehicles per day. The exposure index for this conflict point is computed as shown in figure 53.

$$I = 600 * 10{,}000 = 6{,}000{,}000$$

Figure 53. Equation. Exposure index example for roundabout intersection nonmotorized conflict point RAB-3.

Unsignalized RCUT

As a third intersection alternative, consider the unsignalized RCUT. As in the roundabout, many conflict points at an RCUT involve more than two movements in the traditional sense, due to the way that both vehicular and nonmotorized movements are diverted in the RCUT design.

First, examine merging conflict point RCUT-1, represented by the westbound left-turning movement and the eastbound right-turning movement. The westbound left movement includes the westbound left-turning traffic. Therefore, the volume of this movement at the conflict point is Q_1 = 3,125 vehicles per day. The eastbound right-turning movement at an RCUT includes not only the right-turning traffic coming eastbound on the major road approach, but also the southbound through traffic, which made a right-turn, then a U-turn, and is now making another right-turn at this conflict point. So, the eastbound right-turning volume at the conflict point in questions is Q_2 = 3,125 + 5,000 = 8,125 vehicles per day. The exposure index of this conflict point is computed as shown in figure 54.

$$I = 3{,}125 * 8{,}125 = 25{,}390{,}625$$

Figure 54. Equation. Exposure index example for unsignalized RCUT intersection merging conflict point RCUT-1.

As another example of an RCUT conflict point, consider diverging conflict point RCUT-2 represented by the eastbound through movement and the movement entering the U-turn on the east side of the intersection. The eastbound through movement at this point includes eastbound through, southbound left, and northbound right traffic. This means that Q_1 = 6,250 + 2,500 + 2,500 = 11,250 vehicles per day. The U-turning traffic, on the other hand, is comprised of vehicles making the northbound left and northbound through movements. Therefore, Q_2 = 5,000 + 2,500 = 7,500 vehicles per day. The exposure index of this conflict point is computed as shown in figure 55.

$$I = 11{,}250 * 7{,}500 = 84{,}375{,}000$$

Figure 55. Equation. Exposure index example for unsignalized RCUT intersection diverging conflict point RCUT-2.

As a final example of the exposure index computation at the unsignalized RCUT intersection, consider conflict point RCUT-3, represented by the nonmotorized movement crossing the major road and the westbound through movement. The RCUT alternative in appendix A utilizes a Z-shaped pattern for pedestrian crosswalks, meaning that there is only one crosswalk across the major road. This means that the nonmotorized volume at this conflict point will be comprised of all pedestrian and bicyclist traffic crossing the major road, so Q_1 = 1,200 pedestrians/cyclists per day. The westbound through vehicle movement at this conflict point includes westbound through traffic as well as northbound left traffic. Therefore, Q_2 = 6,250 + 2,500 = 8,750 vehicles per day. The exposure index of this conflict point is computed as shown in figure 56.

$$I = 1{,}200 * 8{,}750 = 10{,}500{,}000$$

Figure 56. Equation. Exposure index example for unsignalized RCUT intersection nonmotorized conflict point RCUT-3.

SEVERITY

This section presents example calculations for the conflict point severity steps of the SSI method. For background on this part of the method, refer to section 3.6 of this report.

Traditional Signalized

As the first example conflict point for the traditional signalized intersection severity calculation, consider crossing conflict point Trad-2, where the southbound through movement on the minor road crosses the northbound left turn from the opposing minor road approach. The first step to computing *P(FSI)* for this conflict point is to identify that this is a vehicle-vehicle conflict point, and therefore should employ the vehicle-vehicle model for conflict point severity. This model requires three inputs: ΔV, α, and k. In turn, the computation of ΔV requires the speeds of the two movements and the conflict angle between them. The speeds and angle can be determined by referring to table 10 and table 11. This example uses the midpoint of the presented typical ranges. In this case, the vehicle speeds for the minor through movement and minor left turn should be 15 mph (the "signal near" speed category) and 25 mph (the "signal far" speed category), respectively, based on the position of the conflict point relative to the stop bars on the approaches where the two movements originate. The conflict point fits the "Crossing – Left Turn" collision type category, so the collision angle is 230 degrees. Therefore, ΔV is computed as shown in figure 57.

$$\Delta V = \frac{\sqrt{(15mph)^2 + (25mph)^2 - 2(15mph)(25mph)(\cos(230\text{ deg}))}}{2} = 18.25mph$$

Figure 57. Equation. *ΔV* example for traditional signalized intersection crossing conflict point Trad-2.

To compute *P(FSI)* for one of the vehicles at the conflict point, this *ΔV* estimate is uses along with the values for α and k determined using the weighted average of the data from Evans (1994). This is shown in figure 58.

$$P_{FSI,U_1,c_{veh}} = \left(\frac{18.25\text{ mph}}{67.29}\right)^{3.79} = 0.00712$$

Figure 58. Equation. Example of *P(FSI)* for one vehicle at traditional signalized intersection crossing conflict point Trad-2.

The final step is to compute the *P(FSI)* value across both vehicles at the conflict point as follows (using the equation in figure 10, where the *P(FSI)* values for both vehicles are the same, computed above in figure 58).

$$P_{FSI,crash,c_{veh}} = 0.00712 + 0.00712 - [0.00712 * 0.00712] = 0.0142$$

Figure 59. Equation. Example of probability of fatality or serious injury for both vehicles at traditional signalized intersection crossing conflict point Trad-2.

This translates to a 1.42 percent probability of at least one fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

For comparison, consider diverging conflict point Trad-3, the northbound through and northbound right-turning movements on the minor road. In this case, following the same procedure as above, the vehicle speeds are 15 mph for both movements (because the movements originate from a minor approach at a signalized intersection, and the conflict point is on the near side of the intersection). The collision angle is 10 degrees. Given these inputs, the calculation of *ΔV* is shown in figure 60.

$$\Delta V = \frac{\sqrt{(15mph)^2 + (15mph)^2 - 2(15mph)(15mph)(\cos(10\text{ deg}))}}{2} = 1.31mph$$

Figure 60. Equation. *ΔV* example for traditional signalized intersection diverging conflict point Trad-3.

Continuing through the calculations, *P(FSI)* for one vehicle at this conflict point is shown in figure 61.

$$P(FSI) = \left(\frac{1.31\text{mph}}{67.29}\right)^{3.79} = 0.000000326$$

Figure 61. Equation. Example of *P(FSI)* for one vehicle at traditional signalized intersection diverging conflict point Trad-3.

Finally, the *P(FSI)* value for both vehicles at the conflict point is computed as follows in figure 62.

$$P_{FSI,crash,c_{veh}} = 3.26 * 10^{-7} + 3.26 * 10^{-7} - [3.26 * 10^{-7} * 3.26 * 10^{-7}] \\ = 0.000000652$$

Figure 62. Equation. Example of *P(FSI)* for both vehicles at traditional signalized intersection diverging conflict point Trad-3.

