Crossing Treatment Process for Safer Shared Use Path Crossings

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16. Abstract

Intersections with roadways are the most dangerous locations along shared use path (SUP) crossings for pedestrians and bicyclists. Despite this, there is limited research on the unique risks of these sites compared to other pedestrian and bicyclist facilities, and limited guidance exists for the geometric and operational characteristics that may necessitate different kinds of crossing treatments. The North Carolina Department of Transportation funded this study to create clear, intuitive guidance for when to implement different treatments at SUP crossing sites across the state. To accomplish this goal, researchers collected video data at 16 different SUP sites with a variety of geometric and operational characteristics. These sites were broken into four general classifications based on the crossing types: unmarked crossings, marked crossings, crossings with refuge islands, and crossings with supplemental yielding or other traffic control devices. At each site, researchers collected a variety of data, including road user volumes, driver yielding behavior, and post-encroachment time.

After collecting these data, researchers developed a Safe System SUP Crossing Evaluation tool that inputs geometric and operational data and outputs a variety of scores based on pedestrian and bicyclist exposure to risk, likelihood of being involved in a severe conflict, severity of potential conflicts, and the site's overall Safe System compliance. These scores were then analyzed using linear regression and logistic regression—alongside variables for treatment type, speed limit, and vehicular traffic, as well as measures of critical post encroachment time—to determine potential guidance for installing different types of countermeasures.

In general, the sites that had the highest degrees of Safe System compliance (i.e., those sites that provided separation in space and time) tended to have the lowest number of critical crossing interactions. Based on these results, the researchers developed a Safe System SUP Crossing Decision tool and relevant case studies that will support NCDOT staff and local practitioners in proactively addressing risks at SUP crossing sites by selecting appropriate crossing treatments.

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Executive Summary

This report details an analysis of shared use paths (SUPs), which are multiuse facilities that support pedestrian, bicyclist, and other non-motorized activities, and presents guidance for evaluating how the design and management of intersections of SUPs with roadways influence the safety of SUP users. SUP crossings are often at midblock locations and often support recreational activities, so the nature of those crossings, as well as the expectations and behaviors of users, may differ from other pedestrian and bicyclist crossing locations. For this reason, there is minimal research that focuses specifically on SUP crossings. The lack of guidance for SUP crossings has been identified as a concern by NCDOT staff, and there is a need for a Safe System-based treatment matrix that addresses traffic composition and roadway separation to mitigate risks to crossing pedestrians and bicyclists.

This report documents the development of a Safe System SUP Crossing Evaluation tool that can be used to measure the risk of a SUP crossing based on its compliance with Safe System principles and to determine appropriate treatments for improving pedestrian and bicyclist safety across a variety of operational and geometric conditions. The report is organized into eleven sections and includes a site selection process, video data collection process, site review process, statistical analyses, recommendations and case studies for treatment, implementation plan, and appendices of additional literature and analytical considerations.

Literature Review

In the literature review, we present evidence on methods for selecting crossing treatments for SUP intersections, including risks to pedestrians and bicyclists, how those risks are measured, and how the risks are mitigated. A summary of the key concepts emerging from the literature are listed here and further discussed Section 1:

- Pedestrian risks are often related to motor vehicle speed, while bicyclist risks are related to the nature of their interactions with motor vehicles. Studies have shown the importance of providing separation for bicyclists and pedestrians from high-speed motor vehicle traffic, and the need for full (grade) separation at crossings with high motor vehicle volumes and speeds.
- Pedestrian and bicyclist safety is typically evaluated using crash data and/or surrogate indicators of safety. Crash data is often sparse and may not be available for sites where risks are present, so some analysts will use surrogate measures, such as conflict analysis, to determine where pedestrians and bicyclists may be at risk of crash occurrence. Studies were found to use a variety of measures to conduct conflict analysis where crash data are insufficient, including time to collision (TTC), post-encroachment time (PET), and deceleration, among others.
- Most of the research to date has focused on identifying and evaluating relevant crossing treatments on non-SUP sites; the extent to which those findings translate to SUP crossings has yet to be robustly evaluated.
- The Safe System Approach focuses on minimizing road user exposure to conflicts, crash likelihood, and severity that result from high crash energy. This approach does not rely solely on crash data to identify risks and select optimal designs to improve safety. Various tools to evaluate risks based on compliance with Safe System principles exist, but so far there has not been a tool designed specifically for SUP crossing locations.
- While there are some specific, municipal policies for SUP crossing treatments, more comprehensive guidance is needed.

Methods

Given the low frequency of crashes per SUP crossing site in North Carolina, researchers collected PET as a surrogate safety measure to provide input for a Safe System-based evaluation of a subset of all trail crossings in the state. The study selected sites for evaluation based on various site characteristics such as speed limit, traffic volume, and number of motor vehicle lanes. The research team developed a crossing inventory of all available sites, which consisted of 76 crossings in North Carolina, to identify a representative sample of sites for evaluation. The site selection process aimed to ensure that a variety of crossing treatments were considered from different regions and land uses across North Carolina as well as representation from different crossing treatment groups. The crossing inventory highlighted that few SUPs in North Carolina exist with higher levels of street crossing protection like signal or stop control or assisted yielding devices. Ultimately, 16 sample sites were selected across four treatment groups (e.g., no marking, marking, refuge island, or supplemental yielding/traffic control). The research team set up cameras for at least two full days at each site to gather data on motor vehicles, pedestrians, and bicyclists. Cameras were set up to observe both weekdays and weekends when possible, and data collection took place from March to June 2022. Coders then reviewed video footage chronologically at each site beginning at 3:00 PM on Friday and ending after 50 interaction events (i.e., crossing events when a motor vehicle was sufficiently close for a potential conflict to occur) were found or until four days of footage had been reviewed, whichever criterion was met first. Each interaction was timestamped and included information about the SUP traveler’s mobility type and the direction of the traveler and motor vehicle, as well as characteristics of the traveler and vehicle such as platoons and whether the vehicle was large. Interactions were categorized into coexistence, avoidance, conflict, or none, and researchers coded whether there was a correct yield from the motor vehicle for avoidance interactions. The PET was also recorded for each interaction. Finally, researchers counted the number of motor vehicles, pedestrians, and cyclists that crossed or used the crossing during the allotted time, regardless of whether they were part of an interaction.

The observational data was analyzed by treatment group and summarized in several categories. The percent of correct yielding behavior was calculated by dividing the number of correct yielding behaviors by the total interactions (where vehicular yielding would be required) per site. The percentage of large passenger vehicles observed, including SUVs and pickup trucks, was also recorded. The total number of pedestrians and bicyclists crossing the roadway during the 50 interactions was counted, and a categorical activity level was assigned based on the median number of crossing pedestrians or bicyclists per treatment group. The time to record 50 interactions was also recorded, as was the total number of avoidance maneuvers observed. At each of these sites, researchers also collected geometric and operational data through desk reviews of site characteristics and. Then each site was scored using the Safe System SUP Crossing Evaluation tool developed specifically for this project.

Analysis

Site characteristic data were recorded through a desk review of sites using Google Maps® or by identifying common traffic characteristics at the site using the video-recorded data. Site characteristics variables were used in evaluating the crossing sites using the Safe System SUP Crossing Evaluation tool. Safe System criteria scores were derived using the Safe System SUP Crossing checklist and the scoring sheets that returned scores based on data input. These scores are subjective assessments of site and operational characteristics based on the Safe System evaluation frameworks found in the literature.

Statistical modeling approaches were used to answer research questions related to predicting the potential for conflict at crossing sites, determining the odds of critical conflicts, and identifying criteria for selecting different treatment types at different locations. Linear and logistic regression models were used to analyze recorded data and site characteristics and Safe System criteria scores. A multi-stage approach was taken to develop a combined model using both site characteristics and Safe System criteria scores. Recorded data were collected through observation of video-recorded interactions at each of the 16 sites and used to provide context to the findings or were used in evaluating the sites using the Safe System SUP Crossing Evaluation tool. Two of the variables in this dataset, logPET (logarithmic transform of post-encroachment time) and CritPET (a binary variable indicating whether PET was within critical range, or less than 1.5 seconds), were used as dependent variables in the modeling process to determine potential decision guidelines for selecting appropriate treatments at crossing locations. A limited set of the variables—treatment type, annual average daily traffic, and speed limit—were used in the statistical modeling process as independent variables to determine guidance for selecting appropriate treatments at crossing locations.

Results

The resulting guidance from these analyses can help practitioners identify high-risk factors and appropriate crossing treatments. The linear regression models show that there is a negative relationship between logPET and the degree of separation between motor vehicles and crossing pedestrians/bicyclists, as well as lower speed limits. However, there is a counterintuitive positive relationship between logPET and the Safe System Evaluation scores, which may be due to confounding factors such as higher order crossing treatments (e.g., stop or signal control) being present at high exposure sites (e.g., sites with higher posted speeds and/or traffic volume).

The logistic regression models showed that certain treatments such as no markings, pavement markings only, or refuge islands increase the likelihood of a critical event compared to traffic control or supplemental yielding. The models also suggest that the log odds of a critical event decrease with lower speed limits and increase with higher AADT. The Safe System criteria and Evaluation scores worked in opposite directions when multiple variables were included in models, and likelihood-related variables may have a larger impact on increasing the log odds of a critical event occurring.

Recommendations and Guidance

The report provides detailed recommendations for installing traffic control and supplemental yielding, refuge islands, and pavement markings based on the study's findings. These recommendations are presented in tables (the Safe System SUP Crossing Treatment Matrix) and compiled into an Excel-based Safe System SUP Crossing Decision tool that recommends interventions based on site characteristics.

The report also provides case studies of crossing sites not included in the sample of 16 sites where video data were collected. These case studies provide illustrations of how to collect useful data, how to use the Safe System SUP Crossing Evaluation tool, and how to select an appropriate treatment type based on the collected data and the Safe System SUP Crossing Treatment Matrix.

Conclusions

This report presents the results of a Safe System-based analysis of SUP crossings in North Carolina, aimed at providing guidance to practitioners when assessing risks to pedestrians and bicyclists and selecting appropriate treatments to mitigate those risks. The analysis was based on an evaluation of 16 different crossing sites, statistical analysis of the relationship between Safe System compliance and treatment groups, and case studies of other crossing sites. The results showed that speed limits and traffic volumes affect the risk of critical events occurring on SUP crossings, and that the proposed Safe System assessment approach can identify potential risks and relevant countermeasures beyond crossing treatments. However, the qualitative nature of the Safe System SUP Crossing Evaluation tool and the unknown link between surrogate safety measures and actual crashes involving pedestrians and bicyclists are limitations of the project. The researchers also documented other noteworthy findings that do not fall into the analysis performed and recommend further calibration of the qualitative Safe System tool through a consensus-building process.

Implementation and Tech Transfer Plan

This project developed resources that NCDOT and municipalities can use to evaluate SUP crossing sites for risk factors and compliance with Safe System principles, and to identify appropriate treatments for those sites. The resources include multiple Microsoft Excel-based spreadsheets, including a Safe System SUP Crossing Checklist, the Safe System SUP Crossing Evaluation tool, and the Safe System SUP Crossing Decision tool, which can be calibrated to local conditions. Engineers and planners can use these tools for scenario testing, and researchers can provide support and training in their use. Video data collection can also feed into the evaluation tool. A Delphi-style consensus building exercise can fine-tune the tool and help identify appropriate treatments and countermeasures.

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1 Introduction

Shared use paths (SUPs) are multiuse facilities that support pedestrian, bicyclist, and other non-motorized travel. These types of facilities can be found in both rural and urban locations and may link recreational facilities or support transit connections. The intersections of shared use paths and roadways that carry motorized traffic are the most dangerous locations for SUP users. These intersections may be characterized by a variety of traffic control and crossing treatment types that may mitigate or increase risks to crossing pedestrians and bicyclists. Engineers and planners often rely upon engineering judgment to determine the most appropriate crossing treatments where SUPs intersect roadways, and NCDOT staff have expressed concern over the lack of guidance for SUP crossings.[1]

Although pedestrian and bicyclist safety has been relatively well-researched in recent years, especially at midblock locations for pedestrians and at intersections for bicyclists, little unique research exists for SUP crossings. The dynamics of pedestrian and bicyclist activity on SUPs, as well as the often-recreational nature of these facilities, may create unique concerns for safety at SUP crossings. The lack of routinely collected pedestrian and bicyclist volume data and the limitations of available crash data can make analyzing these sites and specifying appropriate treatments challenging.

The purpose of this study is to develop guidance for SUP crossing locations in North Carolina. While it was initially proposed that the guidance would be based on a surrogate safety performance function (SPF), the research team and Steering and Implementation Committee (StIC) concluded that a Safe System-based treatment matrix that addresses traffic composition and roadway separation was more appropriate. The Safe System Approach is a traffic safety management paradigm endorsed by the U.S. Department of Transportation[2] wherein roadway agencies proactively address risks to prevent deaths and serious injuries.[3] The Safe System Approach can be conceptualized[4] as the interconnected system of safe vehicles, safe speeds, safe roads, post-crash care, and safe road users that accommodates six key principles:

1. Death and serious injury are unacceptable
2. Humans make mistakes
3. Humans are vulnerable
4. Responsibility is shared
5. Safety is proactive
6. Redundancy is crucial

A few frameworks have been published in traffic safety literature that measure a roadway facility's compliance with the Safe System Approach as the degree to which that facility minimizes a road user's exposure to conflicts, crash likelihood, and the potential severity of a crash as a result of the crash energy (or kinetic energy).[5] Based on this framework for measuring Safe System compliance, this report documents the development of a Safe System SUP Crossing Evaluation tool that can be used to qualitatively measure the risk of a SUP crossing. Based on this information, and by more closely examining the data inputs that produced the corresponding Safe System score, practitioners may be able to determine appropriate treatments for improving SUP crossing safety across a variety of operational and geometric conditions.

This report is organized into eleven sections. Following this introduction, Section 2 provides an overview of pedestrian and bicyclist safety research literature, existing guidance for crossing treatments, and Safe

System evaluation tools. Section 3 explains the site selection process used in this study to develop a sample of sites for data collection and evaluation. Section 4 discusses the video data collection process to capture observed behaviors and other field data at each site, while Section 5 presents the desktop site review process and how these two data streams are used in the Safe System SUP Crossing Evaluation tool. Statistical analyses examining the relationships between the site recorded data, the Safe System evaluations, and treatment type are highlighted in Section 6, and from these analyses, recommendations and case studies for treatment are derived as presented in Section 7. Section 8 draws conclusions about the study. Section 9 presents an implementation plan for how NCDOT staff may use the results. Section 10 lists the works cited, and Section 11 concludes the report with appendices of additional literature and additional analytical considerations.

2 Literature Review

This literature review briefly discusses important concepts for consideration when selecting a crossing treatment for SUP intersections. Relevant topics include risks to pedestrians and bicyclists, how those risks are measured, and how the risks are mitigated. Concepts relevant to the Safe System Approach are also addressed. Finally, general insights into the municipal, state, national, and international policies regarding SUP geometric design, signage, markings, traffic devices, grade separation, and rail crossings are discussed. More information related to these topics can be found in Appendix A.

2.1 Risks to Pedestrians and Bicyclists

Pedestrians and bicyclists are significantly more susceptible to the energies that are transferred during crashes, so these two categories of road users are often grouped together when identifying risks in the built environment. However, not all risks are shared evenly between pedestrians and bicyclists, so treatments identified for one group of road users may be insufficient for the other. Additionally, with the growing popularity of scooters and e-bikes, as well as potential changes in walking and bicycling sparked by the COVID-19 pandemic[6], findings from earlier studies regarding travel speeds and crossing behaviors of SUP users may not be indicative of present safety risks.

