TECH**BRIEF**

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A Safe System-Based Framework and Analytical Methodology for Assessing Intersections

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This document is a technical summary of the Federal Highway Administration report "A Safe System-Based Framework and Analytical Methodology for Assessing Intersections" (FHWA-SA-21-008).

OBJECTIVE

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 project developed a Safe System for Intersections method that can be applied at a project level and be incorporated into an Intersection Control Evaluation alternatives screening process to provide another metric for safety.

INTRODUCTION

Countries with Vision Zero initiatives have identified key principles to guide their national approaches to road safety management— Safe System approaches that result in a Safe System. 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 a Safe System approach is one where the basic design and operational parameter is to not exceed the "level of violence the human body can tolerate without being killed or seriously injured" in the event of a crash.

In its National Road Safety Strategy (2011-2020), the Australian Transport Council (2011) identifies three guiding principles to their Safe System approach, paraphrased below:

- People make mistakes; such mistakes on the road network should not result in death or serious injury.
- There are known physical limits to the amount of force the human body can withstand before serious injury occurs.
- 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.

Achieving a Safe System depends on contributions from the whole transportation system. Safe System documentation sometimes represents the whole system as interacting principles spanning "safe roads," "safe speeds," "safe vehicles," "safe road users," and "post-crash care". This approach is commonly reflected in State Strategic Highway Safety Plan (SHSP) 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).

It is not possible to achieve a Safe System through road infrastructure planning, design, and operation alone. However, road infrastructure characteristics such as geometrics and traffic operation and control strategies can be assessed from a kinetic energy management perspective that is central to the Safe System approach. 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. Intersection projects offer unique opportunities to apply a Safe System approach to planning, design, and operational decisions.

METHODOLOGY

A primary objective of this research effort was to develop a Safe System for Intersections (SSI) analytical methodology that intersection planners and designers can readily implement and that dovetails with the typical project development process—one that incorporates Safe System principles 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. The following represent key considerations and characteristics of the SSI method, with additional detail provided in the full report.

Data Needs

In order to make it readily usable for practitioners during alternatives screening, the SSI method was developed with typically available project data in mind: posted speed limit, average annual daily traffic (AADT) volumes, and the number of through lanes on the intersecting roads. There are also several optional 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 been as utilized or explored historically by the research and practitioner communities. The SSI method offers assumptions and default values for their use, but agency-prescribed or project-specific values could also be applied.

Conflict Point Identification and Classification

A conflict point is any location where the paths of road users coincide (FHWA, 2019). 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 pedestrian conflict points. 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. The SSI method 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) but does consider rear-end conflicts resulting 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 alternatives screening when exact lane arrangements may not be known, the SSI method identifies conflict points on a movement basis. While movement-based conflict points are not dependent on the number of lanes or presence of auxiliary lanes in an alternative, they are disaggregated by each movement combination. For example, where pedestrians cross a minor road leg of a four-legged intersection—where left turns, right turns, and through movements can be made onto and from the minor road—there would be six total conflict points. Figure 1 shows an example of the movement-based conflict points for a traditional minor road stop control intersection. The full report illustrates movement-based conflict points for various intersection alternatives that State agencies with Intersection Control Evaluation (ICE) policies commonly consider as part of a Stage I ICE.

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) in which the exposure index at a given conflict point is simply the product of vehicle or nonmotorized user daily volumes passing through that conflict point. 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 or total exposure through all merging conflict points).