This translates to a 6.52×10^{-5} percent probability of at least one fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

As you can see, the conflict severity for the diverging conflict point is significantly less than for the left turn crossing conflict point. This is because the diverging conflict point involves lower speeds, smaller differential in speeds, and a much smaller collision angle.

As a final example of the severity calculations at a traditional signalized intersection, examine conflict point Trad-4 represented by the nonmotorized movement crossing the east leg and the northbound right turn originating from the minor road. This time, the procedure for computing the conflict point severity is slightly different, since this is a nonmotorized conflict point. There is only one vehicle speed, *V*, which in this case is 15 mph ("signal near" speed category in table 10). Using the equation presented in figure 12, the *P(FSI)* is computed as shown in figure 63.

$$P_{FSI,Ped,c_{ped}} = \frac{1}{1 + e^{3.8432 - 0.1237(15\,mph)}} = 0.121$$

Figure 63. Equation. Example of *P(FSI)* at traditional signalized intersection nonmotorized conflict point Trad-4.

This translates to a 12.1 percent probability of a non-motorized fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

As you can see, the conflict severity for the nonmotorized conflict point is significantly higher than for both the left turn crossing and diverging conflict points, even though the vehicle speed involved was not higher than the vehicle-vehicle examples. This is because nonmotorized road users (i.e., pedestrians and cyclists) are generally much more vulnerable to crash forces than users traveling in motor vehicles.

Roundabout

For the roundabout, this example will examine the same three conflict points as in the exposure index example presented previously.

First, consider crossing conflict point RAB-1 in the northeast quadrant of the intersection. The collision angle for a roundabout crossing conflict point is 60 degrees. Of the two movements at this conflict point, one is "Exiting" and one is "Entering," so the speeds of the movements are 30 mph and 20 mph, respectively. Given these values, *ΔV* is computed as shown in figure 64.

$$\Delta V = \frac{\sqrt{(30mph)^2 + (20mph)^2 - 2(30mph)(20mph)(\cos(60\text{ deg}))}}{2} = 13.23\,mph$$

Figure 64. Equation. *ΔV* example for roundabout intersection crossing conflict point RAB-1.

Using this *ΔV* value, the *P(FSI)* for one vehicle at this conflict point is shown in figure 65.

$$P(FSI) = \left(\frac{13.23mph}{67.29}\right)^{3.79} = 0.00210$$

Figure 65. Equation. Example of *P(FSI)* for one vehicle at roundabout intersection crossing conflict point RAB-1.

Finally, the *P(FSI)* value for both vehicles at the conflict point is computed as follows in figure 66.

$$P_{FSI,crash,c_{veh}} = 0.00210 + 0.00210 - [0.00210 * 0.00210] = 0.00420$$

Figure 66. Equation. Example of *P(FSI)* for both vehicles at roundabout intersection crossing conflict point RAB-1.

This translates to a 0.420 percent probability of at least one fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

Next, consider merging conflict point RAB-2 in the southeast quadrant of the intersection, represented by the circulating movement that is exiting the roundabout eastbound and the movement coming northbound and turning right to also exit the roundabout eastbound. This is a merging conflict point; the collision angle is 45 degrees. Of the two movements at this conflict point, one is "Entering" and one is "Exiting," so the speeds of the movements are once again 20 mph and 30 mph respectively. Given these values, *ΔV* is computed as shown in figure 67.

$$\Delta V = \frac{\sqrt{(20mph)^2 + (30mph)^2 - 2(20mph)(30mph)(\cos(45\text{ deg}))}}{2} = 10.62\,mph$$

Figure 67. Equation. *ΔV* example for roundabout intersection merging conflict point RAB-2.

Using this *ΔV* value, the *P(FSI)* for one vehicle at this conflict point is shown in figure 68.

$$P(FSI) = \left(\frac{10.62\,mph}{67.29}\right)^{3.79} = 0.000916$$

Figure 68. Equation. Example of *P(FSI)* for one vehicle at roundabout intersection merging conflict point RAB-2.

Finally, the *P(FSI)* value for both vehicles at the conflict point is computed as follows in figure 69.

$$P_{FSI,crash,c_{veh}} = 0.000916 + 0.000916 - [0.000916 * 0.000916] = 0.00183$$

Figure 69. Equation. Example of *P(FSI)* for both vehicles at roundabout intersection merging conflict point RAB-2.

This translates to a 0.183 percent probability of at least one fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

As a final example for roundabout severity calculation, consider conflict point RAB-3, represented by the nonmotorized movement crossing the north leg and the southbound entering traffic. The *P(FSI)* is computed by following the same nonmotorized severity process outlined in the traditional signalized intersection example. The vehicle movement is categorized as "Entering" the roundabout, so the vehicle speed, *V*, is 20 mph. Therefore, *P(FSI)* is computed as shown in figure 70.

$$P_{FSI} = \frac{1}{1 + e^{3.8432 - 0.1237(20mph)}} = 0.203$$

Figure 70. Equation. *P(FSI)* example for roundabout intersection nonmotorized conflict point RAB-3.

This translates to a 20.3 percent probability of a non-motorized fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

Unsignalized RCUT

To explore the severity calculations for the unsignalized RCUT example, first examine merging conflict point RCUT-1, represented by the westbound left turning movement and the eastbound right turning movement. This is a merging conflict point, so the collision angle is 45 degrees. The left-turning movement is assigned to the "Major left" speed category (20 mph). The right-turning movement is assigned to the "Major right" speed category (15 mph). Given these values, *ΔV* is computed as shown in figure 71.

$$\Delta V = \frac{\sqrt{(20mph)^2 + (15mph)^2 - 2(20mph)(15mph)(\cos(45 \text{ deg}))}}{2} = 7.08\ mph$$

Figure 71. Equation. *ΔV* example for unsignalized RCUT intersection merging conflict point RCUT-1.

Using this *ΔV* value, the *P(FSI)* for one vehicle at this conflict point is shown in figure 72.

$$P(FSI) = \left(\frac{7.08\ mph}{67.29}\right)^{3.79} = 0.000197$$

Figure 72. Equation. Example of *P(FSI)* for one vehicle at unsignalized RCUT intersection merging conflict point RCUT-1.

Finally, the *P(FSI)* value for both vehicles at the conflict point is computed as follows in figure 73.

$$P_{FSI,crash,c_{veh}} = 0.000197 + 0.000197 - [0.000197 * 0.000197] = 0.000394$$

Figure 73. Equation. Example of *P(FSI)* for both vehicles at unsignalized RCUT intersection merging conflict point RCUT-1.

This translates to a 0.0394 percent probability of at least one fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

Next, consider merging conflict point RCUT-4, represented by the westbound through movement and the movement making a U-turn east of the main intersection. This is once again a merging conflict point, so the collision angle is 45 degrees. The through movement is assigned to the "Major through" speed category (equal to the posted speed limit, or 45 mph in this case). The U-turning movement at the unsignalized RCUT is stop-controlled, so this movement is assigned to the "Stop near" speed category (15 mph) given the location of the conflict point in relation to the stop bar. Given these values, *ΔV* is computed as shown in figure 74.

$$\Delta V = \frac{\sqrt{(45mph)^2 + (15mph)^2 - 2(45mph)(15mph)(\cos(45\text{ deg}))}}{2} = 18.00\,mph$$

Figure 74. Equation. *ΔV* example for unsignalized RCUT intersection merging conflict point RCUT-4.