2.1.1 Pedestrian Risks

Motor vehicle speed is an important factor to consider in safety analysis for pedestrians. In a broad literature synthesis, Sanders et al. (2019) highlighted several studies that document the increasing risk of death and serious injury pedestrians face as impact speeds increase. The research shows that although the risk of pedestrian fatality at an impact speed of 24 miles per hour (mph) is only 10%, that risk of fatality increases to 50% at only 41 mph.[7] Other studies, as documented by the Washington Injury Minimization and Speed Management Policy Guidelines Workgroup, indicate that a driver speed of 20 mph corresponds to a 10% risk of fatality for pedestrians, while an impact speed of just 10 mph corresponds to a 10% risk of serious injury.[8] While these impact speeds and the safety implications have not been explicitly studied at SUP crossings, the physics apply to all types of crossings where unprotected pedestrians are exposed to motor vehicles. Vertical and horizontal deflections can be effective when motor vehicle volumes are low, but full (grade) separation may be necessary when motor vehicle volumes and speeds are high.

In a review of 38 studies on pedestrian safety at intersections and along segments, Thomas et al. (2018) identified a number of latent risk factors in the built environment and traffic operations that can increase crash frequency and crash severity for pedestrians. While this synthesis was not focused on

SUP crossings specifically, many of the segment risks may still be applicable at trail crossings.[9] The risk factors are identified in Table 1.

Table 1. Risk Factors for Pedestrian Crashes at Intersections and Segments

Variable/Risk Factor	Intersections	Segments
Traffic volume	+ (generally positive but not linear)	+ (generally positive but not linear)
High-turning volumes	Unknown threshold	Unknown at present
Functional classes - arterials and collectors compared with local streets	+	+
Proportion of truck/bus traffic in traffic stream	+ (with crash severity)	+ (with crash severity)
Proportion of local streets at intersection (potential surrogate for annual average daily traffic [AADT])	-	Unknown at present
Pedestrian volume	+ (positive, but not linear)	+ (positive, but not linear)
Number of legs > 3 (may also be partial traffic surrogate)	+	Unknown at present
Total lanes on largest leg (5+)	+	Unknown at present
No median/median island	+ (less certain than for segments)	+
Presence/number of transit stops	+	+
Presence of on-street parking	+	+
Presence/number of driveways	+	Unknown (theoretically yes)
Presence of signal	+ (with crash frequencies) - (with crash severity)	Unknown at present
Lack of separate turning movements from walk phase (all red walk phase, or walk and restricted turn phase) (signalized intersections)	+	Unknown at present
Lack of leading pedestrian interval (signalized intersections)	+	-
Presence of four or more through lanes Higher numbers of total lanes	Theoretically yes	+
Presence of TWLTL	Unknown at present	+
Speed limit > 25 mph	Unknown at present	+ (with crash severity) + (with frequency in a few studies)
Vehicle speed	+ (with severity)	+ (with severity)

Notes: table adapted from Thomas, et al (2018)[9]

A more recent study by Schneider et al. (2021) examined 65 hot spot corridors (i.e., roadway segments with high crash frequencies) where six or more fatal pedestrian crashes had occurred in an eight-year period. The researchers found several consistencies between all of the study sites[10]:

- 97% of the study segments were multilane roadways;
- Over 75% of the study segments had speed limits of 30 mph or higher;
- 62% of the roadways had traffic volumes greater than 25,000 vehicles per day (vpd).

The findings of all three of these references demonstrate that the risk of death or serious injury is high for pedestrians when exposure to high-speed traffic is high.

2.1.2 Bicyclist Risks

Like pedestrians, bicyclists are highly susceptible to the energies that transfer from high speeds during crashes. Cushing et al. (2016) note that a bicyclist is twice as likely to be killed in a collision when motor vehicle speeds are 30 mph and 11 times as likely to be killed when motor vehicle speeds are 40 mph when compared to collisions when motor vehicle speeds are 20 mph.[11] Because of this risk, bicyclist safety treatments often focus on providing separation for bicyclists from motor vehicle traffic as speed of the adjacent motorists increase (e.g., shared lanes, bicycle lanes, separated bicycle lanes, etc.).

Bicyclist safety concerns are often measured using crash data, interaction data, and road user surveys. Most of these assessments focus on typical four-leg intersections and bicycle facilities along segments, but insights into bicyclist safety concerns can be applied to shared use path crossings.

A crash data analysis conducted by Isaksson-Hellman and Werneke (2017) found that of 882 motor vehicle-bicyclist collisions recorded in an insurance claims database in Sweden from 2005 to 2012, 78% of crashes occurred when bicyclists and motorists crossed paths. Only 11% of the crashes involved a motorist overtaking a cyclist while traveling in the same direction, although these crashes tended to be more severe.[12]

Other studies have reiterated the importance of providing protected or separated facilities to bicyclists when they must encounter motorists. In a survey of 351 road users in Michigan, Sanders and Judelman (2018) found that the primary concern for respondents was safety when considering bicycling and that most respondents (greater than 60%) prefer separated bicycle facilities regardless of whether the respondent was a frequent cyclist or never bicycled.[13] In an analysis of self-reported comfort levels linked to GPS-based trajectory data in Oregon, Caviedes and Figliozzi (2018) found that the most commonly reported stressor on bicyclists for the 594 weighted trips in the dataset was motor vehicle traffic. Most trip mileage was focused in residential areas with bicycle facilities, with bicycle boulevards and separated paths accounting for the second and third greatest mileage of trips. After exploring these data with ordinal regression models, the researchers found that the only built environment factors that seemed to correspond to an increase in route comfort were separated paths without motor vehicle conflicts. Although these findings may not apply directly to SUP crossings, they do indicate the importance of considering separation when motor vehicle traffic is high.[14]

2.2 Evaluating Safety for Pedestrians and Bicyclists

Pedestrian and bicyclist safety are most often measured using crash data or surrogate indicators of safety. Crash data are derived from police reports, but these data are often sparse and may not capture the full extent of risks to pedestrians and bicyclists in the built environment, so surrogate measures can be used to predict where crashes will occur and their potential severity. Most safety evaluations of pedestrian and bicyclist crossings found in the literature were conducted at typical intersections or at midblock crossings (for pedestrians), but the methods used to measure safety and predict crashes are generally applicable to shared use crossings.

2.2.1 Crash-Based Measures of Safety

Agencies are encouraged to use crash data in network screening processes to identify locations for treatment based on common risk factors.[15] A common use of crash data is the development of crash prediction models called safety performance functions (SPFs).[16] SPFs are essentially equations that combine road use or exposure data (such as annual average daily traffic (AADT)) and roadway facility data (such as segment length or number of legs on major approach) to calculate the predicted number of crashes that might occur in a given year.[17] The number of SPFs and use cases available in the current edition Highway Safety Manual for predicting pedestrian and bicycle crashes is limited[18], so practitioners and researchers often must develop and calibrate their own crash prediction models.[19] Some SPFs (or similar crash prediction models) for pedestrians and bicyclists published in the literature can be found in Appendix A.

Unfortunately, pedestrian and bicyclist crash data tend to be sparse and widely distributed across a roadway network, and it can be difficult to develop statistically valid SPFs without collecting or developing additional measures of exposure. To calibrate SPFs for use at Massachusetts urban and suburban intersections, Xie and Chen (2016) adopted a simplified approach when accounting for pedestrian and bicyclist crashes based on a pedestrian crash adjustment factor.[19] Gates et al. (2016) also used a simplified approach based on a bicyclist adjustment factor to predict crashes at low-speed, signalized intersections.[18] Systemic analyses may circumvent issues of data sparseness when identifying risks in a network, but not all agencies have the statistical capacity to develop new SPFs for pedestrian and bicycle crashes.[9]

Based on currently available research, no SPFs were developed or calibrated for shared use crossing locations in North Carolina.

2.2.2 Surrogate Measures of Safety

Because pedestrian and bicyclist crash data are widely dispersed and often unavailable, some researchers and practitioners use surrogate safety measures based primarily on conflict (i.e., locations where two different traffic streams can come into contact) analysis. A thorough review of surrogate safety measures was conducted by Johnsson et al. (2018).[20] Typically, most surrogate safety measures can be grouped into three categories:

1. Time to collision (TTC)—a measure of the time remaining before a collision occurs assuming road users in conflicting paths do not alter their trajectories or speeds.
2. Post-Encroachment Time (PET)—the time between the moment when the first road user leaves the path of the second road user and the moment when the second reaches the path of the first.
3. Deceleration—the most common evasive action taken by motorists to avoid a collision in urban areas.

Researchers have devised different versions of these three surrogate measures to quantify different elements of risk in conflicts—such as the minimum TTC, the gap time between entries into a conflict spot, the time advantage of road users continuing on their paths and speeds, the deceleration rate, deceleration safety time, etc.—but these additional measures are still generally examined to determine the potential for a crash (and that crash's severity) to occur should motor vehicle and pedestrian or bicycle trajectories cross uncontrolled. Some other surrogate measures include pedestrian step frequency and step length, pedestrian risk index, conflict severity, aggregated crash index, and space occupancy index.[20] Different agencies sometimes define conflicts differently, so the potential use of a surrogate measure likely depends on location.

An example use of surrogate safety measures can be found in a study by Zangenehpour et al. (2015). In this analysis, the researchers collected pedestrian and bicyclist volumes at intersections using video data and then classified different road users using an automated classification scheme. They then used the automated classifications to calculate TTC and PET and compared those results to crash data. The researchers found that video-based surrogate safety measures may be viable for identifying risks to pedestrians and bicyclists at some locations, but not every classification type can reliably identify all road user types.[21] Manually reducing this type of video data, however, may be beyond the scope of some projects.

Zangenehpour et al. (2016) also applied video-based measures of PET to identify the safety efficacy of different bike lane configurations at intersections in Montreal.[22] The researchers concluded that bike lanes on the right side of the street produced safer conditions for bicyclists based on PET than intersections without bike lanes. These examples, though applied at signalized intersections, demonstrate the potential efficacy of surrogate measures for shared use path crossings.

2.3 Identifying Relevant Safety Treatments

Most of the research literature focuses on identifying and evaluating relevant crossing treatments on non-SUP sites (more information on this literature is available in Appendix A). However, two recent studies demonstrate the potential for different data types to be used to identify risks and prescribe countermeasures at shared use path crossings. The first combined crash data and surrogate safety data shared through a crowdsourced data platform to predict bicyclist incidents (self-reported crashes or near-misses, a type of surrogate measure similar to TTC) at 32 multiuse trail (i.e., SUP) intersections in British Columbia. The researchers found that of all reported incidents, the proportion of incidents that resulted in collisions was higher at SUP intersections (38%) than at typical intersections (32%). They also found that the proportion of incidents leading to injuries was higher at SUP intersections (33%) than at typical intersections (15%). Using a negative binomial regression model, they found a statistically significant relationship between trail sight distance and bicyclist-reported incidents.[23] These results indicate that treating sight distance to improve the visibility of both bicyclists and motorists on the approaching roadway may be an effective method for reducing some crashes, but the results are somewhat counterintuitive and may indicate that the comfort afforded by increased sight distance means cyclists approach intersections with less caution.[23]

A second study used field observations to identify a suite of treatments for different risks at shared use path crossings adjacent to rail-grade crossings. The researchers conducted a conflict analysis by recording and then separating movements for pedestrians and bicyclists from train and motor vehicle trajectories. They observed several risk factors at these types of locations and grouped them into three categories[24]:

- Built environment - speed, crossing design, railroad crossing and path distance, stop line, insufficient crossing infrastructure, transit stop, road/street infrastructure, visibility

- Lack of path user information - speed, signage, non-compliance
- Lack of driver information - negotiation, vehicle speed, signage

They then identified solutions for each of these categories and outlined a process for selecting the right solution. These treatments, grouped by problem category, include:

- Built environment - design speed:
  - Change speed limits
  - Ensure speed limits are posted and visible
  - Include crossing area in school zone if there is a school zone adjacent
- Built environment - vertical crossing design:
  - Add signage
  - Install RRFBs (and automate if there is a nearby school zone)
  - Raise crosswalks if there is a nearby school zone
- Built environment - horizontal crossing design:
  - Move path closer to railroad tracks
  - Install variable message signs
  - Install (and automate RRFBs) if there is a nearby school zone
  - Install a traffic signal if there is a nearby school zone
- Built environment - stop line:
  - Move stop line closer to railroad tracks
  - Raise crosswalks
  - Dynamic enveloping if there is a nearby school zone
  - Add conflict zone traffic paint if there is a nearby school zone
- Built environment - insufficient crossing infrastructure:
  - Supply crossing options
  - Relocate crossing
  - Add pavement markings
  - Add zebra stripes
  - Dynamic enveloping if there is a nearby school zone
  - Install crossing treatment (e.g., RRFB) if there is a nearby school zone
- Built environment - transit stop:
  - Move transit stop or eliminate stop
- Built environment - road/street infrastructure:
  - Implement physical separation
  - Install pre-made concrete separation blocks
  - Install pavement markings or zebra stripes
  - Install quick curb if there is a school zone nearby
  - Install bollards if there is a school zone nearby
- Built environment - visibility:
  - Add signage
  - Add street lights
- Lack of path user information - trail speed:
  - Install speed treatment
  - Add signage

- Lack of path user information - signage:
    - Add signage
    - Add tactile warning surfaces
    - Install variable message signs or in-pavement markers if there is a school zone nearby
- Lack of path user information - non-compliance:
    - Install obstructions
    - Install variable message signs
- Lack of driver information - negotiation:
    - Dynamic enveloping
    - Install conflict paint
    - Raise crosswalks if a school zone is nearby
    - Install and automate RRFBs if a school zone is nearby
- Lack of driver information - vehicle speed:
    - Install speed treatment
    - Install PHBs
    - Install conflict paint
    - Install active speed signs
- Lack of driver information - signage:
    - Add signage
    - Add pavement markings
    - Install speed treatments, especially if there a school zone is nearby

The treatments identified by Alligood et al. (2018) may not be fully relevant to this North Carolina SUP crossing study because rail-grade crossings are more complex[24] than the majority of the SUP crossings documented in later chapters throughout this report. However, the general principles of speed management, lighting, and separation are relevant to a Safe System-based evaluation.

2.4 The Safe System Approach

As mentioned, the Safe System Approach differs from other transportation safety management systems in that Safe System frameworks do not necessarily rely on crash data to identify risks and select optimal designs to improve safety. Instead, Safe System-compliant designs are those that simply minimize road user exposure to conflicts, crash likelihood, and severity that results from high crash energy.[5] An example framework of treatments that can address these three parameters within different intersection contexts is reproduced in Table 2.

Table 2. Listing of Pedestrian and Bicyclist Safety Measures at Intersections in Compliance with Safe System Principles[5]

At intersections									
Safe System treatment	**Exposure**	**Likelihood**	**Severity**	**City Hubs**	**City Streets**	**City Places**	**Activity Streets & Boulevards**	**Movement Corridors & Connectors**	**Local Streets**
Signalised intersections with 'Scramble' phasing (30 km/h speed limit)		✓	✓	✓	✓		✓		
Limit access by mode	✓	✓	✓	✓		✓			
Raised signalised intersections with 30 km/h ramps		✓	✓	✓	✓		✓		
Safety platforms (30 km/h or lower) on all approaches		✓	✓	✓	✓	✓			✓
Geo-fencing technology for trams, trucks and other large vehicles		✓	✓	✓	✓	✓	✓		
Signalised roundabout with exclusive turn phases for public transport, cyclists and pedestrians		✓	✓	✓			✓	✓	
Grade-separation of pedestrians and cyclists from vehicular traffic		✓		✓					
Roundabouts with 20/30 km/h wombat crossings		✓	✓		✓	✓	✓	✓	✓
Threshold platforms at intersections with side-streets		✓	✓	✓	✓	✓		✓	
Raised intersections with 30 km/h (or lower) platforms		✓	✓	✓	✓	✓	✓	✓	✓
Signalised 'tennis ball' intersections (30 km/h design)		✓	✓					✓	
All-way stop signs		✓	✓			✓		✓	✓
Restricted access intersection	✓	✓	✓			✓		✓	✓

The Federal Highway Administration (FHWA) recently published a guide to intersection evaluation and design based on Safe System principles.[25] This guide adapts the same concept of evaluating intersection alternatives based on exposure, crash likelihood, and crash severity, but it weaves in additional criteria, such as predicted crashes and adjustments for complexity. To use this framework, practitioners:

1. Collect relevant data (e.g., posted speed limit, AADT, and number of through lanes on each approach)
2. Identify and classify conflict points
3. Calculate exposure per approach
4. Determine the severity of each conflict
5. Adjust for the complexity of movements at the intersection
6. Compare intersection alternatives based on a Safe System for Intersections (SSI) score

This method is not without limitations, such as assumptions that group bicyclist movements with pedestrian movements through intersections, but its framework may provide a more useful approach to selecting appropriate treatments at shared use path crossings based on simple principles, data, and conflict identification.