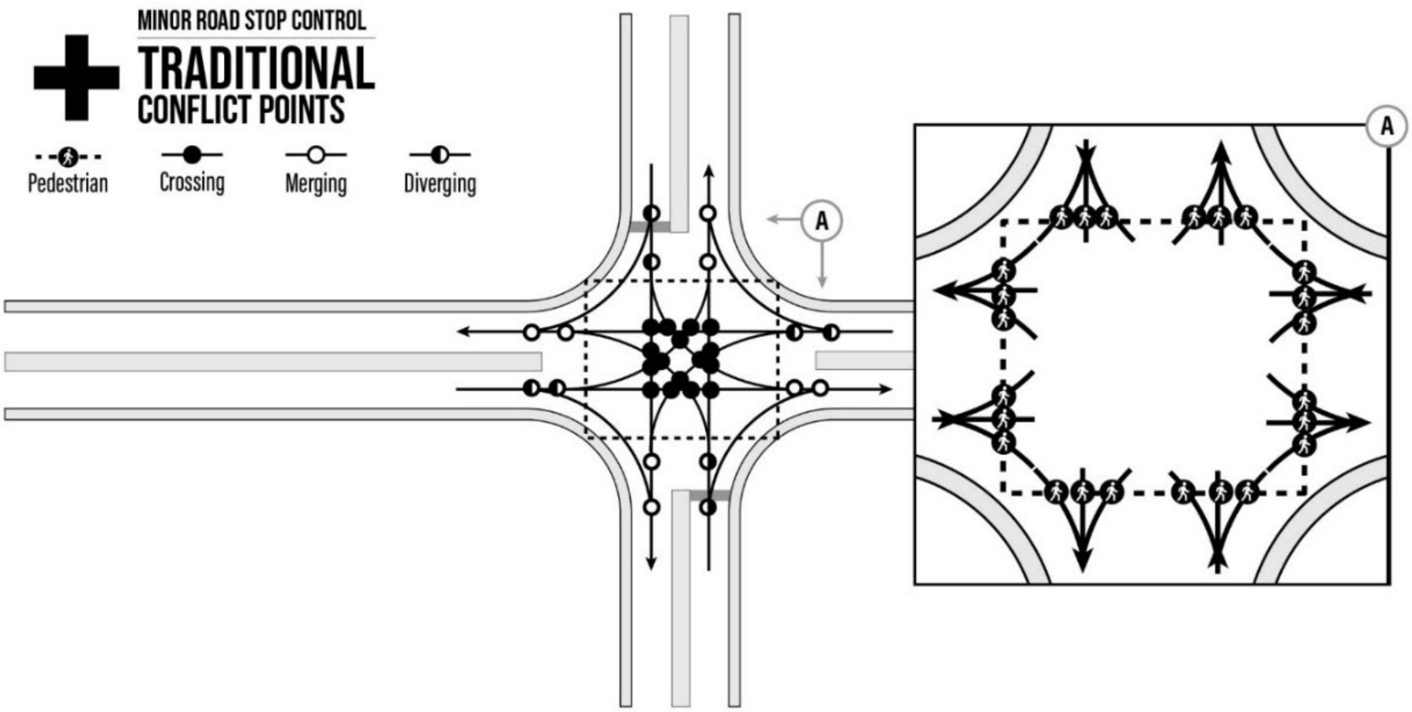

Figure 1. Graphic. Diagram of movement-based conflict points for Traditional Minor Road Stop Control intersections.

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 maximum abbreviated injury scale (MAIS), 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). MAIS 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 is another benefit of the MAIS scale. The SSI method defines fatal and serious injuries as injuries with MAIS scores of 3 or above.

The full report details the calculations used to estimate conflict point severity for the SSI method. 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. With limited existing research into speed prediction at intersections, the SSI method adopts a simplified set of speed assumptions to cover the various maneuvers at intersections that can be adjusted based on local knowledge or any data that become available in the future. The collision angle used to compute conflict point severity in the SSI method is based on the convention established in Jurewicz et al. (2017); to facilitate efficient application to a variety of intersections, the SSI method identifies five categories of potential collision types and proposes a typical range of collision angles for each 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.

Movement Complexity, User Workload, and the SSI Score

Concepts related to user behavior and the workload imposed (or mitigated) by the intersection design and operations will also affect the crash risk per given level of exposure. As such, the SSI method considers features corresponding to the overall intersection form and size that could impact the task complexity for users making specific movements at an intersection. The complexity concepts are applicable at the movement level, with the corresponding complexity factors being applied to the appropriate conflict points along that same movement. The SSI method derives two main complexity factors. The first intersection complexity factor 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. This first complexity factor applies to both vehicle and nonmotorized movements through an intersection and therefore to the vehicle-vehicle and vehicle-nonmotorized conflict points along those movements. The second intersection complexity factor is an additional nonmotorized complexity factor. This second factor accounts for indirect and nonintuitive movements at an intersection that may present additional complexity for pedestrians and cyclists. The SSI method assumes intersection attributes associated with lower levels of complexity for all users will ultimately bring it into closer alignment with a Safe System.

Results and Potential Use

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 values representing higher levels of Safe System performance (i.e., lower chances of fatalities and serious injuries).

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.

Summary and Future Expansion of the SSI Methodology

While U.S. intersection planning and design practices have incorporated Safe System principles to some extent over the last several decades, work remains to be done. The SSI method developed through this research effort 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 include multiple MOEs and a set of SSI scores that can serve as additional safety metrics to inform the process of screening intersection alternatives, such as during a Stage I ICE.

Looking to the future, there are multiple opportunities to expand the SSI framework. The full report details these opportunities, organizing them into two categories: 1) SSI enhancements for common intersection planning and design applications and 2) SSI enhancements for broader Safe System implementation.

SSI enhancements for common intersection planning and design applications include the following:

- Incorporate more refined identification and analysis of pedestrian and bicyclist conflict points, with a promising potential approach being to develop multiple alternatives for a single intersection type that differ by pedestrian and bicycle accommodation – e.g., Restricted Crossing U-turn (RCUT) with sidewalk and on-street bike lanes, RCUT with shared use paths, RCUT with sidewalks and separated bike lanes and a protected intersection.

- Expand to other conflict types, such as rear-end conflicts that result from speed differentials that arise from traffic congestion or deceleration and merge and diverge conflicts that may vary in their location along an intersection approach due to lane changing, including weaving movements.

- Develop data and models to support intersection speed prediction that would provide insights to expected operating speeds by intersection type, type of traffic control, movement, and traffic volume variations throughout the day.

- Develop, validate and calibrate relationships between the SSI metrics/scores and crash-based models (such as those in the HSM) in order to better target reductions in fatal and serious injury crashes at intersections.

In addition to use by intersection planners and designers within the typical project development process, the fundamental building blocks of the SSI method 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 and support continued dialogue on steps to achieve a vision of zero fatalities and serious injuries in the U.S. The following are ideas for broader Safe System implementation:

- 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 SSI method could incorporate different aspects of vehicle design, such as vehicle size and automated driving system technologies, if corresponding data or assumptions are available.
- The existing structure of SSI method could incorporate user characteristics and behavior in an average/aggregate way; at some point, the large number of possible user and vehicle type combinations could lend themselves to a Safe System 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.

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