Using this *ΔV* value, the *P(FSI)* for one vehicle at this conflict point is shown in figure 75.

$$P(FSI) = \left(\frac{18.00\,mph}{67.29}\right)^{3.79} = 0.00675$$

Figure 75. Equation. Example of *P(FSI)* for one vehicle at unsignalized RCUT intersection merging conflict point RCUT-4.

Finally, the *P(FSI)* value for both vehicles at the conflict point is computed as follows in figure 76.

$$P_{FSI,crash,c_{veh}} = 0.00675 + 0.00675 - [0.00675 * 0.00675] = 0.0135$$

Figure 76. Equation. Example of *P(FSI)* for both vehicles at unsignalized RCUT intersection merging conflict point RCUT-4.

This translates to a 1.35 percent probability of at least one fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point.

Finally, consider conflict point RCUT-3, represented by the nonmotorized movement crossing the major road and the westbound through turning movement. The vehicle movement is categorized as "Major through," so the vehicle speed, *V*, is 45 mph. Therefore, *P(FSI)* is computed as shown in figure 77.

$$P_{FSI} = \frac{1}{1 + e^{3.8432 - 0.1237(45 mph)}} = 0.849$$

Figure 77. Equation. *P(FSI)* example for roundabout intersection nonmotorized conflict point RCUT-3.

This translates to an 84.9 percent probability of a non-motorized fatal or serious injury occurring as a result of a crash between conflicting road users making the movements that define this conflict point. This *P(FSI)* value is so high due to the high speed of the traffic on the major road in this example.

COMPLEXITY

This section presents example calculations for the complexity steps of the SSI method, including the conflicting traffic complexity factor and nonmotorized complexity factor. For background on this part of the method, refer to section 3.7 of this report.

Traditional Signalized

Conflicting Traffic Complexity Factor

Computing the conflicting traffic complexity factor involves determining the three separate parameters: $a_{traffic\ control}$, $a_{conflicting\ lanes}$, and $a_{conflicting\ speed}$.

Traffic Control. The first parameter is the traffic control parameter. Since the intersection is signalized, all movements are signal-controlled.

To begin the example of the traffic control parameter for the traditional signalized intersection, consider the crossing conflict point Trad-1, represented by the eastbound through movement and the northbound right-turning movement. The signal phases of the two movements in question at conflict point Trad-1 operate in a fully protected manner (since the SSI method does not consider the provision of right-turn-on-red). Using the *BTCAV* of 0.01 for protected movements and a weighting factor, *f*, of 0.5 (as discussed in chapter 4), the traffic control parameter is computed as shown in figure 78.

$$a_{traffic\ control} = 0.01 + (1 - 0.5) * (1 - 0.01) = 0.505$$

Figure 78. Equation. Traffic control parameter example for traditional signalized intersection crossing conflict point Trad-1.

Next, consider crossing conflict point Trad-2, where the southbound through movement conflicts with the northbound left turn from the minor. As noted in table 41, the minor road left turns are not fully protected at this intersection, but rather operate under protected/permitted phasing. Using the *BTCAV* of 0.85 for protected/permitted movements and *f* = 0.5, the traffic control parameter is computed as shown in figure 79.

$$a_{traffic\ control} = 0.85 + (1 - 0.5) * (1 - 0.85) = 0.925$$

Figure 79. Equation. Traffic control parameter example for traditional signalized intersection left turn crossing conflict point Trad-2.

As a third example of the traffic control parameter at the traditional signalized intersection alternative, consider conflict point Trad-5 where the northbound through meets the westbound through movement on the major road. These two movements are fully protected by the signal phasing. Therefore, the traffic control parameter for conflict point Trad-5 is computed using the same equation and inputs as in figure 78, resulting in $a_{traffic\ control}$ = 0.505.

Conflicting Lanes. The second parameter in the conflicting traffic complexity factor calculation is the conflicting lanes parameter. For this parameter, one must first identify the lower movement involved in each conflict point from the following list:

1. Major through and right turn.
2. Major left turn.
3. Minor through and right turn.
4. Minor left turn.
5. Nonmotorized.

For our first traditional signalized intersection example conflict point, Trad-1 (the eastbound through and northbound right conflict point), the lower movement on the list is the northbound right.

The next step is to identify the cross score for the lower movement, the northbound right. The northbound right turn does not cross any intersection approaches, so the cross score is zero.

The third step is to determine the merge score for the lower movement. The merge score considers the number of lanes carrying conflicting traffic as that conflicting traffic approaches the merging conflict point. Table 12 shows the equations for the merge score. To calculate the merge score, note that at conflict point Trad-1, the right-turning movement from the minor road is merging with through-moving traffic from a major road approach having two through traffic lanes (the eastbound through movement), therefore M = 1 and N_M = 2. The calculation of the merge score in this example is shown in figure 83.

$$Merge\ score = M(1 + W_2) = 1(1 + 0.75) = 1.75$$

Figure 80. Equation. Merge score example for traditional signalized intersection merging conflict point Trad-1.

The merge score is added to the cross score to determine the conflicting lane parameter, $a_{conflicting\ lanes}$, as illustrated in figure 81.

$$a_{conflicting\ \ lanes} = Cross\ Score + Merge\ Score = 0 + 1.75 = 1.75$$

Figure 81. Equation. Conflicting lanes parameter example for traditional signalized intersection merging conflict point Trad -1.

For the next example of the conflicting lanes parameter, examine conflict point Trad-2, where the southbound through movement meets the northbound left-turning movement. The northbound left turn is the lower movement on the list of movements. The northbound left turn movement crosses the near-side approach of the major road carrying eastbound conflicting traffic—two lanes in this case—plus the opposing minor road approach carrying southbound conflicting traffic—one lane in this case. A median is not present to provide refuge to the left-turning vehicle and allow a two-stage movement. Thus, the resulting crossing score for this left turn from the minor road is 2 + 1 = 3.

In this example, the left-turning movement from the minor road is merging with traffic from a major road approach having two through traffic lanes (the westbound through movement), therefore $M = 1$ and $N_M = 2$. The merge score is then calculated in the same way as shown in figure 83, resulting again in a merge score of 1.75. The merge score is added to the cross score to determine the conflicting lane parameter, $a_{conflicting\ lanes}$, for conflict point Trad-2 as illustrated in figure 82.

$$a_{conflicting\ \ lanes} = Cross\ Score + Merge\ Score = 3 + 1.75 = 4.75$$

Figure 82. Equation. Conflicting lanes parameter example for traditional signalized intersection crossing conflict point Trad-2.

This value of the conflicting lanes parameter would also apply to all other crossing and merging conflict points in which the northbound left turn is the lower movement on the list of movements.