2.5 Relevant Shared Use Path Guidelines

2.5.1 MUTCD Guidance

The Manual for Uniform Traffic Control Devices (MUTCD) is commonly referenced by city and state agencies. The relevant portions of the MUTCD as they relate to markings, traffic signals and beacons, and signage are summarized in Tables 3-7 below.[27]

Table 3. Relevant MUTCD Signage Guidelines

Guideline	Reference
Road users approaching a signalized intersection or other signalized area, such as a midblock crosswalk, shall be given a clear and unmistakable indication of their right-of-way assignment.	4D.12-02
If yield (stop) lines are used at a crosswalk that crosses an uncontrolled multi-lane approach, Yield Here To (Stop Here For) Pedestrians (R1-5 series) signs shall be used.	3B.16-13
When a Non-Vehicular Warning sign is placed at the location of the crossing point, a diagonal downward pointing arrow (W16-7P) plaque shall be mounted below the sign.	5C.09-04
Because non-intersection pedestrian crossings are generally unexpected by the road user, warning signs should be installed for all marked crosswalks at non-intersection locations and adequate visibility should be provided by parking prohibitions.	3B.18-11

Table 4. Relevant MUTCD Markings Guidelines

Guideline	Reference
Stop lines shall consist of solid white lines extending across approach lanes to indicate the point at which the stop is intended or required to be made.	3B.16-06
Stop lines should be 12 to 24 inches wide.	3B.16-08
Yield lines shall consist of a row of solid white isosceles triangles pointing toward approaching vehicles extending across approach lanes to indicate the point at which the yield is intended or required to be made.	3B.16-07
The individual triangles comprising the yield line should have a base of 12 to 24 inches wide and a height equal to 1.5 times the base. The space between the triangles should be 3 to 12 inches.	3B.16-09
Stop lines at midblock signalized locations should be placed at least 40 feet in advance of the nearest signal indication.	3B.16-11
If yield or stop lines are used at a crosswalk that crosses an uncontrolled multi-lane approach, the yield lines or stop lines should be placed 20 to 50 feet in advance of the nearest crosswalk line, and parking should be prohibited in the area between the yield or stop line and the crosswalk.	3B.16-12
When crosswalk lines are used, they shall consist of solid white lines that mark the crosswalk. They shall not be less than 6 inches or greater than 24 inches in width.	3B.18-04
If transverse lines are used to mark a crosswalk, the gap between the lines should not be less than 6 feet. If diagonal or longitudinal lines are used without transverse lines to mark a crosswalk, the crosswalk should be not less than 6 feet wide.	3B.18-05
For added visibility, the area of the crosswalk may be marked with white diagonal lines at a 45-degree angle to the line of the crosswalk or with white longitudinal lines parallel to traffic flow.	3B.18-13

Guideline	Reference
If used, the diagonal or longitudinal lines should be 12 to 24 inches wide and separated by gaps of 12 to 60 inches. The design of the lines and gaps should avoid the wheel paths if possible, and the gap between the lines should not exceed 2.5 times the width of the diagonal or longitudinal lines.	3B.18-15
The word STOP shall not be placed on the pavement in advance of a stop line, unless every vehicle is required to stop at all times.	3B.20-15

The need for a traffic control signal at an intersection or midblock crossing shall be considered if an engineering study finds that one of the following criteria is met (4C.05-02):

Table 5. Relevant MUTCD Traffic Control Signal Guidelines

Guideline	Reference
For each of any 4 hours of an average day, the plotted points representing the vehicles per hour on the major street (total of both approaches) and the corresponding pedestrians per hour crossing the major street (total of all crossings) all fall above the curve in Figure 4C-5; or	Fig. 4C-5
For 1 hour (any four consecutive 15-minute periods) of an average day, the plotted point representing the vehicles per hour on the major street (total of both approaches) and the corresponding pedestrians per hour crossing the major street (total of all crossings) falls above the curve in Figure 4C-7.	Fig. 4C-7
The Pedestrian Volume signal warrant shall not be applied at locations where the distance to the nearest traffic control signal or STOP sign controlling the street that pedestrians desire to cross is less than 300 feet, unless the proposed traffic control signal will not restrict the progressive movement of traffic.	4C.05-4

Table 6. Relevant MUTCD Pedestrian Hybrid Beacons Guidelines

Guideline	Reference
A pedestrian hybrid beacon face shall consist of three signal sections, with a CIRCULAR YELLOW signal indication centered below two horizontally aligned CIRCULAR RED signal indications.	4F.02-02
When an engineering study finds that installation of a pedestrian hybrid beacon is justified, then: A. At least two pedestrian hybrid beacon faces shall be installed for each approach of the major street, B. A stop line shall be installed for each approach to the crosswalk, C. A pedestrian signal head conforming to the provisions set forth in Chapter 4E shall be installed at each end of the marked crosswalk, and	4F.02-03

Guideline	Reference
D. The pedestrian hybrid beacon shall be pedestrian actuated.	
When an engineering study finds that installation of a pedestrian hybrid beacon is justified, then: A. The pedestrian hybrid beacon should be installed at least 100 feet from side streets or driveways that are controlled by STOP or YIELD signs, B. Parking and other sight obstructions should be prohibited for at least 100 feet in advance of and at least 20 feet beyond the marked crosswalk, or site accommodations should be made through curb extensions or other techniques to provide adequate sight distance, C. The installation should include suitable standard signs and pavement markings, and D. If installed within a signal system, the pedestrian hybrid beacon should be coordinated.	4F.02-04
Guidance for installation of pedestrian hybrid beacons on streets with speeds < 35 mph	Fig. 4F-1
Guidance for installations of pedestrian hybrid beacons on streets with speeds > 35 mph	Fig. 4F-2

Table 7. Relevant MUTCD Railroad and Light Rail At-Grade Crossings Guidelines

Guideline	Reference
Traffic control devices mounted adjacent to pathways at a height of less than 8 feet measured vertically from the bottom edge of the device to the elevation of the near edge of the pathway surface shall have a minimum lateral offset of 2 feet from the near edge of the device to the near edge of the pathway.	8D.03-02
The minimum mounting height for post-mounted signs on pathways shall be 4 feet, measured vertically from the bottom edge of the sign to the elevation of the near edge of the pathway surface.	8D.03-03
Pathway grade crossing traffic control devices shall be located a minimum of 12 feet from the center of the nearest track.	8D.03-04
The minimum sizes of pathway grade crossing signs shall be as shown in the shared-use path column in Table 9B-1.	8D.03-05
When overhead traffic control devices are used on pathways, the clearance from the bottom edge of the device to the pathway surface directly under the sign or device shall be at least 8 feet.	8D.03-06
If used at pathway grade crossings, the pathway stop line should be a transverse line at the point where a pathway user is to stop. The pathway stop line should be placed at least 2 feet further from the nearest rail than the gate, counterweight, or flashing-light signals (if any of these are present) is placed, and at least 12 feet from the nearest rail.	8D.04-01
Detectable warning surfaces that contrast visually with adjacent walking surfaces, either light-on-dark or dark-on-light, can be used to warn pedestrians about the locations of the tracks at a grade crossing. The “Americans with Disabilities Act Accessibility Guidelines for Buildings and	8D.04-04

Guideline	Reference
Facilities (ADAAG)" contains specifications for design and placement of detectable warning surfaces.	
Except as provided in Paragraph 2, where active traffic control devices are not used, a Crossbuck Assembly shall be installed on each approach to a pathway grade crossing.	8D.05-01
The Crossbuck Assembly may be omitted at station crossings and on the approaches to a pathway grade crossing that is located within 25 feet of the traveled way at a highway-rail or highway-LRT grade crossing.	8D.05-02
If used, swing gates shall be designed to open away from the track(s) so that pathway users can quickly push the gate open when moving away from the track(s). If used, swing gates shall be designed to automatically return to the closed position after each use.	8D.05-06
If used at a pathway grade crossing, an active traffic control system shall include flashing-light signals for each direction of the pathway. A bell or other audible warning device shall also be provided.	8D.06-01
Separate active traffic control devices may be omitted at a pathway grade crossing that is located within 25 feet of the traveled way of a highway-rail or highway-LRT grade crossing that is equipped with an active traffic control system.	8D.06-02
If used at pathway grade crossings, alternately flashing red lights shall be aligned horizontally and the light units shall have a diameter of at least 4 inches. The minimum mounting height of the flashing red lights shall be 4 feet, measured vertically from the bottom edge of the lights to the elevation of the near edge of the pathway surface.	8D.06-03
Automatic gates may be used at pathway grade crossings.	8D.06-06
If used at a pathway grade crossing, the height of the automatic gate arm when in the down position should be a minimum of 2.5 feet and a maximum of 4 feet above the sidewalk.	8D.06-07
If used, the gate configuration, which might include a combination of automatic gates and swing gates, should provide for full width coverage of the pathway on both approaches to the track.	8D.06-08

2.5.2 Relevant AASHTO Guidelines

Currently, the *AASHTO Guide for the Development of Bicycle and Pedestrian Facilities* provides extensive standards for the design of SUPs. AASHTO defines SUPs as "bikeways that are physically separated from motorized vehicular traffic by an open space or barrier and either within the highway right-of-way or within an independent right-of-way." SUP users include bicyclists of all ages, pedestrians, roller skaters, skateboarder, horses and riders, and many other modes. Section 5.3 of the guide outlines the current state of practice with regards to shared use path crossing design. This section categorizes SUP crossings into midblock, sidepath, and grade-separated crossings.[26]

Midblock crossings are defined as "located outside of the functional area of many adjacent intersections." The guide states that designing midblock crossings requires consideration of many variables including "mix and volume of path users, the speed and volume of motor vehicle traffic (…), the configuration of the road, the amount of sight distance that can be achieved (…), and other factors." A summary of guidelines as related to midblock crossings are as follows[26]:

- Must be conspicuous to road and path users
- Sight distance must be maintained to meet traffic control needs
- Intersections and approaches must be on flat grades
- Intersections must be as close to right angle as practical

The AASHTO midblock crossing guidelines also provide detailed standards to accommodate stopping sight distance for both roadway motorists and SUP users. Sight triangle guidance for SUP midblock crossings is outlined in the AASHTO *Guide for Development of Bicycle Facilities* Tables 6 and 7 (Figures 1 and 2 below). Specific crossing treatment specifications are left to engineering judgement; implementation of signals is outlined in the MUTCD.[26]

U.S. Customary

$$t_a = \frac{S}{1.47V_{path}}$$

$$t_g = t_a + \frac{w + L_a}{1.47V_{path}}$$

$$a = 1.47V_{road}t_g$$

where:

t_g	=	travel time to reach and clear the road (s)
a	=	length of leg sight triangle along the roadway approach (ft)
t_a	=	travel time to reach the road from the decision point for a path user that doesn't stop (s)
w	=	width of the intersection to be crossed (ft)
L_a	=	typical bicycle length = 6 ft (see Chapter 3 for other design users)
V_{path}	=	design speed of the path (mph)
V_{road}	=	design speed of the road (mph)
S	=	stopping sight distance for the path user traveling at design speed (ft)

Metric

$$t_a = \frac{S}{0.278V_{path}}$$

$$t_g = t_a + \frac{w + L_a}{0.278V_{path}}$$

$$a = 0.278V_{road}t_g$$

where:

t_g	=	travel time to reach and clear the road (s)
a	=	length of leg sight triangle along the roadway approach (m)
t_a	=	travel time to reach the road from the decision point for a path user that doesn't stop (s)
w	=	width of the intersection to be crossed (m)
L_a	=	typical bicycle length = 1.8 m (see Chapter 3 for other design users)
V_{path}	=	design speed of the path (km/h)
V_{road}	=	design speed of the road (km/h)
S	=	stopping sight distance for the path user traveling at design speed (m)

Figure 1. AASHTO Length of Roadway Leg of Sight Triangle[26]

U.S. Customary		
$t_a = \dfrac{1.47V_e - 1.47V_b}{a_i}$ $t_g = t_a + \dfrac{w + L_a}{0.88V_{road}}$ $b = 1.47V_{path}t_g$		
where:		
t_g	=	travel time to reach and clear the path (s)
b	=	length of leg sight triangle along the path approach (ft)
t_a	=	travel time to reach the path from the decision point for a motorist that doesn't stop (s). For road approach grades that exceed 3 percent, value should be adjusted in accordance with AASHTO's *A Policy on Geometric Design of Highways and Streets* (5)
V_e	=	speed at which the motorist would enter the intersection after decelerating (mph) (assumed 0.60 × road design speed)
V_b	=	speed at which braking by the motorist begins (mph) (same as road design speed)
a_i	=	motorist deceleration rate (ft/s^2) in intersection approach when braking to a stop not initiated (assume -5.0 ft/s^2)
w	=	width of the intersection to be crossed (ft)
L_a	=	length of the design vehicle (ft)
V_{path}	=	design speed of the path (mph)
V_{road}	=	design speed of the road (mph)

Metric		
$t_a = \dfrac{0.278V_e - 0.278V_b}{a_i}$ $t_g = t_a + \dfrac{w + L_a}{0.167V_{road}}$ $b = 0.278V_{path}t_g$		
where:		
t_g	=	travel time to reach and clear the path (s)
b	=	length of leg sight triangle along the path approach (m)
t_a	=	travel time to reach the path from the decision point for a motorist that doesn't stop (s). For road approach grades that exceed 3 percent, value should be adjusted in accordance with AASHTO's *A Policy on Geometric Design of Highways and Streets* (5)
V_e	=	speed at which the motorist would enter the intersection after decelerating (km/h) (assumed 0.60 × road design speed)
V_b	=	speed at which braking by the motorist begins (km/h) (same as road design speed)
a_i	=	motorist deceleration rate (m/s^2)in intersection approach when braking to a stop not initiated (assume -1.5 m/s^2)
w	=	width of the intersection to be crossed (m)
L_a	=	length of the design vehicle (m)
V_{path}	=	design speed of the path km/h)
V_{road}	=	design speed of the road km/h)

Note: This table accounts for reduced motor vehicle speeds per standard practice in AASHTO's ***A Policy on Geometric Design of Highways and Streets*** (5).

Figure 2. Length of Path Leg of Sight Triangle[26]

2.6 Other Traffic Control Guidelines

2.6.1 Traffic Control and Supplemental Yielding Guidance

A scan of municipal, regional, and national policies related to traffic control devices for SUP crossings and midblock crossings is summarized below. Most cities are dependent upon both the vehicular and pedestrian traffic present at the midblock crossing when justifying the use of Rectangular Rapid Flash Beacons (RRFBs) or Pedestrian Hybrid Beacons (PHBs). Other municipalities and countries have municipality-wide or country-wide policies requiring specific traffic control devices at specific crossings.

The NCDOT *Pedestrian Crossing Treatment Evaluation Guidance* outlines suggestions for when to include RRFBs, PHBs, and traffic signals at midblock pedestrian crossings.[28] Recommendations for installing additional treatments such as RRFBs, PHBs, and traffic signals for midblock crossings are outlined in Figure 3. Currently, engineers and planners are recommended to follow the flow-chart for pedestrian only crossings with the following conditions: two-lane roads with a posted speed limit greater than 40 mph or greater than 15,000 vpd; three lane or four lane roads with a raised median with posted speed limited greater than 40 mph or traffic volumes greater than 9,000 vpd or posted speed limits less than 30 mph with traffic volumes greater than 12,000 vpd; four+ lane roads without a raised median with posted speed limits greater than 35 mph or greater than 9,000 vpd. Guidance for PHBs follows MUTCD guidance for PHBs which is outlined in Figures 4 and 5.

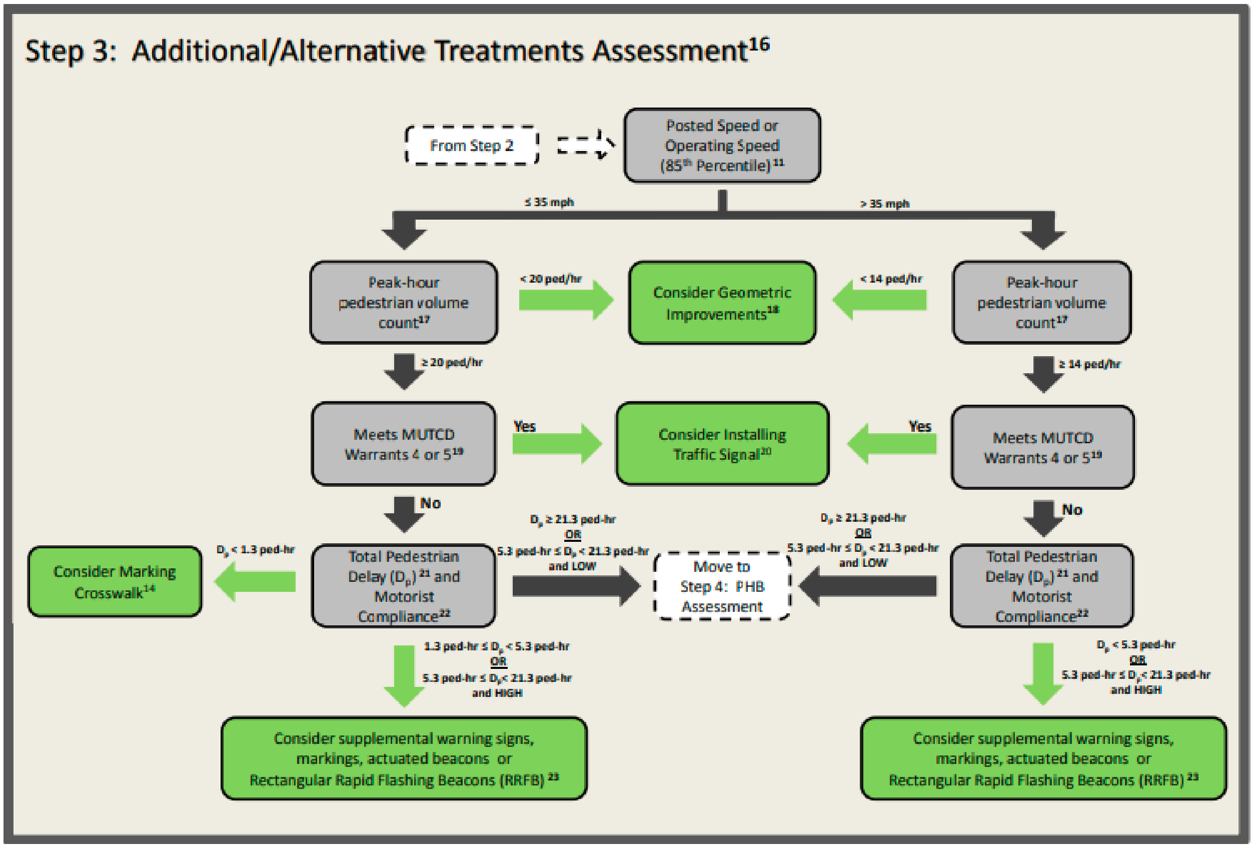

Figure 3. Guidance for Additional Treatments at Midblock Pedestrian Crossings[28]

Cary, NC requires RRFBs on all two to five lane roads with speeds between 35-45 mph. PHBs are optional at greater speeds depending on engineering judgment.[29] Some cities opt to only follow certain parts of the thresholds for PHB guidance from the MUTCD. For instance, Charlotte, NC refers to Figures 4F-1 and 4F-2 from the MUTCD in their guidance (Figures 4 and 5 below), but only for streets with an AADT greater than 12,000.[30]

Traffic control guidance from other municipalities and countries can be found in Appendix A.

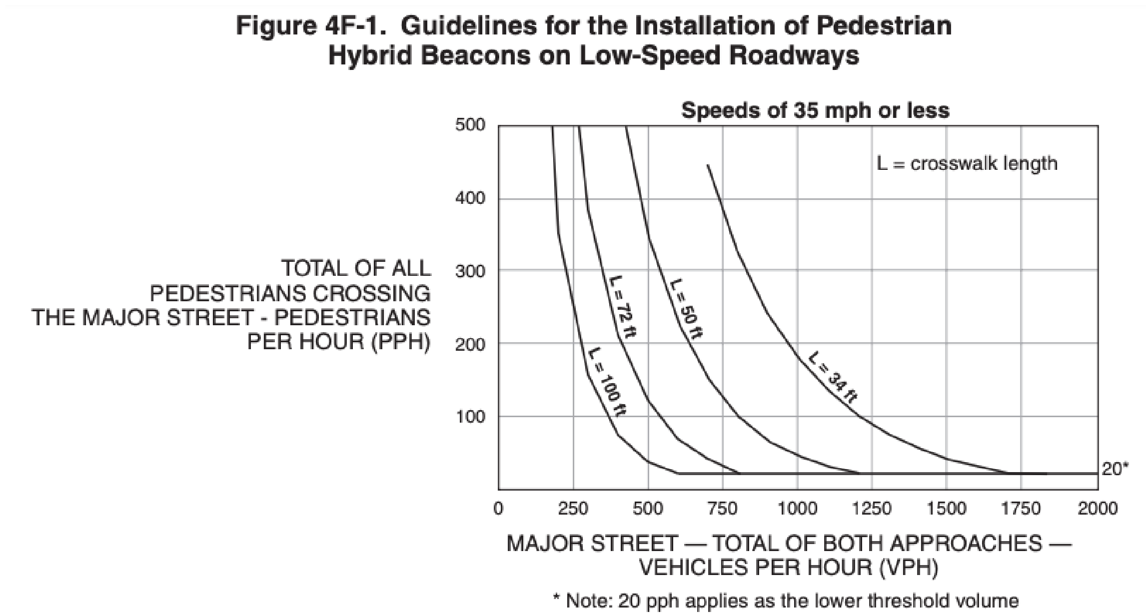

Figure 4. MUTCD PHB Guidelines for Streets < 35 mph[26]

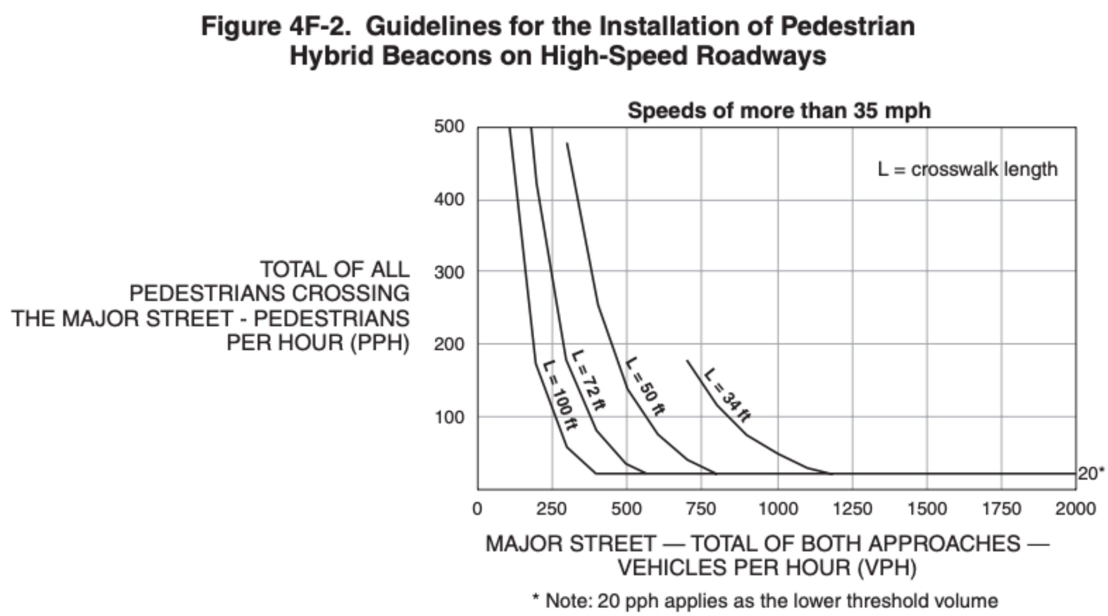

Figure 5. MUTCD PHB Guidelines for Streets > 35 mph[26]

2.6.2 Crosswalk Marking Policies and Guidelines

Charlotte, NC has different policies around crosswalk treatments depending on factors such as speed, number of lanes, and whether the SUP midblock crossing is in a residential area or not. All two to three lane roads require a ten feet wide longitudinal crosswalk with curb ramps on either side. The following provisions are recommended if the speed of vehicles is below 35 mph and required if the speed of vehicles is above 35 mph: rumble strips (in non-residential areas), speed tables (in residential areas), or high visibility pavement markings. Additionally, if there is a median present over six feet in width, the median should replace the center lane and be within 200 feet in either direction of the crossing. The crossing itself should be flush through the median and angled through the median to orient bicyclists and pedestrians towards oncoming traffic. Additionally, all four to five lane roads follow the same provisions as two to three lane roads, with the additional requirement that the crossing use an alternative pavement surface, and the city no longer outlines the use of speed tables.[30]

Other marking guidance and example markings can be found in Appendix A.

2.6.3 Signage Policies and Guidelines

Cary, NC requires that stop and warning signs be placed on trails as they approach a midblock crossing. Additionally, the city requires that fluorescent yellow-green trail warning signs be placed along the road approaching the crossing.[29] In Apex, fluorescent yellow-green pedestrian warning signs with a downward diagonal arrow are required at midblock SUP crossings, and additional signs may be required on a site-by-site basis.[31]

Other signage guidance and example markings can be found in Appendix A.

2.7 Grade Separation Policies and Guidelines

Town of Cary requires that a crossing be grade separated when crossing a controlled access facility. Otherwise, the town recommends grade separation when crossing a facility with design speed greater than 45 mph, four lanes or more, or poor horizontal or vertical site distances. Additionally, grade separation is recommended when the SUP has a high user volume.[29]

Town of Apex similarly requires a grade separation when crossing a controlled access facility. The town also provides recommendations for grade separation when crossing a facility with a speed limit of 45 mph or higher, four or more lanes, and high user volumes on the SUP. Apex also requires that the grade separated crossing be greater than 1,000 feet away from the nearest signalized crossing.[31]

Other grade separation guidance and example markings can be found in Appendix A.

2.8 Other Crossing Treatment Considerations

At-grade rail crossings may require additional considerations, but the research team was unable to identify specific municipal guidelines within North Carolina. Similarly, some agencies in North America have published policies on separating cross-rides (i.e., markings to extend a bicycle facility across a street) and crosswalks. Information on these different considerations can be found in Appendix A.

Some trails will use two low fences obstructing either side of the path to slow down bicycle traffic and make trail users aware they are approaching an intersection. While potentially effective, the spacing between the fences must be carefully considered to not hinder wheelchair users. Bicycles with trailers, recumbent bicyclists, and pedestrians with strollers could also be inconvenienced by choosing this method over traditional signage. Examples of intentional trail obstructions are included with examples of signage in Appendix A.

3 Site Selection Process

Based on the literature review, the research team devised a research approach to collect PET data on observed interactions between SUP travelers and motorists at 16 trail crossings with different roadway characteristics and crossing treatments. Separately, we scored each site using the Safe System SUP

Crossing Evaluation tool developed through this project. The relationship between the PET data and the Safe System scores were then analyzed. Analyzing this relationship, and variations in PET and Safe System scores among the different treatment category groups, provided a basis for determining potential decision guidelines for when different treatment types should be applied to SUP crossings.

Sites for evaluation in this study were selected based on a variety of operational and geometric characteristics as well as variation in representation across geographic regions in North Carolina. To identify a genuinely representative sample of sites for evaluation, the research team compiled a crossing inventory of all 76 available sites in the state. This section documents that process and decision criteria for sites included in the final evaluation.

3.1 Developing a Crossing Inventory

Researchers inventoried SUP and roadway crossings in North Carolina to determine existing options for roadway crossing treatments. Researchers started with a review of sites in the Pedestrian and Bicycle Infrastructure Network (PBIN) inventory and then conducted a desk review to identify potentially relevant sites. The desk review focused on significant SUPs with midblock crossings in North Carolina, including the American Tobacco Trail in Durham, Wake and Chatham Counties; the Blue Line Trail in Charlotte; the French Broad River Trail in Asheville; the Walnut Creek Trail in Raleigh; the Tar River Greenway in Greenville; Wilmington Cross City Trail in Wilmington; and the Isothermal Rail Trail in Rutherford County. The research team focused specifically on midblock crossing locations because pedestrian and bicyclist safety at SUP crossings at conventional intersections will be dictated by the intersection design and operational parameters (and may be assessed by existing tools like the SSI[25]). A total of 76 crossings were inventoried. The following levels of protection groups and subgroups were determined at the time of the inventory, although some have had alternate treatments installed since:

- No markings *(11)*
  - Note that completely unmarked crossings are not permitted by NCDOT, so these are standard crossings with no additional markings or noncompliant crosswalks.
- Markings
  - Stop Line *(1)*
    - Note that this site does not include advanced yield lines.
  - Alternative Pavement *(1)*
    - Note that this site has a different pavement material for the crossing that provides visual contrast.
  - Continental Crossings *(18)*
  - Ladder Crossings *(4)*
  - Ladder Crossings with Green Paint *(5)*
- Pedestrian Refuge Islands *(8)*
- Supplemented Yielding – Note that some sites have additional signage, and sites with crossing-related signage are not penalized for visual complexity in the Safe System SUP Crossing Evaluation too.
  - Rectangular Rapid Flash Beacons *(2)*
  - User Actuated Overhead Flashing Yellow Lights *(2)*
- Traffic Signal
  - User actuated traffic signal *(1)*

- Grade Separation
    - Underpasses *(13)*
    - Tunnels *(5)*
    - Pedestrian Bridges *(2)*
    - Pedestrian and Rail Bridges *(3)*

The crossing inventory highlighted that few trails in North Carolina exist with higher levels of trail user protection like traffic signals, stop signs, or PHBs at midblock sites. Most crossings consisted of simple continental crosswalk markings. Grade separation was often built due to the alignment of the trail along natural topography rather than primarily to protect trail users from motor vehicles; bridges previously built for motor vehicle traffic to cross a river or creek provided for trail underpasses when the trail was later constructed along the river or creek.

Researchers organized crossings based on available data by features that would likely affect the safety of trail users, such as crossing street's speed limit, traffic volume, and number of vehicle lanes. Groupings were influenced by the Zegeer et al. (2001) groupings for analyzing marked and unmarked crosswalks; number of lanes were subdivided further than the original Zegeer et al. grouping.[32] Results are highlighted in Table 8.