As a third example, consider conflict point Trad-5, where the northbound through movement meets the westbound through movement. The northbound through movement is lower on the list of movements. The northbound through movement crosses both the eastbound approach on the near-side of the intersection – two through lanes in this case – and the westbound approach on the far side of the intersection – another two lanes. A median is not present to provide refuge and allow a two-stage movement. Thus, the resulting cross score for the minor road through movement is 2 + 2 = 4.

The next step is to determine the merge score for the northbound through movement. The northbound through movement is not one of the movements where the merge score applies. Therefore, the value of M is 0 and the merge score for this movement is also 0. The merge score is added to the cross score to produce the conflicting lane parameter, $a_{conflicting\ lanes}$, as shown in figure 83.

$$a_{conflicting\ \ lanes} = Cross\ Score + Merge\ Score = 4 + 0 = 4$$

Figure 83. Equation. Conflicting lanes parameter example for traditional signalized intersection crossing conflict point Trad-5.

Note that this value of the conflicting lanes parameter would also be applied to any other crossing and merging conflict points at which the northbound through is the lower-priority movement.

Speed of Conflicting Traffic. For the first example of the conflicting speed parameter,

$a_{conflicting\ speed}$, refer to conflict point Trad-1 (eastbound through at northbound right). The conflicting speed parameter requires one input: V_c, the conflicting vehicle speed. This is the highest speed of any of the traffic streams conflicting with the lower movement. In this case, the lower movement is the northbound right, and it only has one traffic stream: the eastbound through. Using the speed assumptions in table 10, the eastbound through movement is assigned the posted speed limit, or 45 mph in this case (based on taking the midpoint value of the typical range represented in the table).

The conflicting speed parameter is computed by plugging this conflicting vehicle speed into figure 84, which calculates a 15 percent reduction in crash likelihood for every 10 percent reduction in vehicle speed below a benchmark of 60 mph.

$$a_{conflicting\ \ speed} = 1 - \left(\frac{60 - V_C}{60} * \frac{0.10}{0.15}\right) = 1 - \left(\frac{60 - 45mph}{60} * \frac{0.10}{0.15}\right) = 0.833$$

Figure 84. Equation. Conflicting speed parameter example for traditional signalized intersection merging conflict point Trad-1.

Next, consider conflict point Trad-2 (southbound through at northbound left). In this case, the lower movement (the northbound left) has several conflicting traffic streams: eastbound through, westbound through, and southbound through. The highest speed of any of these conflicting traffic streams belongs to the major road through movements at 45 mph, so the conflicting speed parameter is calculated the same as shown in figure 84 and is equal to 0.833.It follows that the conflicting speed parameter for conflict point Trad-5 (northbound through at westbound through) is also 0.833 in this example.

Computing the Conflicting Traffic Complexity Factor. The traffic control parameter, conflicting lanes parameter, and conflicting speed parameter are multiplied together to produce the conflicting traffic complexity factor, as shown in figure 17.

The results of the conflicting traffic complexity factor for the three traditional signalized intersection example conflict points used here are shown in figure 85, figure 86, and figure 87.

$$L_{1,Trad\ -1} = 0.505 * 1.75 * 0.833 = 0.736$$

Figure 85. Equation. Conflicting traffic complexity factor example for traditional signalized intersection merging conflict point Trad-1.

$$L_{1,Trad-2} = 0.925 * 4.75 * 0.833 = 3.66$$

Figure 86. Equation. Conflicting traffic complexity factor example for traditional signalized intersection crossing conflict point Trad-2.

$$L_{1,Trad-5} = 0.505 * 4 * 0.833 = 1.68$$

Figure 87. Equation. Conflicting traffic complexity factor example for traditional signalized intersection crossing conflict point Trad-5.

Nonmotorized Movement Complexity Factor

The nonmotorized movement complexity factor, L_2, is also computed for each conflict point in addition to the conflicting traffic complexity factor. However, for vehicle-vehicle conflict points the nonmotorized movement complexity factor is set to 1, as described in section 3.7.3. Additionally, the nonmotorized movement complexity factor is only applied to nonmotorized conflict points with movements that are part of indirect pedestrian movements or that encounter nonintuitive motor vehicle movements. None of the nonmotorized conflict points at the traditional signalized intersection exhibit these characteristics, so the value of L_2 is equal to one for all nonmotorized conflict points at a traditional signalized intersection.

Roundabout

Conflicting Traffic Complexity Factor

Traffic Control. In the case of the traffic control parameter for the roundabout intersection design, none of the movements at the roundabout are signal- or stop-controlled (but rather, yield controlled). Therefore, the traffic control parameter at all roundabout conflict points is simply 1.

Conflicting Lanes. For the conflicting lanes parameter, first consider crossing conflict point RAB-1 (northeast quadrant, northbound exiting at westbound entering). The lower priority movement at a roundabout is the entering movement. At this entry of the 2x1 roundabout, the traffic entering from the major road and continuing in the circulatory roadway is crossing the conflicting exiting movement that is being carried by one circulating lane. Therefore, the cross score for crossing conflict point RAB-1 is 1. The merge score does not apply at crossing conflict point RAB-1. The value of *M* is 0 and the merge score for crossing conflict point RAB-1 is also 0. The conflicting lanes parameter for crossing conflict point RAB-1 is the cross score plus the merge score, which is 1.

Next, consider merging conflict point RAB-2 (southeast quadrant, northbound right-turning and eastbound exiting). In this case, the entering movement is once again the lower-priority movement. But in this case, there are two circulating lanes in the roundabout due to the geometry of a 2x1 roundabout at this entry. In this case, the lower-priority movement is not crossing the exiting movement being carried by these two lanes, so the cross score is 0. The merge score does apply and is calculated as shown in figure 88 with M = 1 and N_M = 2.

$$Merge\ score = M(1 + W_2) = 1(1 + 0.75) = 1.75$$

Figure 88. Equation. Merge score example for roundabout intersection merging conflict point RAB-2.

As an example of a nonmotorized conflict point, examine conflict point RAB-3 (nonmotorized movement crossing the north leg). The nonmotorized movement passing through this conflict point is the lower movement on the list of movements, and it is crossing both the entering and exiting traffic streams on the north leg. However, the SSI method assumes that all roundabouts have pedestrian refuge islands (i.e., splitter islands) on all approaches (as stated in appendix A). Therefore, the nonmotorized movement must only cross one of these traffic streams at a time. Since the nonmotorized road user at this point is crossing the minor approach of a 2x1 roundabout, there is only one lane in each direction on the approach, and thus the cross score for this conflict point is equal to 1. The conflicting lanes parameter for nonmotorized conflict points uses the nonmotorized turn score in place of the merge score. In this case, due to the geometry of roundabouts, the nonmotorized road user at conflict point RAB-3 is not scanning any other approaches for oncoming traffic beyond the approach being crossed. Therefore, the nonmotorized turn score is 0, and the conflicting lanes score for conflict point RAB-3 is 1 + 0 = 1.