Table 8. SUP Crossings by Road Characteristic Group

Traffic Volume*	**Speed****	**Lanes*****	**Treatment**	**Total Crossings**
High	high	high	Grade Separation	4
high	high	med	Grade Separation	2
high	high	low	Grade Separation	1
high	med	med	Refuge Island	1
high	med	med	Traffic Control	1
high	med	med	Grade Separation	2
high	low	low	Markings	1
Med	high	low	Grade Separation	2
med	med	low	Grade Separation	1
med	low	low	Refuge Island	1
Low	high	low	Grade Separation	1
low	high	low	Supplemented Yielding	1
low	med	med	Grade Separation	3
low	med	low	No markings	4
low	med	low	Markings	3

Traffic Volume*	Speed**	Lanes***	Treatment	Total Crossings
low	med	low	Refuge Island	3
low	med	low	Supplemented Yielding	2
low	med	low	Grade Separation	1
low	low	med	Markings	2
low	low	med	Refuge Island	1
low	low	med	Grade Separation	4
low	low	low	No markings	4
low	low	low	Markings	14
low	low	low	Refuge Island	1
low	low	low	Grade Separation	1

* Traffic volume category is based on AADT(high = >15,000 vpd; medium = 12,000-15,000 vpd; low = <12,000 vpd)
**Speed is based on speed limit (high = 35-45 mph; medium = 25-35 mph; low = < 25 mph)
***Lanes is further derived from the Zegeer et al. (2001) parameters[32] (high = 5+ lanes; medium = 3-4 lanes; low = 2 or fewer lanes)

3.2 Site Selection

A primary goal of the site selection process was to ensure that a variety of crossing treatments were considered from a wide selection of different regions and land uses across North Carolina. After examining the *North Carolina Pedestrian Crossing Guidance*[33] and verifying treatment presence by visually inspecting potential study sites using Google Street View ® to confirm that the treatments matched those inventoried for the PBIN, the research team suggested prioritizing crossings along the American Tobacco Trail (ATT), the Blue Line Trail (BLT), and the Isothermal Rail Trail (IRT) due to existing relationships with planners associated with those trails. Additional crossings along other trails—such as the Walnut Creek Trail (WCT), the Cross City Trail (CCT), and the Tar River Greenway (TRG)—were chosen to ensure there was at least one crossing per treatment group. When possible, four crossings per treatment group were chosen to provide for variable speed and motor vehicle traffic volumes within each group. Crossings with no AADT available were defaulted to an AADT of 5,000. Some initially prioritized sites were not suitable to observe due to construction; others were changed because the on-site treatment had changed. Table 9 shows the locations of the crossings that were observed.

Table 9. Observed SUP Crossings Sites

Treatment Group	Location	Roadway	Traffic Volume	Posted Speed Limit	Lanes
Traffic Control	American Tobacco Trail	Fayetteville Street	15,500	35	3
Supplemented Yielding	American Tobacco Trail	West Woodcroft Parkway	9,500	35	2
Supplemented Yielding	American Tobacco Trail	East Cornwallis	8,700	45	2
Supplemented Yielding	Walnut Creek Trail	Gorman Street	16,500	35	4
Supplemental Yielding	Isothermal Rail Trail	East Main	8,700	20	2
Refuge Island	Blue Line Trail	Remount Road	14,000	35	2
Refuge Island	Walnut Creek Trail	Garner Road	11,500	35	3
Refuge Island	Cross City Trail	George Anderson Drive	5,000	25	2
Refuge Island	Walnut Creek Trail	Avent Ferry Road (Lake Johnson North)	8,500	35	2
Pavement Markings	Tar River Greenway	East 5th Street	12,000	35/25 (SZ)*	2
Pavement Markings	Blue Line Trail	New Bern Street	5,000	20	2
Pavement Markings	Isothermal Rail Trail	Duke Street	1,600	35	2
Pavement Markings	Isothermal Rail Trail	Withrow Road	5,400	35	2
No Markings	Isothermal Rail Trail	North Oak Street	5,000	20	3
No Markings	Isothermal Rail Trail	US Highway 64	4,300	35	2
No Marking	Walnut Creek Trail	Avent Ferry Road (Lake Johnson South)	8,400	35	2

* Variable speed limit due to school zone

4 Observational Video Data Collection

A camera was set up at each of the sites for at least two full days and generally for three to five days. The goal for each setup was to have the camera set up far enough away to give a view of vehicles traveling from both directions on the street, the crossing area, and some view of pedestrians and bicyclists approaching along the SUP.

When logistically possible, cameras were set up to observe both on weekdays and weekend days to gather a mix of commuter and recreational traffic from SUP users. The team tried to avoid days with inclement weather to maximize the numbers of SUP users; collection therefore began in March of 2022 and concluded in June 2022. Each camera had local storage which was collected, brought back to the ITRE offices, and downloaded. All safety precautions were duly observed during the data collection process and the staff answered the questions of any curious bystanders.

4.1 Video Reduction Methods

Data were extracted through a manual video review of each SUP crossing site. Coders reviewed footage at the same start-time of 3PM on Friday for each site and watched the subsequent daylight hours in chronological order until reaching 50 interaction events. A screenshot of the coding tool, as well as a brief description of the coding process, are included in Appendix C.

Coders examined every instance in which a SUP user attempted to cross the road at a crossing site. If no motor vehicle was present in the camera's field of view for the duration of the crossing, the crossing was not coded, though the SUP user was counted as part of the total pedestrian or bicycle count for the site.

When crossings occurred in the presence of a motor vehicle (i.e., one or motor vehicles was present in the camera's field of view), they were counted as interaction events and coded as follows:

- None - one or more motor vehicles were present at the time of the crossing but were too far away from the crossing to be relevant.
- Coexistence - the SUP user crossed in the presence of one or more motorists, but neither the SUP traveler nor the motorists altered their speed or trajectory in relation to each other.
- Avoidance - the SUP traveler attempted to cross the road and either they or a motorist altered their speed or trajectory in relation to each other (e.g., gradually slowed, stopped, or changed lateral positioning).
- Conflict - the SUP traveler attempted to cross the road and at least one traveler (SUP traveler, motorist, or both) exhibited a sudden change in speed or trajectory (e.g., hard braking, swerving) to prevent a crash.

Given the variation in usage across the study sites, the amount of time needed to reach 50 interactions varied. This variation in the number of hours of video coded per site allowed for variability in both the overall frequency of SUP users crossing each street (*crossing* event) and whether a motorist was also present at the time each crossing was attempted (*interaction* event). Interactions begin the moment the first traveler reaches the crosswalk, whether that is when the SUP user first attempts to cross the road, or when the first motor vehicle enters the crosswalk—whichever came first. The start of the interaction is marked in the data with a timestamp.

For each interaction, the SUP traveler's mobility type and the direction of the traveler and motorist were coded. Characteristics for each traveler were also coded. Characteristics included whether there were platoons for either the SUP traveler or motorist, and if the motor vehicle was large (i.e., a sport utility vehicle (SUV) or larger). When multiple SUP users are traveling as a group, they are considered part of the same *party* and coded as a single interaction. Multiple motor vehicles crossing or waiting to cross were considered a *platoon*. When coding interactions, the behaviors of each user in a platoon were taken into consideration to identify avoidance maneuvers.

For avoidance and conflict interactions, researchers coded whether there was a correct yield from the motorist. A correct yield was defined as the motorist slowing down or braking for the SUP traveler to cross the street. If the SUP traveler was approaching the crossing and was within the appropriate stopping sight distance and had to stop for the motor vehicle to pass, it was coded as an incorrect yield. Although the coexistence interaction does not involve a change in speed or direction, researchers coded incorrect yielding if they determined that the motorist should have stopped for the SUP traveler.

The last component recorded per interaction was the calculated PET. PET is the time between when a motor vehicle leaves the conflict zone and a pedestrian or bicyclist enters it (or the opposite if the pedestrian or bicyclist precedes the motor vehicle). The conflict zone was determined as the crossing area that both actors passed through at each site. If a SUP user passed first, researchers would calculate the elapsed time between when the SUP user exited the conflict zone and when the motorist entered the conflict zone. If a motorist passed the conflict zone first, researchers would then calculate the elapsed time between when the motorist's vehicle left the conflict zone and when the SUP user entered the conflict zone. If a SUP user was still in the conflict zone when a vehicle entered the conflict zone, or vice versa, the PET would be zero (note this does not mean a crash occurred, rather that both a motor vehicle and a SUP user were present in the crosswalk at the same time). PET was selected as the surrogate safety measure for this study because, as reported by Johnsson et al. (2018), research has generally shown a correlation between the conflicts indicated by a "critical" PET value and crash frequencies[20]. Although many of these correlations specifically related to vehicular interactions, a 2023 study by Anwari et al. specifically examined surrogate safety measures at midblock crossing locations in Florida. The authors modeled PET and other surrogate safety measures and concluded that pedestrian crossing treatments, like RRFBs, potentially improve safety by increasing the temporal gap between when vehicle and pedestrian trajectories intersect at crossing locations. The authors claimed that the temporal benefits provided by crossing treatments validated crash-based studies.[34] More critically for this study and its Safe System focus, pedestrian and bicyclist crashes tend to be rare events, and using only crash data rather than a more proactive measure like critical PET may cause sites where interactions between pedestrians and bicyclists are high risk to be missed in countermeasure selection.

At each site, researchers counted the number of vehicles, pedestrians, and cyclists that crossed or used the crossing during the allotted time. The counts were regardless of whether the vehicle, pedestrian, or cyclist were part of an interaction. Counts of each type of mode ended with the 50th interaction.

4.2 Summary of Recorded Data

Summary data of the statistics collected through video reduction are shown in Table 10. These data are grouped by treatment group and include:

- Percent of correct yielding behavior – the percentage of times that correct yielding behavior was observed out of all interactions per site.
- Percent large passenger vehicles observed – the percentage of observed vehicles that were either SUVs, pickup trucks, or larger. While NCDOT's GIS platform for AADT reports the annual average daily truck traffic for some roads, recent research indicates that SUV-sized vehicles are disproportionately more likely to kill or injure pedestrians in crashes than smaller personal vehicles (e.g., sedans) at speeds between 20 mph and 39 mph.[35]
- Total pedestrians observed – the total number of pedestrians counted crossing the roadway during the 50 interactions. Note that each pedestrian was counted even if a crossing platoon was recorded as only one interaction.
- Average pedestrians per hour – the total number of observed pedestrians divided by the time in hours to record 50 interactions. Note that in the case of the BLT & Remount crossing, 39 pedestrians were observed in half an hour, leading to an hourly rate of 78 pedestrians.
- Hourly pedestrian activity compared to median – the categorical activity level of pedestrian activity per treatment group. Due to the significant differences in pedestrian activity and time to identify 50 interactions between sites, a relative measure of activity level was assigned to each site based on the median value of pedestrians per treatment group. High, low, or no activity correspond to above the median, equal to or below the median, or absent, respectively. This

categorical grouping allows the Safe System tool to be calibrated for local conditions rather than measured against urban sites that may exhibit high demand.

- Total bicyclists observed – the total number of bicyclists counted crossing the roadway during the 50 interactions.
- Average bicyclists per hour – the total number of observed bicyclists divided by the time in hours to record 50 interactions.
- Hourly bicycle activity compared to median – the categorical activity level of bicyclist activity per treatment group, calculated using the same method as pedestrian activity.
- Time to record 50 interactions – the total time (in hours) required to code 50 interactions.
- Total avoidance maneuvers observed – the number of times a user had to make a trajectory adjustment to avoid a collision.

Note that no injuries were observed at any of the treatment sites, and the distribution of avoidance maneuvers, incorrect yielding behaviors, and large vehicles are widely distributed across all treatment groups. PET will be discussed in greater detail in Section 6, so it is excluded from Table 10.

Table 10. Summary of Recorded Data per Treatment Group

Treatment Type	Site Name	Percent Correct Yielding Observed	Percent Large Passenger Vehicles Observed	Total Pedestrians Observed	Average Pedestrians per Hour	Hourly Pedestrian Activity Compared to Median	Total Bicyclists Observed	Average Bicyclists per Hour	Hourly Bicycle Activity Compared to Median	Time to Record 50 Interactions (hours)	Total Avoidance Maneuvers Observed
Traffic Control/ Supplemental Yielding	ATT & Cornwallis	48.0	12.0	22	2	low	90	9	High	9.8	24
	ATT & Fayetteville	46.0	32.0	10	2	low	26	5	Low	5.3	23
	ATT & W Woodcroft	45.7	2.0	15	10	high	21	14	High	1.5	32
	WTC & Gorman*	60.0	18.0	32	8	high	11	3	Low	4.0	33
	IRT & East Main	20.4	30.6	16	1	low	37	3	Low	13.0	10
Refuge Island	WCT & Lake Johnson North	62.0	32.0	84	9	low	1	1	Low	9.3	31
	BLT & Remount	71.4	32.0	39	78	high	3	6	Low	0.5	38
	WCT & Garner	23.1	28.0	13	1	low	57	5	Low	10.7	24
	CCT & George Anderson	56.4	31.4	174	15	high	74	6	Low	12.0	27
Pavement Markings	IRT & Duke	16.7	38.0	31	3	low	170	14	High	12.5	16
	BLT & New Bern	72.0	44.0	56	28	high	9	5	Low	2.0	35
	TRG & East 5th	61.4	32.0	47	12	low	29	7	low	4.0	31
	IRT & Withrow	25.5	48.0	41	4	low	70	6	Low	11.7	18
No Markings	IRT & North Oak	14.7	32.0	23	2	low	150	13	low	11.5	20
	IRT & Highway 64	18.8	52.0	2	1	low	32	16	High	2.0	7
	WCT & Lake Johnson South	14.0	36.0	85	8	high	0	0	none	11.3	6

*Note that the WTC & Gorman SUP crossing has a PHB traffic signal, but a lack of motorist yielding was still observed.

5 Safe System Evaluation Methods

This section presents the steps taken to develop the Safe System SUP Crossing Evaluation tool. Instructions for using the tool are included in Appendix C. To develop the Safe System SUP Crossing Evaluation tool, researchers scanned available literature to identify roadway and operational characteristics that may influence pedestrian and bicyclist exposure to risk, that affect the potential severity of crashes that may occur, and that increase or decrease the likelihood for crashes to occur.[25,36] These characteristics, described as elements throughout this section, were then organized by which Safe System criterion to which they are most linked. Then, a weight was assigned to each element to produce a score for each Safe System criterion (i.e., an exposure criteria score, a likelihood criteria score, and a severity criteria score). Finally, these scores were then normalized on a scale of 1-4 (based on other Safe System evaluation frameworks[36]), and each criteria weight (e.g., an exposure criteria score equal to 8 will be normalized as an exposure weight of 3) was then multiplied to generate a final Safe System evaluation score. Note that pedestrians and bicyclists are scored separately per direction, and each criterion has an average of the two directions per pedestrians and per bicyclists. Finally, the Safe System evaluation score uses averages for the weights for pedestrians and bicyclists.

5.1 Scoring Elements

To develop the Safe System SUP Crossing Evaluation tool, researchers identified relevant geometric and operational data common to SUP sites. This initial list of elements were presented during an interim meeting, and additional elements were identified. Revisions were also made to the initial list, such as a clarification on the appropriate width necessary for a center median to count as a refuge island.

5.1.1 Data Elements

The common elements across SUP crossing sites include:

- Geometric and design elements of the site:
    - Functional classification of the roadway (i.e., local, collector, arterial)
    - Number of lanes in each direction
    - Lane width (per lane)
    - Presence of raised median
    - Median width
    - Presence of bicycle facilities
    - Presence of crossing treatment
    - Type of crossing treatment (e.g., traffic control or supplemental yielding)
    - Sight distance (per approach) for drivers
    - Sight triangles (or apparent obstructions) for SUP users
- Operational characteristics of the roadway
    - Speed limit
    - Operating speeds (or surrogate if unavailable)
    - Volumes per user type (during recorded periods) along both the road and the SUP.
    - Traffic composition (i.e., percent of larger passenger vehicles)
    - On-street parking (if any)
    - One-way or two-way flow of traffic
    - Conflicts between movements

- Roadway lighting
- SUP-related signage
- Additional signage not connected to SUP crossing but within stopping sight distance
- Access points

Linking these design and operational elements to scoring criteria produces:

- Elements that affect exposure:
  - Functional classification
  - Volumes of each user type
  - On-street parking
  - One-way or two-way flow of traffic
  - Conflicts between movements
  - Median width
  - Lane width
  - Number of lanes
- Elements that affect likelihood of crash:
  - Presence of median
  - Presence of bike facilities (note that bike facilities are not included in lane width)
  - Presence of crossing treatment
  - Type of crossing treatment
  - Sight distance
  - Sight triangles/trailhead visual obstructions
  - Roadway lighting
  - Signage
- Elements that affect severity of crash:
  - Speed limit
  - Operating speed
  - Traffic composition
  - Elements that affect SUP crossing complexity (e.g., access points and visual clutter) and may influence driver ability to decelerate

5.1.2 Assigning Element Scores

Elements were grouped into point values based on importance to safety. Although these point attributions involve some subjectivity, as they do in the Safe System frameworks used as the basis for this evaluation[36,37,5], researchers have attempted to distinguish between serious threats to safety and minor threats to safety (that may be considered threats to security or comfort), as done with red flags and yellow flags in NCHRP Report 948, i.e. the “20-Flags Method”.[38] The rationale for each scoring criterion is explained per item. A benefit of this Safe System SUP Crossing Evaluation tool is that the spreadsheet can be calibrated to local conditions or refined based on validation with crash data.