Conflicting Speed. In most cases at a roundabout, the conflicting vehicle speed that applies to the lower-priority movement is the circulating speed (here assumed to be 25 mph). This is the case for conflict points RAB-1, RAB-2, and RAB-4. The conflicting speed parameter is computed by plugging this conflicting vehicle speed into figure 89.

$$a_{conflicting\ \ speed} = 1 - \left(\frac{60 - V_C}{60} * \frac{0.10}{0.15}\right) = 1 - \left(\frac{60 - 25mph}{60} * \frac{0.10}{0.15}\right) = 0.611$$

Figure 89. Equation. Conflicting speed parameter example for roundabout intersection conflict points RAB-1, RAB-2, and RAB-4.

The exceptions to this are the nonmotorized conflict points. Due to the placement of crosswalks and presence of splitter islands for pedestrian refuge at roundabouts, the nonmotorized movements have a conflicting vehicle speed equal to either the entering or exiting speed. In the case of conflict point RAB-3, where the nonmotorized movement conflicts with the southbound entering movement, the entering speed is applied. This results in a conflicting speed parameter as shown in figure 90.

$$a_{conflicting\ \ speed} = 1 - \left(\frac{60 - V_C}{60} * \frac{0.10}{0.15}\right) = 1 - \left(\frac{60 - 20mph}{60} * \frac{0.10}{0.15}\right) = 0.556$$

Figure 90. Equation. Conflicting speed parameter example for roundabout intersection nonmotorized conflict point RAB-3.

Computing the Conflicting Traffic Complexity Factor. The traffic control parameter, conflicting lanes parameter, and conflicting speed parameter are multiplied together to produce the conflicting traffic complexity factor, as shown in figure 17.

The results of the conflicting traffic complexity factor for the four roundabout example conflict points are shown in figure 91, figure 92, figure 93, and figure 94.

$$L_{1,RAB-1} = 1 * 1 * 0.611 = 0.611$$

Figure 91. Equation. Conflicting traffic complexity factor example for roundabout intersection crossing conflict point RAB-1.

$$L_{1,RAB-2} = 1 * 1.75 * 0.611 = 1.07$$

Figure 92. Equation. Conflicting traffic complexity factor example for roundabout intersection merging conflict point RAB-2.

$$L_{1,RAB-3} = 1 * 1 * 0.556 = 0.556$$

Figure 93. Equation. Conflicting traffic complexity factor example for roundabout intersection nonmotorized conflict point RAB-3.

$$L_{1,RAB-4} = 1 * 1.75 * 0.611 = 1.07$$

Figure 94. Equation. Conflicting traffic complexity factor example for roundabout intersection merging conflict point RAB-4.

Nonmotorized Movement Complexity Factor

As an example of the nonmotorized movement complexity factor, consider the nonmotorized movement crossing the north leg of the 2x1 roundabout at conflict point RAB-3. Due to the geometry of a modern roundabout and the placement of crosswalks, nonmotorized road users travel around the perimeter of the roundabout. For this reason, the calculations in this report apply the indirect paths indicator to all nonmotorized conflict points at roundabouts. The nonintuitive vehicle movements indicator does not apply to roundabouts, so it is set to zero. The value of the nonmotorized movement complexity factor for conflict point RAB-3 (and all other nonmotorized roundabout conflict points) is therefore 2, as shown in figure 95.

$$L_2 = 1 + i_{indirect} + i_{nonintuit\ ive} = 1 + 1 + 0 = 2$$

Figure 95. Equation. Nonmotorized movement complexity factor example for roundabout intersection nonmotorized conflict point RAB-3.

Unsignalized RCUT

Conflicting Traffic Complexity Factor

Traffic Control. To demonstrate the traffic control parameter for the unsignalized RCUT intersection, first consider merging conflict point RCUT-1 (westbound left-turn and eastbound right-turn). The left-turn movements at unsignalized RCUTs are typically stop-controlled, so the two movements in question operate under stop-control. Using the *BTCAV* of 0.45 for stop-controlled movements and (once again) a weighting factor, *f*, of 0.5, the traffic control parameter is computed as shown in figure 96.

$$a_{traffic\ control} = 0.45 + (1 - 0.5) * (1 - 0.45) = 0.725$$

Figure 96. Equation. Traffic control parameter example for unsignalized RCUT intersection merging conflict point RCUT-1.

Conflict point RCUT-2 (eastbound through and eastbound U-turn) is a diverging conflict point, and thus does not have any traffic control applied to it, so the traffic control parameter is equal to 1.

Conflict point RCUT-3, where the nonmotorized movement crossing the major road conflicts with the westbound through movement, does not have any traffic control adjustment applied to it. This is because at the unsignalized RCUT there is no stop control or signal control applied to through-traffic on the major road. In some cases, a pedestrian signal or other measure may be installed to control vehicle traffic while nonmotorized road users cross the major road, but that is not considered for the purpose of this example. Therefore, the traffic control parameter for conflict point RCUT-3 is also equal to one.

Finally, examine conflict point RCUT-4, where the U-turning traffic east of the main intersection meets the westbound through traffic. The U-turns at unsignalized RCUTs are typically stop-controlled, so the traffic control parameter is computed the same way as in figure 96 and is equal to 0.725.

Conflicting Lanes. For the first example of the conflicting lanes parameter at the unsignalized RCUT, examine conflict point RCUT-1 (westbound left-turn merging with eastbound right-turn). In this case the westbound left movement is the lower movement. It crosses one approach (the eastbound approach) carrying conflicting traffic. The eastbound approach has two lanes. The cross score for this conflict point is 2. the merge score does not apply to this conflict point, therefore *M* = 0 and the merge score also equals 0. The conflicting lanes parameter is computed as shown in figure 97.

$$a_{conflicting\ \ lanes} = Cross\ Score + Merge\ Score = 2 + 0 = 2$$

Figure 97. Equation. Example of conflicting lanes parameter for unsignalized RCUT intersection merging conflict point RCUT-1.

Conflict point RCUT-2 (where the east U-turn movement diverges from the eastbound through) is a diverging conflict point, so the conflicting lanes parameter is set to equal one.

At conflict point RCUT-3, where the nonmotorized movement crosses the westbound through movement, the nonmotorized movement crosses one major approach at a time due to the presence of median refuge inherent in the design of an RCUT (see appendix A). the major road carries two lanes in each direction in this example, so the cross score for conflict point RCUT-3 is equal to 2. As with the roundabout, at this point the nonmotorized road user is not scanning any other approaches for oncoming traffic, so there is no pedestrian turn score applied to the conflict point. The conflicting lanes parameter for conflict point RCUT-3 is computed as shown in figure 98.

$$a_{conflicting\ \ lanes} = Cross\ Score + Turn\ Score = 2 + 0 = 2$$

Figure 98. Equation. Example of conflicting lanes parameter for unsignalized RCUT intersection nonmotorized conflict point RCUT-3.

Finally, the merge score comes into play for conflict point RCUT-4, where the westbound through movement meets the U-turn movement east of the main intersection. The U-turning movement is the lower movement on the list of movements. It does not cross any approaches carrying conflicting traffic, so the cross score is 0. The merge score applies to this conflict point, so the merge score is computed as shown in figure 99 with M = 1 and N_M = 2.

$$Merge\ score = M(1 + W_2) = 1(1 + 0.75) = 1.75$$

Figure 99. Equation. Merge score example for unsignalized RCUT intersection merging conflict point RCUT-4.