The elements assigned to the exposure category, grouped by small effect (1 point) or large effect (2 points) and linked to literature as possible, are shown in Table 11. There is a total of 14 possible points that can be applied for exposure in the Safe System SUP Crossing Evaluation tool.

Note that the pedestrian and bicycle volume measurements in this evaluation tool are qualitative rather than quantitative. There is limited research on what constitutes high, medium, or low pedestrian or bicycle volume. However, these qualitative values may be difficult to assign without ready access to pedestrian and bicyclist field counts at a crossing location. To the extent possible, practitioners should consider using any local counts available, but if those counts are unavailable, the qualitative value could potentially be assigned by assuming a range of volumes measured in this project based on treatment type. Those ranges based on Table 10, are shown in the corresponding cells in Table 11.

Table 11. Scoring Considerations and Rationale for Exposure

Exposure Effect	Consideration for Element	Rationale for Inclusion and Point Assignment
Small (1 point)	The functional classification is collector or higher order	This item is included to capture an element of driver expectation regarding mobility and pedestrian/bicyclist presence. The Movement and Place framework demonstrates that roads that serve to provide high movement (arterials) or to connect these corridors to streets with high pedestrian and bicyclist activity should avoid intersecting pedestrian and bicyclist movements.[5]
Small (1 point)	The average lane width is greater than 12 feet	If 12-ft lanes are assumed to be standard for vehicular traffic, lane widths narrower than this thereby have lower physical exposure and take less time to cross. Crossing width is a criterion for consideration in pedestrian exposure risk in the Austroads Safe System Matrix.[36]
Small (1 point)	The median width is insufficient for multiple waiting pedestrians or bicyclists	During a meeting with the StIC, it was pointed out that only physical medians greater than or equal to 6-ft in width count as refuge islands, so anything less than this serves as an additional point of exposure for crossing pedestrians and bicyclists if they are not able to adequately wait on the refuge.
Small (1 point)	There is on-street parking on at least one side of the street	Striped parking has a positive association with midblock pedestrian crashes[9], but these parking lanes do not facilitate high speed vehicular traffic to the same extent as travel lanes.
Large (2 points)	There are numerous reported conflicts/ interactions at this site	Conflicts are the critical measure of exposure in the FHWA SSI calculation.[25]
Large (2 points)	Pedestrians and bicyclists must cross more than one lane on this side of the street	Multilane crossings may be either yellow or red flags in the 20 Flags framework.[38]
Large (2 points)	Motorized traffic volume is high	Motor vehicle traffic is a key consideration in the Austroads Safe System Matrix, where exposure is assigned a score of 3 or 4 if AADT is above 5,000 vpd or 10,000 vpd, respectively.[36] However, the Zegeer crossing categories use cutoffs of 12,000 vpd and 15,000 vpd for treatment groups 2 and 3,[32] so the SUP Safe System tool assigns 1 point if vehicular volume per lane is greater than or equal to 6,000 vpd (so slightly greater than that required by Austroads) and 2 points if greater than or equal to 7,500 vpd.
Large (2 points)	Pedestrian volume is high	The Austroads Safe System matrix assigns 2 points if there are more than 10 pedestrians per day.[36] In this SUP Safe System framework, high pedestrian activity is assigned 2 points, while low pedestrian activity is assigned 1 point (and none is assigned 0 points).

		Potential breakpoints for pedestrian hourly activity based on Table 10 by treatment group are: • No markings: low ≤ 2 < high pedestrians per hour • Pavement markings: low ≤ 8 < high pedestrians per hour • Refuge island: low ≤ 12 < high pedestrians per hour • Traffic control: low ≤ 2 < high pedestrians per hour
Large (2 points)	Bicycle volume is high	The Austroads Safe System matrix assigns 2 points if there are more than 10 bicyclists per day.[36] In this SUP Safe System framework, high bicyclist activity is assigned 2 points, while low bicyclist activity is assigned 1 point (and none is assigned 0 points). Potential breakpoints for pedestrian hourly activity based on Table 10 by treatment group are: • No markings: low ≤ 13 < high bicyclists per hour • Pavement markings: low ≤ 6.5 < high bicyclists per hour • Refuge island: low ≤ 12 < 5.5 high bicyclists per hour • Traffic control: low ≤ 5 < high bicyclists per hour
Large (2 points)	Traffic flow is two-way	Research shows a negative association between one-way traffic flow and pedestrian collisions at night.[9]

The elements assigned to the likelihood category, grouped by small effect (1 point) or large effect (2 points) and linked to literature as possible, are shown in Table 12. There is a total of 12 possible points that can be applied for likelihood in the Safe System SUP Crossing Evaluation tool.

Table 12. Scoring Considerations and Rationale for Likelihood

Likelihood Effect	**Considerations for Element**	**Rationale for Inclusion and Point Assignment**
Small (1 point)	There is limited roadway lighting at the crossing location	Schneider et al. (2021) highlighted multiple studies that link darkness or poor visibility to pedestrian risk[10], but the exact relationship between lighting and pedestrian safety is complex (and sometimes counterintuitive.[9]
Small (1 point)	There are no warning signs ahead of the crossing location	In the 20 Flags framework, sight distance for gap acceptance movements is a red flag for pedestrians and bicyclists. The framework suggests that stopping sight distance must be provided.[38] This item is only 1 point rather than 2 because signs are a component of ensuring adequate stopping sight distance, but there may be other elements of the crossing that can also warn that a crossing is ahead.
Large (2 points)	There is no median	Two-way left-turn lanes are positively associated with pedestrian crashes at midblock and under dark conditions.[9]
Large (2 points)	There is no crossing treatment (beyond simple markings)	This is a variable that effectively allows users to adjust the score for treatment type.
Large (2 points)	Bike facilities intersect the crossing location	If a crossing pedestrian or bicyclist is struck by a bicyclist on the roadway, they may be knocked into the path of motor vehicle traffic, so this item is considered a component of crash likelihood.
Large (2 points)	Sight distance for path users is limited at this location	In the 20 Flags framework, sight distance for gap acceptance movements is a red flag for pedestrians and bicyclists. The framework suggests that intersection sight distance must be provided.[38]

Large (2 points)	Sight triangles for motorists are limited at this location	In the 20 Flags framework, sight distance for gap acceptance movements is a red flag for pedestrians and bicyclists. The framework suggests that view angles must be provided.[38]

The elements assigned to the severity category, grouped by small effect (1 point) or large effect (2 points) and linked to literature as possible, are shown in Table 13. There are 7 possible points that can be applied for severity in the Safe System SUP Crossing Evaluation tool.

Table 13. Scoring Considerations and Rationale for Severity

Severity Effect	**Considerations for Element**	**Rationale for Inclusion and Point Assignment**
Small (1 point)	There are indicators (such as observed yielding behavior) that drivers are less likely to decelerate to safer impact speeds at the SUP crossing	Given that speed limit is not a perfect approximation of impact speed, an item was introduced following the StIC interim meeting to account for the lack or presence of vehicle deceleration.
Small (1 point)	There are access points that make the crossing location complex	The SSI includes methods to account for intersection complexity and user mental workload and how those relationships may affect crash risk.[25] Although the complexity term was not directly incorporated into the Safe System SUP tool, following the StIC interim meeting, a term that attempts to account for how access points may increase the complexity of a crossing site and draw driver attention away from crossing pedestrians and bicyclists, thereby leading to a lack of deceleration, was introduced. The cutoff point for access points increasing the complexity of the site is greater than 3 access points within the stopping sight distance on a particular approach. Access points are a yellow or red flag within the 20 Flags framework.[38]
Small (1 point)	There are traffic control devices or signs unrelated to the SUP crossing that make the crossing location complex	The SSI includes methods to account for intersection complexity and user mental workload and how those relationships may affect crash risk.[25] Although the complexity term was not directly incorporated into the SUP Safe System tool, following the StIC interim meeting, a term that attempts to account for how additional signs and traffic control devices may increase the complexity of a crossing site and draw driver attention away from crossing pedestrians and bicyclists, thereby leading to a lack of deceleration, was introduced. The cutoff point for additional traffic devices increasing the complexity of the site is greater than 2 devices within the stopping sight distance on a particular approach.
Large (2 points)	The speed limit exceeds 30 mph	Velocity is one of the two key components of kinetic energy. The SSI shows an estimated 51.8% risk of serious injury at approximately 33 mph.[25] Given the uncertain link between impact speed and posted speed limit, 30 mph is used as a threshold for 2 points.
Large (2 points)	The traffic composition at least 30% large vehicles	Mass is the other key component of kinetic energy. The relationship between SUVs and the risk of a pedestrian suffering a death or serious injury in a crash[35] was previously noted. A traffic composition of 30% larger vehicles is proposed as a cutoff point.

After each element was assigned a weight, a Microsoft Excel workbook was created that links to a Safe System SUP Crossing Checklist. The workbook fills in the appropriate weights per element within the appropriate Safe System criteria tables per pedestrian per direction based on the information provided in the checklist. The workbook then computes an average criterion score per road user type, normalizes those scores as the criteria weights, and then returns the Safe System evaluation score. The exposure, The Safe System SUP Crossing Checklist is shown in Appendix C.

Figure 6 below details the element weights across each Safe System criterion. Note that the element scores are calculated per SUP approach per user type to allow for variations in pedestrian and bicyclist activity. The scores are then averaged for the overall site criteria scores.

After the total criteria scores were calculated, researchers then normalized those scores so that a Safe System evaluation score could be calculated as the product of each criteria weight. The scores were normalized into weights to follow the format used in other frameworks (e.g., the Austroads Framework[35]) and so that no Safe System criterion exerts more influence on the final score than others. However, a future direction for research may be to examine the weights in light of the results of this project and other future evaluations and to recalculate the weights as necessary. The conversion between the criteria Scores and criteria weights is shown in Table 14. Note that no weights equal to zero are possible to avoid the conclusion that sites with zero pedestrian or bicyclist traffic are inherently safe.

Table 14. Criteria Scoring Matrix

Weight	Exposure	Likelihood	Severity
1	Criterion score 1-3	Criterion score 1-3	Criterion score 1
2	Criterion score 4-6	Criterion score 4-6	Criterion score 2-3
3	Criterion score 7-10	Criterion score 7-9	Criterion score 4-5
4	Criterion score 11-14	Criterion score 10-12	Criterion score 6-7

Researchers designed the Safe System SUP Crossing Evaluation tool to return both criteria scores and a final Safe System evaluation score so that users can see which criteria (and ultimately, which elements within that criteria) most affect the total score to make countermeasure selection easier. The final possible scores are summarized in Table 15.

Table 15. Final Safe System Scores

Criterion	Pedestrians	Bicyclists	Safe Systems Score
Exposure	/4	/4	Average/4
Likelihood	/4	/4	Average/4
Severity	/4	/4	Average/4
Product	/64	/64	Average/64

	All			
	Direction 1		Direction 2	
	Ped	Bike	Ped	Bike
Exposure Criteria				
Small effect (1 point each)				
§ The functional classification is collector or higher order	1	1	1	1
§ The average lane width is greater than 12 feet	0	0	0	0
§ The median width is insufficient for multiple waiting pedestrians or bicyclists	1	1	1	1
§ There is on-street parking on this side of the street	1	1	1	1
Large effect (2 points each)				
§ There are numerous reported conflicts/interactions at this site	0	0	0	0
§ Pedestrians and bicyclists must cross more than one lane on this side of the street	0	0	0	0
§ Motorized traffic volume is high	0	0	0	0
§ Pedestrian volume is high	0	[redacted]	0	[redacted]
§ Bicycle volume is high	[redacted]	0	[redacted]	0
§ Traffic flow is two-way	0	0	0	0
Exposure Criteria Total	3	3	3	3
Pedestrian Exposure Average		3		
Bicyclist Exposure Average		3		
Likelihood Criteria				
Small effect (1 point each)				
§ There is limited roadway lighting at the crossing location	0	0	0	0
§ There are no warning signs ahead of the crossing location	0	0	0	0
Large effect (2 points each)				
§ There is no median	0	0	0	0
§ There is no crossing treatment (beyond simple markings)	0	0	0	0
§ Bike facilities intersect the crossing location	0	0	0	0
§ Sight distance for path users is limited at this location	0	0	0	0
§ Sight triangles for motorists are limited at this location	0	0	0	0
Likelihood Criteria Total	0	0	0	0
Pedestrian Likelihood Average		0		
Bicyclist Likelihood Average		0		
Severity Citeria				
Small effect (1 point each)				
§ There are indicators (such as observed yielding behavior) that drivers are less likely to decelerate to safer impact speeds at the SUP crossing	0	0	0	0
§ There are access points that make the crossing location complex	0	0	0	0
§ There are traffic control devices or signs unrelated to the SUP crossing that make the crossing location complex	0	0	0	0
Large effect (2 points each)				
§ The speed limit exceeds 30 mph	0	0	0	0
§ The traffic composition is at least 30% large vehicles.	0	0	0	0
Severity CriteriaTotal	0	0	0	0
Pedestrian Severity Average		0		
Bicyclist Severity Average		0		

Figure 6. Safe System Criteria Scoring Tables in the Safe System SUP Crossing Evaluation Tool

6 Analysis Results

This section presents the statistical analysis methods and analytical results used to test the relationships between PET, Safe System scores, and treatment group.

6.1 Variables

Throughout this section, common variables will be referenced by the variable name.

6.1.1 Recorded Data

These variables (shown in Table 16) were collected through observation of video-recorded interactions at each of the 16 sites. Two of the variables in this dataset, logPET and CritPET, were used as dependent variables in the modeling process to determine potential decision guidelines for selecting appropriate treatments at crossing locations. The other variables provided context to the findings and/or were used in evaluating the crossing sites using the Safe System SUP Crossing Evaluation tool.

Table 16. Recorded Data Variables

Variable Name	Variable Definition	Numeric or Categorical
PET	Post-encroachment time	Numeric
logPET	Logarithmic transform of PET	Numeric
CritPET	Flag for whether the PET was critical or not	Categorical
Action	Action taken to avoid collision	Categorical
YieldParty	Indicator of who the yielding party was during an interaction	Categorical
Cyield	Flag for whether the yielding action was correct	Categorical
NumPedInv	Number of pedestrians involved in the interaction	Numeric
NumBikInv	Number of bicyclists involved in the interaction	Numeric
LargeVeh_bin	Flag for whether the vehicle involved in the interaction was large	Categorical

6.1.2 Site Characteristic Data

These variables (shown in Table 17) were recorded through a desk review of sites using Google Maps® or by identifying common traffic characteristics at the site using the video-recorded data. A limited set of the variables—TreatType, AADT, and SpeedLim—were used in the statistical modeling process as independent variables to determine decision guidelines for selecting appropriate treatments at crossing locations. The other variables were used in evaluating the crossings sites using the Safe System SUP Crossing Evaluation tool.