Conflicting Speed. All movements through crossing or merging conflict points at an RCUT interact with at least one major road through movement. This means that the conflicting vehicle speed for all of the vehicle-vehicle crossing and merging conflict points as well as the nonmotorized conflict points crossing the major road is equal to the major road through speed. In this case that is 45 mph. Therefore, the conflicting speed parameters for conflict points RCUT-1, RCUT-2, RCUT-3, and RCUT-4 are all equal, and are calculated as shown in figure 100.

$$a_{conflicting\ \ speed} = 1 - \left(\frac{60 - V_C}{60} * \frac{0.10}{0.15}\right) = 1 - \left(\frac{60 - 45mph}{60} * \frac{0.10}{0.15}\right) = 0.833$$

Figure 100. Equation. Conflicting speed parameter example for unsignalized RCUT intersection conflict points RCUT-1, RCUT-2, RCUT-3, and RCUT-4.

Computing the Conflicting Traffic Complexity Factor. The traffic control parameters, conflicting lanes parameters, and conflicting speed parameters are multiplied together to produce the conflicting traffic complexity factor, as shown in figure 17.

The results of the conflicting traffic complexity factor for the four unsignalized RCUT intersection example conflict points used here are shown in figure 101, figure 102, figure 103, and figure 104.

$$L_{1,RCUT-1} = 0.725 * 2 * 0.833 = 1.21$$

Figure 101. Equation. Conflicting traffic complexity factor example for unsignalized RCUT intersection merging conflict point RCUT-1.

$$L_{1,RCUT-2} = 1 * 1 * 0.833 = 0.833$$

Figure 102. Equation. Conflicting traffic complexity factor example for unsignalized RCUT intersection diverging conflict point RCUT-2.

$$L_{1,RCUT-3} = 1 * 2 * 0.833 = 1.67$$

Figure 103. Equation. Conflicting traffic complexity factor example for unsignalized RCUT intersection nonmotorized conflict point RCUT-3.

$$L_{1,RCUT-4} = 0.725 * 1.75 * 0.833 = 1.06$$

Figure 104. Equation. Conflicting traffic complexity factor example for unsignalized RCUT intersection merging conflict point RCUT-4.

Nonmotorized Movement Complexity Factor

As an example of the nonmotorized movement complexity factor, consider the nonmotorized movement crossing the major road and intersecting with the westbound movement at conflict point RCUT-3. Due to the Z-crossing pattern typically employed at RCUT intersections, nonmotorized road users who are crossing the major road may be required to take an indirect path. For this reason, the indirect paths indicator is applied to all nonmotorized conflict points crossing the major road at RCUTs. The nonintuitive vehicle movements indicator is not applied, so it is set to 0. The value of the nonmotorized movement complexity factor for conflict point RCUT-3 is therefore 2, as shown in figure 105.

$$L_2 = 1 + i_{indirect} + i_{nonintuitive} = 1 + 1 + 0 = 2$$

Figure 105. Equation. Nonmotorized movement complexity factor example for unsignalized RCUT intersection conflict point RCUT-3.

SUMMARY OF EXAMPLE RESULTS

The information in table 43, table 44, and table 45 summarizes the inputs and results of the example calculations presented in this appendix.

Table 43. Summary of exposure calculation example results.

Intersection Type	Conflict Point Name	Q_1	Q_2	I
Traditional Signalized	T-1	6,250	2,500	15,625,000
	T-2	5,000	2,500	12,500,000
Roundabout	RAB-1	8,125	9,375	76,171,875
	RAB-2	8,750	2,500	21,875,000
	RAB-3	600	10,000	6,000,000
Unsignalized RCUT	RCUT-1	3,125	8,125	25,390,625
	RCUT-2	11,250	7,500	84,375,000
	RCUT-3	1,200	8,750	10,500,000

Table 44. Summary of severity calculation example results.

Intersection Type	Conflict Point Name	V_1	V_2	*Angle*	ΔV	$P(FSI)_{one\ veh}$	$P(FSI)$
Traditional Signalized	T-2	15	25	230	18.25	0.00712	0.0142
	T-3	15	15	10	1.31	0.000000326	0.000000652
	T-4	--	15	--	--	--	0.121
Roundabout	RAB-1	30	20	60	13.23	0.00210	0.00420
	RAB-2	30	20	45	10.62	0.000916	0.00183
	RAB-3	--	20	--	--	--	0.203
Unsignalized RCUT	RCUT-1	20	15	45	7.08	0.000197	0.000394
	RCUT-3	--	45	--	--	--	0.849
	RCUT-4	45	15	45	18.00	0.00675	0.0135

Note: -- represents calculation steps that were not necessary for a given conflict point (e.g., ΔV is not calculated for nonmotorized conflict points and the pedestrian complexity indicators $i_{indirect}$ and $i_{nonintuitive}$ do not apply to vehicle-vehicle conflict points).

Table 45. Summary of complexity calculation example results.

Intersection Type	Conflict Point Name	*BTCAV*	*f*	$a_{traffic\ control}$	$a_{conflicting\ lanes}$	V_c	$a_{conflicting\ speed}$	L_1	$i_{indirect}$	$i_{nonintuitive}$	L_2
Traditional Signalized	T-1	0.01	0.5	0.505	1.75	45	0.833	0.736	--	--	1
	T-2	0.85	0.5	0.925	4.75	45	0.833	3.66	--	--	1
	T-5	0.01	0.5	0.505	4	45	0.833	1.68	--	--	1
Roundabout	RAB-1	1	0.5	1	1	25	0.611	0.611	--	--	1
	RAB-2	1	0.5	1	1.75	25	0.611	1.07	--	--	1
	RAB-3	1	0.5	1	1	20	0.556	0.556	1	0	2
	RAB-4	1	0.5	1	1.75	25	0.611	1.07	--	--	1
Unsignalized RCUT	RCUT-1	0.45	0.5	0.725	2	45	0.833	1.21	--	--	1
	RCUT-2	1	0.5	1	1	45	0.833	0.833	--	--	1
	RCUT-3	1	0.5	1	2	45	0.833	1.67	1	0	2
	RCUT-4	0.45	0.5	0.725	1.75	45	0.833	1.06	--	--	1

Note: -- represents calculation steps that were not necessary for a given conflict point (e.g., ΔV is not calculated for nonmotorized conflict points and the pedestrian complexity indicators $i_{indirect}$ and $i_{nonintuitive}$ do not apply to vehicle-vehicle conflict points).

COMPUTATION OF THE SSI SCORE

Once these calculations have been performed for all the conflict points at a given intersection alternative, the SSI score can be computed for that alternative according to the procedure outlined in section 3.7. This section of appendix B will display how to compute the SSI score for one alternative, the unsignalized RCUT.

The following tables (Table 46, Table 47, Table 48, Table 49) contain the full results for the exposure index (*I*), probability of fatality or serious injury (*P(FSI)*), conflicting traffic complexity factor (L_1), and nonmotorized movement complexity factor (L_2) for all 24 conflict points at an unsignalized RCUT (depicted in figure 39). The rightmost column in these tables shows the exposure-severity-complexity product for each conflict point, computed by multiplying the contents other four columns as described in section 3.7. At the bottom of each table, the sum of the exposure-severity-conflict points is shown for each conflict point type. This represents E_t.

Table 46. Exposure-severity-complexity product results for unsignalized RCUT crossing conflict points.

Conflict Point Type	Conflict Point Name	*I*	*P(FSI)*	L_1	L_2	Exposure-Severity-Complexity Product
Crossing	--	27,343,750	0.0903	1.208	1	2,983,102
Crossing	--	27,343,750	0.0903	1.208	1	2,983,102
					Sum:	**5,966,203**

Note: -- represents conflict points that were not included in the example calculations in appendix B.

Table 47. Exposure-severity-complexity product results for unsignalized RCUT merging conflict points.

Conflict Point Type	Conflict Point Name	*I*	*P(FSI)*	L_1	L_2	Exposure-Severity-Complexity Product
Merging	--	87,500,000	0.0134	1.057	1	1,237,263
Merging	RCUT-1	25,390,625	0.000390	1.208	1	11,972
Merging	--	87,500,000	0.0134	1.057	1	1,237,263
Merging	--	25,390,625	0.000390	1.208	1	11,972
Merging	RCUT-4	93,750,000	0.0134	1.057	1	1,325,639
Merging	--	93,750,000	0.0134	1.057	1	1,325,639
					Sum:	**5,149,750**

Note: -- represents conflict points that were not included in the example calculations in appendix B.

Table 48. Exposure-severity-complexity product results for unsignalized RCUT diverging conflict points.

Conflict Point Type	Conflict Point Name	*I*	*P(FSI)*	L_1	L_2	Exposure-Severity-Complexity Product
Diverging	--	52,734,375	0.00365	1	1	192,385
Diverging	--	71,093,750	0.00701	1	1	498,056
Diverging	RCUT-2	84,375,000	0.00365	1	1	307,817
Diverging	--	52,734,375	0.00365	1	1	192,385
Diverging	--	71,093,750	0.00701	1	1	498,056
Diverging	--	84,375,000	0.00365	1	1	307,817
					Sum:	**1,996,516**

Note: -- represents conflict points that were not included in the example calculations in appendix B.

Table 49. Exposure-severity-complexity product results for unsignalized RCUT nonmotorized conflict points.

Conflict Point Type	Conflict Point Name	*I*	*P(FSI)*	L_1	L_2	Exposure-Severity-Complexity Product
Nonmotorized	--	4,875,000	0.121	3.750	1	2,202,898
Nonmotorized	--	1,875,000	0.321	2.719	1	1,634,659
Nonmotorized	--	6,000,000	0.121	2.166	1	1,565,978
Nonmotorized	--	9,750,000	0.121	1.667	2	3,916,263
Nonmotorized	--	10,500,000	0.849	1.667	2	29,699,369
Nonmotorized	RCUT-3	10,500,000	0.849	1.667	2	29,699,369
Nonmotorized	--	9,750,000	0.121	1.667	2	3,916,263
Nonmotorized	--	4,875,000	0.121	3.750	1	2,202,898
Nonmotorized	--	1,875,000	0.321	2.719	1	1,634,659
Nonmotorized	--	6,000,000	0.121	2.166	1	1,565,978
					Sum:	**78,038,336**

Note: -- represents conflict points that were not included in the example calculations in appendix B.

The conflict point type SSI score, SSI_t, can be computed for each of the four conflict point types *t* according to figure 15. For this unsignalized RCUT example, these calculations are carried out in figure 106, figure 107, figure 108, and figure 109.

$$SSI_{crossing} = 100 \times \exp\left(-\frac{1}{13,700,000} \times 5,966,203\right) = 64.69$$

Figure 106. Equation. Example conflict point type SSI score for unsignalized RCUT crossing conflict points.

$$SSI_{merging} = 100 \times \exp\left(-\frac{1}{13,700,000} \times 5,149,750\right) = 68.67$$

Figure 107. Equation. Example conflict point type SSI score for unsignalized RCUT merging conflict points.

$$SSI_{diverging} = 100 \times \exp\left(-\frac{1}{13{,}700{,}000} \times 1{,}996{,}516\right) = 86.44$$

Figure 108. Equation. Example conflict point type SSI score for unsignalized RCUT crossing conflict points.

$$SSI_{nonmotorized} = 100 \times \exp\left(-\frac{1}{13{,}700{,}000} \times 78{,}038{,}336\right) = 0.34$$

Figure 109. Equation. Example conflict point type SSI score for unsignalized RCUT crossing conflict points.

Based on these conflict point type SSI scores, the SSI intersection score for the unsignalized RCUT in this example can then be computed according to the equation in figure 16. The result of this calculation is shown in figure 110. This score represents the overall Safe System performance of the unsignalized RCUT in this example.

$$SSI_{int} = 100 \times \exp\left[-\frac{1}{13{,}700{,}000} \times (5{,}966{,}203 + 5{,}149{,}750 + 1{,}996{,}516 + 78{,}038{,}336)/4\right] = 18.95$$

Figure 110. Equation. Example intersection SSI score for unsignalized RCUT.

REFERENCES

American Association of State Highway Transportation Officials (2018). *A Policy on Geometric Design of Highways and Streets.* The American Association of State Highway and Transportation Officials, Washington, D.C.

Australian Transport Council (2011). *National Road Safety Strategy 2011-2020*. Australian Transport Council, Canberra, Australia.

Belin, M., Tillgren, P., & Vedung, E. (2012). Vision Zero – A Road Safety Policy Innovation. *International Journal of Injury Control and Safety Promotion, 19*(2), 171-179.

Burch, C., Cook, L., & Dischinger, P. (2014). A Comparison of KABCO and AIS Injury Severity Metrics Using CODES Linked Data. *Traffic Injury Prevention, 15*(6), 627-630.

Campbell, J.L., Lichty, M.G., Brown, J.L., Richard, C.M., Graving, J.S., Graham, J., …, & Harwood, D. (2012). *Human Factors Guidelines for Road Systems: Second Edition* [NCHRP Report 600]. National Academies of Science, Engineering, and Medicine, Washington, D.C.

Chidester, A.B. & Isenburg, R.A. (2001). The Pedestrian Crash Data Study – Final Report. National Highway Traffic Safety Administration, Washington, D.C.

Corben, B., Van Nes, N., Logan, D. & Archer, J. (2010). *Kinetic Energy Management Model and Safe Intersection Design Principles* [Report No. 316c]. VicRoads, Victoria, Australia.

De Haven, H. (1942). Mechanical analysis of survival in falls from heights of fifty to one hundred and fifty feet. Reproduced in *Injury Prevention, 6*(1), 62–68 (2000).