Table 17. Site Characteristic Variables

Variable Name	Variable Definition	Numeric or Categorical
Fun_Class	Functional classification of the roadway	Categorical
MaxLNum	Maximum number of vehicular lanes on either approach	Numeric
MaxLWidth	Maximum lane width of vehicular lanes on either approach	Numeric
TreatType	Crossing treatment type	Categorical
AADT	Annual average daily (vehicular) traffic	Numeric
HourlyP	Hourly average of crossing pedestrians during the period of recorded video	Numeric
HourlyB	Hourly average of crossing bicyclists during the period of recorded video	Numeric
Light_class	Indicator variable for whether a light source was visible from the trailhead on no, one, or both sides of the crossing	Categorical
SpeedLim	Speed Limit	Categorical
SSD_class	Indicator variable for whether the crossing sign was adequately placed to allow vehicles to come to a complete stop within the necessary stopping sight distance for the posted speed limit on no, one, or both approaches of the crossing	Categorical

Variable Name	Variable Definition	Numeric or Categorical
SightTri_class	Indicator variable for whether there were clear sight triangles for vehicles approaching the crossing on no, one, or both approaches.	Categorical
SightObs_class	Indicator variable for whether there were sight obstructions for crossing pedestrians and bicyclists on no, one, or both trailheads.	Categorical
BL_class	Indicator variable for whether a bicycle lane intersected the crossing on no, one, or both approaches.	Categorical
AccessTot	Total number of access points between both approaches	Numeric
TraffDType	Total number of additional traffic control signs or devices within the stopping sight distance of the trail crossing between both approaches	Numeric
NumCrit	Total number of critical conflicts measured per site, based on the CritPET variable	Numeric

6.1.3 Safe System Variables

The following score variables (shown in Table 18) were produced using the Safe System SUP Crossing Evaluation tool. These scores are subjective assessments of site and operational characteristics based on the general risk equation:

$$Risk = Exposure * Likelihood * Severity \quad (1)$$

Table 18. Safe System Evaluation Variables

Variable Name	Variable Definition	Numeric or Categorical
ExpScore	Exposure Criteria Score	Numeric
LikScore	Likelihood Criteria Score	Numeric
SevScore	Severity Criteria Score	Numeric
SSEScore	Safe System Evaluation Score	Numeric

Note that the Safe System scores may be correlated with some site and operational characteristics, but this potential correlation is difficult to accurately model given the categorical nature of many of the variables and the translational nature of the Safe System scores. For these reasons, multiple models were tested for each research question using the separate variable sets.

6.2 Analytical Approach

The goal of this project is to produce Safe System-based guidance for identifying the most appropriate crossing treatments at shared use path crossing sites in North Carolina. To develop this guidance, three statistical modeling approaches were undertaken to answer related research questions, including:

1. Can a practitioner predict the PET between road users at crossing sites?
2. Can a practitioner determine the odds of a particular conflict being critical?
3. Can the Safe System Evaluation framework, using inputs from the site characteristic and video recording datasets, be used to determine potential criteria for selecting different treatment types at different crossing locations?

To answer research question 1, a linear regression model was used, generally following Equation 2:

$$logPET = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n \quad (2)$$

Where:
logPET = the response variable (in this case, the logarithmic transform of the time between intersecting road users)
β_0 = the intercept of the model
β_n = the coefficient of variable n
x_n = the value of variable n

A linear regression model can be used to identify statistically significant variables (those with p-values less than or equal to 0.05, indicating 95% confidence in the model results). These statistically significant variables can help practitioners identify different operational and site characteristics that may correspond to high or low values of logPET and that therefore may indicate potential risk factors.

The rationale for using logPET rather than PET was an assessment of the distribution of the data. Note that the PET values—aside from some extreme outliers where crossing road users needed to wait a long time to cross—are largely clustered around 0-5 seconds. This results in a skewed, rather than normal distribution, as can be seen in Figure 7.

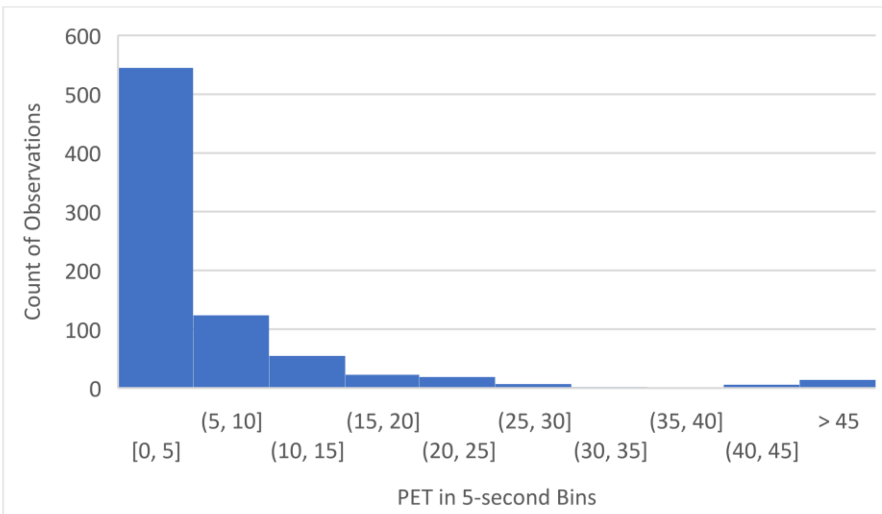

Figure 7. Histogram of PET

Unfortunately, linear regression depends on an assumption of normality. One method for dealing with a lack of normality is to transform data. In this case, a logarithmic transform of PET will produce a mostly normal distribution, as can be seen in Figure 8. Note that the logarithmic transform used is the natural log, and that the natural log of 0 is undefined. Therefore, a first step was taken to round conflicts where PET = 0 seconds (interactions where both motor vehicles and crossing pedestrians and bicyclists were simultaneously present in the crosswalk) to 0.01 first before the logarithmic transform was applied. There are still a few outliers in the data at these sites with extremely small PET values, but the distribution shown in Figure 8 is more normal and can likely be predicted in linear regression.

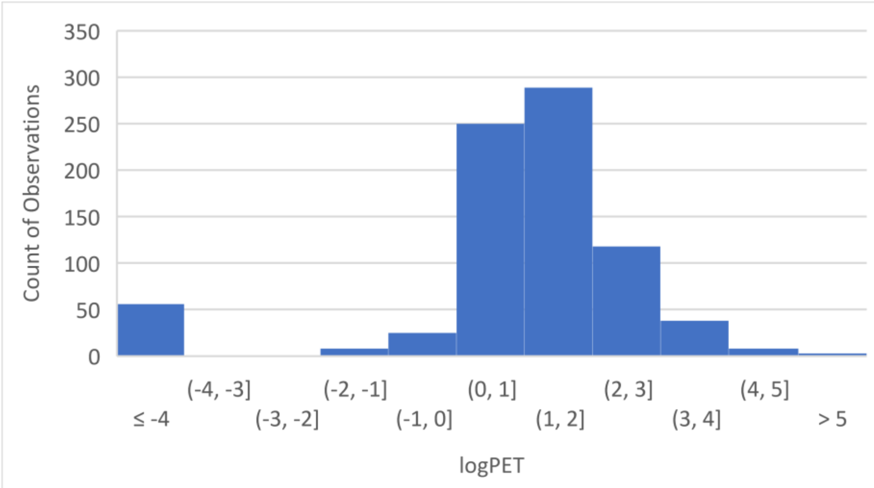

Figure 8. Histogram of LogPET

It is worth noting that the prediction of logPET does complicate the interpretation of results. For this reason, the discussion focuses on the general sign and association of independent variables rather than on the magnitude of the effects. Note that a mix of forward and backward regression was used to identify statistically significant variables. Model fit was assessed using the r^2 statistic that generally conveys how much of the variance of the model the selected variables explain. Low r^2 values are common in road safety research. In the case of different sets of statistically significant variables providing a sound model fit, the set of variables that provided the greatest r^2 statistic were selected, although only a limited set of input variables are presented below to focus on treatment criteria.

To answer research question 2, logistic regression models were developed. Logistic regression can be used when the response variable is categorical; statistically significant variables indicate the log odds of the selected outcome occurring in comparison to one or more alternative outcomes. For this research question**,** CritPET is the response variable, and the outcome being modeled is the log odds of a conflict being critical (PET < 1.5 seconds).[21]

$$log\,\frac{\Pr\,(Y=critical)}{\Pr\,(Y=non-critical)} = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n \qquad (3)$$

Where:
Pr(Y=critical) = the probability of a conflict being critical
Pr(Y=non-critical) = the probability of a conflict being non-critical
β_0 = the intercept of the model
β_n = the coefficient of variable n
x_n = the value of variable n

Using Equation 3, the odds ratio of any of the independent variables can be calculated as:

$$OR = Exp(\beta) = \frac{\beta_{critical}}{\beta_{non-critical}} \qquad (4)$$

Where:
OR = the odds ratio for an individual independent variable’s coefficient
β = the ratio of the coefficient estimates for critical PET to non-critical PET

When interpreting the results of a logistic regression model, the sign of the coefficient indicates whether that variable increases the log odds of the PET being critical (+) or the log odds of PET being non-critical (-). Model fit was assessed using the Akaike Information Criterion (AIC); lower AIC values indicate better fit.

The final modeling approach taken was to visually assess the Safe System (and related criteria) scores for each of the 16 sites by examining the box and whisker plots (i.e., the plots showing mean and standard deviations for each Safe System criteria score by treatment type) coupled with insights from the regression models. This analysis involved an examination of primarily median scores. This analysis is discussed in Section 7 to explain the final recommendations provided for selecting treatments.

For the two regression modeling approaches, a multi-stage approach was taken:

1. Develop a model using recorded data and site characteristic variables
2. Develop a model using Safe System scores
3. Develop a combined model of both site characteristics and Safe System scores

As the Safe System scores are derived by examining site characteristics and recorded data, it may be helpful to practitioners to use those data collected in desk reviews to identify sites where critical interactions occur. Conversely, the Safe System scores convey more generalized information about risk factors and the magnitude of issues that may correspond to critical interactions. If practitioners only have access to a more subjective Safe System assessment (e.g., AADT, speed limit, and crossing demand), they may still be able to determine an appropriate crossing treatment after quickly examining the site.

6.3 Results

6.3.1 Linear Regression

For all of the linear regression models developed, the sample included 800 interactions recorded across the 16 sites. PET is the response variable.

Site Characteristic Modeling

As mentioned, the goal of this linear regression model is to determine the relationship between primary site characteristics (AADT, speed limit, treatment type, number of lanes, lane width, and functional classification) that affect logPET in order to determine potential treatment type criteria. Forward and backward regression methods were tested to identify statistically significant variables at the p=0.05 level, and multiple sets of variables were tested and compared using both statistical significance and the r^2 criteria to determine the most useful set of explanatory variables that can provide insight into treatment selection. Table 40 in the Appendix summarizes the site characteristic variable sets, as well as decision criteria, tested.

The most relevant model for determining the relationship between logPET and site characteristics and that may be useful for setting treatment type guidance is the model using only TreatType as the independent variable. Table 19 shows the effects of the different treatment type categories on logPET. Compared to traffic control/supplemental yielding, which is used as the reference category, no pavement markings and refuge islands are negatively associated with logPET, indicating that the time between vehicles and pedestrian and bicyclists crossing the site decreases as the caliber of treatment decreases. The intercept was also statistically significant for this model.

Table 19. Effects of Treatment Type on logPET

Variable	Category	Coefficient	Standard Error	P-value
TreatType	NoMark	-0.193418881	0.10256603	0.0597
	PaveMark	-0.554905316	0.09577480	<.0001
	RefIsland	-0.832379391	0.09249566	<.0001
	TraffCon	Base category	-	-
Intercept	-	1.729348084	0.09249566	<.0001

Safe System Modeling

Three of the Safe System scores—the exposure score, the likelihood score, and the total Safe System score—were statistically significant for predicting logPET. Exposure corresponded to an r^2 value of 0.048451, which is the best fit of the different Safe System variables taken individually, so only the exposure-only model is highlighted in Table 20. Exposure was positively associated with logPET. This result is counterintuitive but likely aligns with the results of the TreatType model discussed previously. As the exposure score of a crossing increases, the logPET seems to increase as well. A possible explanation for this finding may be that the sites that tend to have roadway characteristics that can impact exposure (e.g., larger lane widths, more lanes to cross, higher traffic volumes, etc.) all tend to be associated with sites that already have higher-order crossing treatments (like traffic control devices and medians). Therefore, practitioners often already compensate high exposure risk with improved crossing treatments, thereby providing conditions in which PET can be longer.

Table 20. Effects of Exposure Score on logPET

Variable	Category	Coefficient	Standard Error	P-value
ExpScore	-	0.1591835967	0.02596780	<0.0001
Intercept	-	0.0716148332	0.21174542	0.7353

A model including all Safe System scores was also attempted, but the likelihood score was not statistically significant in this model. The signs of the variable coefficients in Table 21 indicate that a high severity score corresponds to a lower logPET; the exposure score and Safe System score work in the opposite direction of the severity score, but with lower magnitudes. These results may indicate that exposure and the Safe System score are capturing some site effects that increase logPET.

Table 21. Effects of Exposure Score, Severity Score, and Safe System Score on logPET

Variable	Category	Coefficient	Standard Error	P-value
ExpScore	-	0.0845350647	0.02799494	0.0026
SevScore	-	-.2286516241	0.04587391	<.0001
SSEScore	-	0.0428155101	0.00673904	<.0001
Intercept	-	0.9668655323	0.27234610	0.0004

Combined Modeling

Combined models of site characteristics and Safe System scores were also tested. Because functional classification obfuscated the effects of treatment type, it was excluded from this set of models. Lane width and number of lanes were also excluded because they were not statistically significant previously. However, all Safe System-relevant scores were retested.

The t-comparison effects of a model with TreatType, SpeedLim, ExpScore, SevScore, and SSEScore can be seen in Table 22. All treatment types are associated with lower logPET when compared to traffic control/supplemental yielding. A 25 mph speed limit is positively associated with logPET compared to 35 mph speed limits, perhaps because these lower speed limit sites are associated with decreased risk. Both the exposure score and severity score are negatively associated with logPET, perhaps indicating greater risks when these scores are high; the Safe System score conveys the opposite effect but has a much lower magnitude. This counterintuitive result may indicate that the Safe System score in this model is capturing some other protective effects of the sites.

Table 22. Effects of Treatment Type, Speed Limit, Exposure Score, Severity Score, and Safe System Score on logPET

Variable	Category	Coefficient	Standard Error	P-value
TreatType	NoMark	-1.192333974	0.21346230	<.0001
	PaveMark	-1.198075191	0.17093113	<.0001
	RefIsland	-0.974860407	0.13693953	<.0001
	TraffCon	Base category	-	-
SpeedLim	20	0.068860723	0.13802477	0.6180
	25	0.381235255	0.17347919	0.0283
	45	-0.307352265	0.18188551	0.0915
	35	Base category	-	-
ExpScore	-	-0.178030031	0.05946597	0.0028
SevScore	-	-0.186647731	0.06854954	0.0066
SSEScore	-	0.077255070	0.01253374	<.0001
Intercept	-	3.100311139	0.63250584	<.0001

The t-comparison effects of a slightly different model that excludes the SSEScore can be seen in Table 23. Although the model fit is worse than that of the model shown in Table 22, the model in Table 23 may provide more utility to practitioners, as its results may more easily indicate decision guidance for treatments and because the Safe System score itself may be correlated with both exposure score and severity score. As with the model in Table 22, all treatment types are associated with lower logPET when compared to traffic control/supplemental yielding. Additionally, the two lower speed limits (20 and 25) are associated with higher logPET than 35 mph. AADT is also negatively associated with logPET, indicating that PET may decrease as traffic volume increases. Contrastingly, both Safe System criteria now have opposite coefficient signs as they did in the model in Table 22, perhaps indicating a countereffect to the other site characteristics. The intercept for this model is not statistically significant.