Ecola, L., Popper, S.W., Silberglitt, R., & Fraade-Blanar, L. (2018). The Road To Zero: A Vision for Achieving Zero Roadway Deaths by 2050. National Safety Council, Itasca, IL.

Evans, L. (1994). Driver Injury and Fatality Risk in Two-Car Crashes Versus Mass Ratio Inferred Using Newtonian Mechanics. *Accident Analysis & Prevention, 26*(5), 609-616.

FHWA (2017). About the Strategic Highway Safety Plan. https://safety.fhwa.dot.gov/shsp/about.cfm. Accessed September 24, 2020.

FHWA (2019). Crossover-Based Intersections. https://safety.fhwa.dot.gov/intersection/innovative/crossover/. Accessed September 24, 2020.

FHWA (2020). The Safe System Approach [FHWA-SA-20-015]. https://safety.fhwa.dot.gov/zerodeaths/docs/FHWA_SafeSystem_Brochure_V9_508_200717.pdf. Accessed December 28, 2020.

Glauz, W.D. & Migletz, D.J. (1980). *Application of Traffic Conflict Analysis at Intersections* [NCHRP Report 219]. National Academies of Science, Engineering, and Medicine, Washington, D.C.

Gustafson, J. (2018). Uniformity of Terminology for Circular Intersection Designs. *Transportation Research Record: The Journal of the Transportation Research Board, 2672*(34), 63-72.

Haddon, W. (1980). Advances in the epidemiology of injuries as a basis for public policy. *Public Health Reports, 95*(5), 411–421.

Hakkert, A.S. & Mahalel, D. (1978). Estimating the Number of Accidents at Intersection from a Knowledge of Traffic Flows on the Approaches. *Accident Analysis & Prevention, 10,* 69-79.

Harmon, T., Bahar, G., & Gross, F. (2018). *Crash Costs for Highway Safety Analysis* [FHWA-SA-17-071]. Federal Highway Administration, Washington, D.C.

Hauer, E. (2005). The Road Ahead. *Journal of Transportation Engineering, 131*(5), 333-339.

Hughes, W., Jagannathan, R., Sengupta, D., & Hummer, J. (2010). *Alternative Intersections/Interchanges: Informational Report (AIIR)* [FHWA-HRT-09-060]. Federal Highway Administration, Washington, D.C.

Johansson, R. (2009). Vision Zero – Implementing a Policy for Traffic Safety. *Safety Science, 47*(6), 826-831.

Joksch, H.C. (1993). Velocity Change and Fatality Risk in a Crash – A Rule of Thumb. *Accident Analysis & Prevention, 25*, 103-104.

Jurewicz, C., Tofler, S., Makwasha, T., & Matta, J. (2015). *Improving the Performance of Safe System Infrastructure* [Report No. AP-R498-15]. Austroads Ltd., Sydney, Australia.

Jurewicz, C., Sobhani, A., Chau, P., Woolley, J., & Brodie, C. (2017). *Understanding and Improving Safe System Intersection Performance* [Report No. AP-R556-17]. Austroads Ltd., Sydney, Australia.

Mooren, L., Grzebieta, R., & Job, S. (2011). Safe System – Comparison of this Approach in Australia. In Proceedings of the Australasian College of Road Safety Conference – "A Safe System: Making it Happen!", Melbourne, Australia.

New Zealand Ministry of Transport (2010). *Safer Journeys 2020: New Zealand's Road Safety Strategy 2010-2020.* New Zealand Ministry of Transport, Wellington, New Zealand.

NHTSA (2016). 2015 Motor Vehicle Crashes: Overview. National Highway Traffic Safety Administration, Washington, D.C.

NHTSA (2017). 2016 Motor Vehicle Crashes: Overview. National Highway Traffic Safety Administration, Washington, D.C.

NHTSA (2020a). Traffic Safety Facts: Early Estimate of Motor Vehicle Traffic Fatalities in 2019. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812946. Accessed December 28, 2020.

NHTSA (2020b). Traffic Safety Facts Annual Report Tables. https://cdan.nhtsa.gov/tsftables/tsfar.htm. Accessed September 24, 2020.

NHTSA (2020c). Traffic Safety Facts: Preview of Motor Vehicle Traffic Fatalities in 2019. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813021. Accessed December 28, 2020.

NSC (2016). U.S. DOT, National Safety Council Launch Road to Zero Coalition to End Roadway Fatalities. National Safety Council, Itasca, IL. https://www.nsc.org/in-the-newsroom/us-dot-national-safety-council-launch-road-to-zero-coalition-to-end-roadway-fatalities. Accessed September 24, 2020.

Robertson, L.S. (1983). Injuries – Causes, Control Strategies, and Public Policy. *Journal of Public Policy, 4*(4), 359-360.

Sanders, R., Schultheiss, B., Judelman, B., Burchfield, R., Nordback, K., Gelinne, D., …, Koonce, P. (2020). *Guidance to Improve Pedestrian and Bicyclist Safety at Intersections* [NCHRP Research Report 926]. National Academies of Science, Engineering, and Medicine, Washington, D.C.

Schultheiss, B., Goodman, D., Blackburn, L., Wood, A., Reed, D., & Elbech, M. (2019). *Bikeway Selection Guide* [Report No. FHWA-SA-18-077]. Federal Highway Administration, Washington, D.C.

Stamatiadis, N., Kirk, A., Hartman, D., Jasper, J., Wright, S., King, M., & Chellman, R. (2018). *An Expanded Functional Classifications System for Highways and Streets* [NCHRP Research Report 855]. National Academies of Science, Engineering, and Medicine, Washington, D.C.

SWOV (2013). *Sustainable Safety: Principles, Misconceptions and Relations with Other Visions.* SWOV Institute for Road Safety Research.

Tefft, B.C. (2013). Impact Speed and a Pedestrian's Risk of Severe Injury or Death. *Accident Analysis & Prevention, 50*, 871-878.

Tingvall, C., & Haworth, N. (1999). Vision Zero – An Ethical Approach to Safety and Mobility. Presented at the 6th ITE International Conference Road Safety & Traffic Enforcement: Beyond

2000, Melbourne, Australia. https://www.monash.edu/muarc/our-publications/papers/visionzero. Accessed September 24, 2020.

USDOT (2020). Benefit-Cost Analysis Guidance for Discretionary Grant Programs. Office of the Secretary, U.S. Department of Transportation, Washington, D.C.

Wegman, F., Aaerts, L., & Bax C. (2008). Advancing Sustainable Safety: National Road Safety Outlook for The Netherlands for 2005-2020. *Safety Science, 46,* 323-343.

Woolley, J., Stokes, C., Turner, B., & Jurewicz, C. (2018). *Towards Safe System Infrastructure: A Compendium of Current Knowledge* [Report No. AP-R560-18]. Austroads Ltd., Sydney, Australia, 2018.

For More Information:
Visit https://safety.fhwa.dot.gov/intersection/

FHWA, Office of Safety
1200 New Jersey Ave. SE
Washington, DC 20590

FHWA-SA-21-008