Table 23. Effects of Treatment Type, Speed Limit, AADT, Exposure Score, and Severity Score on logPET

Variable	Category	Coefficient	Standard Error	P-value
TreatType	NoMark	-.2964409602	0.14705573	0.0442
	PaveMark	-.6720329003	0.14876881	<.0001
	RefIsland	-.6786913835	0.13485432	<.0001
	TraffCon	Base category	-	-
SpeedLim	20	0.4585738493	0.12565734	0.0003
	25	0.5502123463	0.18039659	0.0024
	45	0.1379822710	0.16771571	0.4109
	35	Base category	-	-
AADT	-	-.0000365788	0.00001563	0.0196
ExpScore	-	0.1699393022	0.04422019	0.0001
SevScore		0.1581331220	0.04423652	0.0004
Intercept	-	-.0918087988	0.40416597	0.8204

Summary of Key Findings for the Linear Regression Models

Based on the results discussed throughout this section, but especially those pertaining to the models shown in Tables 19, 22, and 23, the following general observations about the relationships between logPET, treatment type, site characteristics, and Safe System compliance can be derived, including:

- logPET tends to decrease as the degree of separation between motor vehicles and crossing pedestrians/bicyclists decreases, as conveyed by the repeated results that show all types of treatments, when compared to traffic control/supplemental yielding, are negatively associated with logPET.
- logPET tends to increase when speed limits are lower.
- The Safe System scores tended to be positively associated with logPET, which is a counterintuitive relationship. However, it is likely that sites with high exposure tended to also be sites with higher order crossing treatments in place, and the magnitudes of the coefficients on the Safe System variables and treatment type may indicate this confounding relationship between the variables.

6.3.2 Logistic Regression

Given the complex relationship between the variables as revealed through the linear regression models, logistic regression models that capture the log odds of conflicts being critical (PET<1.5 seconds) may provide more clarity and allow clearer crossing guidance to be distilled. For all of the linear regression models developed, the sample included 800 interactions recorded across the 16 sites. CritPET is the response variable.

Site Characteristic Modeling

As with the linear regression models, a limited set of key site characteristic variables (treatment type, speed limit, AADT, AADT*speed limit (an interaction variable), functional classification, number of lanes, and lane width) were tested in regression models with the goal of identifying crossing treatment criteria. These logistic regression model results convey the log odds of an interaction between a motor vehicle and a pedestrian/bicyclist being critical or non-critical. Table 41 in the Appendix reports the model results, but AIC is reported instead of r^2.

Table 24 presents the analysis of effects of the different treatment type categories on CritPET. Traffic control/supplemental yielding is again used as the reference level. All treatment types, when compared to traffic control/supplemental yielding, increase the log odds of a conflict being critical. Pavement markings had the largest effect.

Table 24. Effects of Treatment Type on CritPET

Variable	Category	Coefficient	Odds Ratio	Standard Error	P-value
TreatType	NoMark	0.8063	2.240	0.2935	0.0060
	PaveMark	1.4158	4.120	0.2601	<.0001
	RefIsland	1.2902	3.634	0.2621	<.0001
	TraffCon	Base category	-	-	-
Intercept	-	-2.1926	-	0.2109	<.0001

The inclusion of speed limit to the logistic regression model produces similar results for treatment type. 25 mph speed limits, compared to 35 mph speed limits, decrease the log odds of an interaction being critical. The 20 mph speed limit increases the log odds of a critical PET, potentially because the lower speed sites in the sample also tended to have the lower category crossing treatments. The 45 mph speed limit category was not statistically significant. The AADT variable is associated with an increase in the log odds of a critical PET, indicating that as traffic volume increases, the risk of a critical conflict increases.

Table 25. Effects of Treatment Type, Speed Limit, and AADT on CritPET

Variable	Category	Coefficient	Odds Ratio	Standard Error	P-value
TreatType	NoMark	0.9781	2.659	0.3655	0.0075
	PaveMark	1.6339	5.124	0.3365	<.0001
	RefIsland	1.6294	5.101	0.2923	<.0001
	TraffCon	Base category	-	-	-
SpeedLim	20	0.6192	1.857	0.2466	0.0120
	25	-1.1965	0.302	0.5418	0.0272
	45	-1.4822	0.227	1.0466	0.1567
	35	Base category	-	-	-
AADT	-	0.000066	1.000	0.000032	0.0409
Intercept	-	-2.9798	-	0.4875	<.0001

Safe System Modeling

As with the site characteristics, Safe System scores were tested to determine if measures of exposure, likelihood, severity, or total Safe System compliance increase or decrease the log odds of an interaction between a motor vehicle and pedestrian/bicyclist being critical.

Based on the results of a model with ExpScore and SevScore included as independent variables, shown further in Table 26, the exposure score increased the log odds of an interaction being non-critical, with a one-unit increase in exposure associated with an approximately 20% decrease in the log odds of critical conflict. SevScore was statistically significant for predicting the likelihood of a conflict being critical at $p<0.05$; a one-unit increase in severity is associated a 21% increase in the log odds of a conflict being critical. These two factors may function in opposite direction because several sites with high exposure (due to factors like lane width and number of lanes to cross) tend also to be sites with traffic control or supplemental yielding. Another possible explanation is that the interactions were only coded when pedestrians or bicyclists and motor vehicles were present, so the methods developed for this analysis may already select for situations where exposure is high but the PET is low. The exposure score calculation uses hourly pedestrian and bicyclist crossing counts rather than only those pedestrians and bicyclists observed during interactions, but since the recordings were discontinued after 50 interactions were observed, safe crossings where no motor vehicles were present may have been excluded from the analysis. This limitation of the data collection method may potentially inflate the exposure score. It should not be concluded that sites with high exposure are necessarily safer; the model seems to be capturing an effect of the kinds of roadways in the sample that already feature the highest category of crossing treatments.

Table 26. Effects of Exposure Score and Severity Score on CritPET

Variable	Category	Coefficient	Odds Ratio	Standard Error	P-value
ExpScore	-	-0.1992	0.819	0.0712	0.0052
SevScore	-	0.1952	1.216	0.0798	0.0145
Intercept	-	-0.5208	-	0.7342	0.3915

Combined Modeling

Finally, site characteristics and Safe System factors were tested together to determine the log odds of interactions being critical.

The results of the best fitting of these models are shown in Table 27. When compared to traffic control or supplemental yielding, all other treatment types are associated with increased log odds of a critical event. Compared to 35 mph speed limits, 25 mph speed limits are associated with a decrease in the log odds of a critical event. It should be noted that with a 90% significance level (p=0.1), a speed limit of 45 mph is associated with a decrease in the log odds of a critical event. This is counterintuitive, but may be explained by the presence of other measures—such as traffic control devices—to mitigate the effects of high motor vehicle speeds at these locations. The AADT variable is associated with an increase in the log odds of an event being critical, meaning that for all sites, as AADT increases, the log odds of a critical event increases.

The two Safe System criteria in this model work in opposite directions. As the likelihood score increases, the log odds of a critical event occurring increases. As the Safe System score increases, the log odds of a critical event decreases. However, the magnitude of the effect of the likelihood score is almost double that of the Safe System score, meaning that for critical PET, the site characteristics that contribute to the likelihood of a crash occurring—poor visibility and missing, protective separation—contribute more to critical conflicts.

Table 27. Effects of Treatment Type, Speed Limit, AADT, Likelihood Score, and Safe System Score on CritPET

Variable	Category	Coefficient	Odds Ratio	Standard Error	P-value
TreatType	NoMark	1.3285	3.775	0.4529	0.0034
	PaveMark	2.3958	10.977	0.4614	<.0001
	RefIsland	1.5228	4.585	0.2906	<.0001
	TraffCon	Base category	-	-	-

SpeedLim	20	0.2584	1.295	0.2670	0.3332
	25	-1.5480	0.213	0.5529	0.0051
	45	-1.8818	0.152	1.0610	0.0761
	35	Base category	-	-	-
AADT	-	0.000111	1.000	0.000039	0.0044
LikScore	-	0.2476	1.281	0.2440	0.0117
SSEScore	-	-0.1207	0.886	0.0995	0.0128
Intercept	-	-2.7634	-	0.4802	<.0001

Summary of Key Findings for the Logistic Regression Models

Based on the results discussed throughout this section, but especially those pertaining to the models shown in Tables 25 and 27, the following general observations about the relationships between critical PET, treatment type, site characteristics, and Safe System compliance can be derived, including:

- As with the linear regression models, the logistic regression models demonstrated that no markings, pavement markings only, and refuge islands are associated with an increase in the log odds of a critical event compared to traffic control and supplemental yielding.
- The relationship between speed limit and critical PET seems to vary depending on other site characteristics or variables included in the models, but based on the models, the log odds of a critical event are decreased when the posted speed limit is 25 mph rather than 35 mph.
- Considering all sites, as the AADT increases, the log odds of a critical event occurring tend to increase.
- The Safe System scores tended to work in opposite directions when multiple variables were included in models, but likelihood-related variables may have a larger impact than exposure-related variables for increasing the log odds of a critical event occurring when traffic control and supplemental yielding are not provided. The exposure-related variables may be capturing an effect of the PET-recording methods used in this study.

6.3.3 Summary of Statistical Distributions

Key site characteristics and the corresponding Safe System criteria score per site, grouped by treatment type, are shown in Table 28. These site characteristics, and the relevant ranges in the Safe System scores and critical events, are useful for determining the roadway conditions under which different treatment types should be applied. Across all sites, AADT ranges from 1,600 vpd to 16,500 vpd, with a median value of 8,600 vpd and an average value of 8,725 vpd. Eleven of 16 sites have 35 mph speed limits. The average PET across all sites ranges from 2.3 seconds to 18.6 seconds, with a median PET of 5.1 seconds and an average PET of 6.7 seconds.

Potential guidance for when to install different types of treatments were derived by examining the summary statistics in Table 29, the box and whisker plots in Figures 9-13, and the findings from the linear and logistic regression models. The recommendations are provided in Section 7.

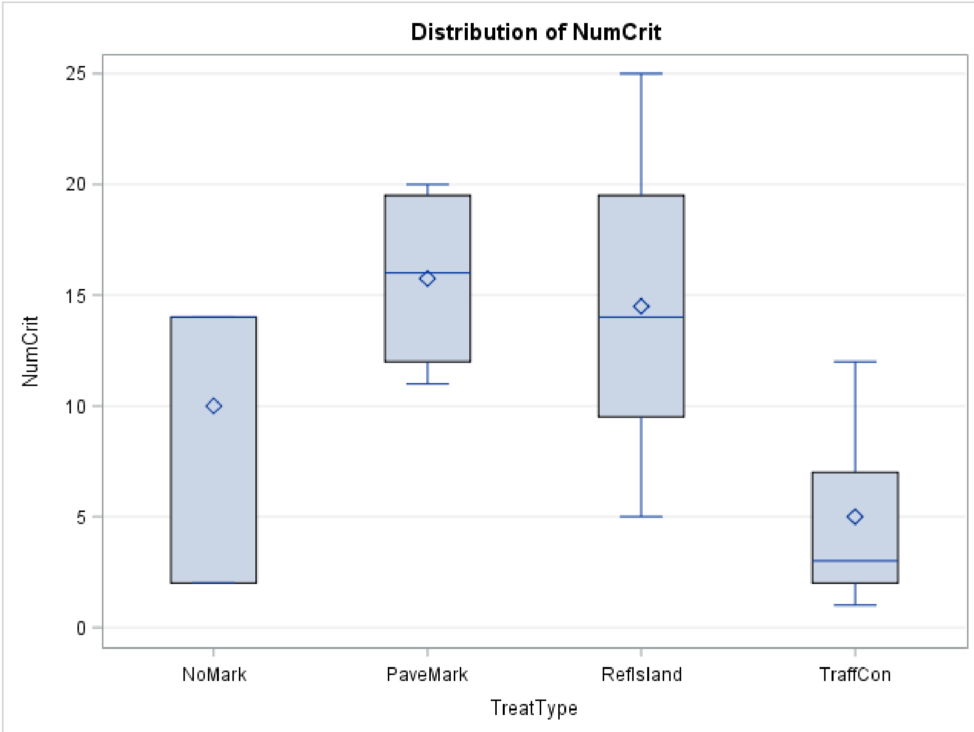

Figure 9. Distribution of Number Critical Events by Treatment Group

When comparing across treatment groups, the number of critical events (shown in Table 29 and Figure 9) was maximized at sites with refuge islands, although the highest mean and median critical events occurred at sites with pavement markings only. The minimum, maximum, mean, and median counts of critical events were all lowest at sites with traffic control and supplemental yielding.

As can be seen in Figure 10 and Table 28, the exposure score tended to be highest at sites with traffic control or supplemental yielding. As discussed previously, this finding is unexpected but may indicate that practitioners in North Carolina are already installing higher-level treatments that provide separation in time when the potential exposure to severe conflicts is high for pedestrians and bicyclists crossing roadways. The elements associated with exposure (e.g., numbers of lanes, functional classification, AADT, etc.) tend to be maximized at sites with traffic control and supplemental yielding. Another potential explanation, as mentioned, is that the method used in this study may not truly capture exposure because interactions between SUP users and motor vehicles would indicate crossing maneuvers where the exposure to a potential conflict is non-zero. Although the researchers did count all crossing pedestrians and bicyclists and used these sums to calculate hourly crossings for each type of SUP user for input in the evaluation tool, the data collection method focused specifically on interactions where a crash is possible. Further refinement of the method discussed in this report may be necessary to better balance recorded interactions with total observed volume.

Table 28. Summary Statistics for Critical Events and Safe System Criteria per Treatment Group

Metric	Statistic	No Markings	Pavement Markings	Refuge Islands	Traffic Control/ Supplemental Yielding
Number of Critical Events	Minimum	2.0	11.0	5.0	1.0
	Maximum	14.0	20.0	25.0	12.0
	Mean	10.0	15.8	14.5	5.0
	Median	14.0	16.0	14.0	3.0
Exposure Score	Minimum	7.0	7.0	6.5	7.0
	Maximum	8.5	8.0	9.5	11.5
	Mean	7.5	7.5	7.4	9.2
	Median	7.0	7.5	6.8	9.0
Likelihood Score	Minimum	4.5	4.0	0.5	2.0
	Maximum	8.5	5.5	6.0	6.0
	Mean	7.0	4.9	2.8	3.8
	Median	8.0	5.0	2.3	4.0
Severity Score	Minimum	3.0	4.0	3.0	3.0
	Maximum	5.5	5.5	5.0	6.0
	Mean	4.5	4.9	4.0	3.6
	Median	5.0	5.0	4.0	3.0
Safe System Score	Minimum	15.0	18.0	5.0	6.0
	Maximum	36.0	24.0	18.0	24.0
	Mean	23.0	19.5	9.5	12.8
	Median	18.0	18.0	7.5	12.0

Table 29. Summary of Site Characteristics

Treatment Type	Site Name	Functional Classification	Speed Limit	Annual Average Daily Traffic	Average PET	Number of Critical Events	Exposure Score	Likelihood Score	Severity Score	Safe System Score
Traffic Control/Supplemental Yielding	ATT & Cornwallis	collector	45	8700	7.7	1	8.5	5	3	12
	ATT & Fayetteville	arterial	35	15500	16.3	3	10	6	6	24
	ATT & W Woodcroft	collector	35	9500	2.8	12	9	2	3	6
	WTC & Gorman	arterial	35	16500	10.9	2	11.5	4	3	16
	IRT & East Main	arterial	20	8700	18.6	7	7	2	3	6
Refuge Island	WCT & Lake Johnson North	collector	35	8500	3.0	14	6.5	2	5	9
	BLT & Remount	collector	35	14000	3.1	25	9.5	6	5	18
	WCT & Garner	collector	35	11500	2.8	14	7	0.5	3	6
	CCT & George Anderson	collector	25	5000	3.8	5	6.5	2.5	3	5
Pavement Markings	IRT & Duke	collector	35	1600	5.1	11	7.5	5	5	18
	BLT & New Bern	local	20	5000	5.1	19	7.5	4	4	18
	TRG & East 5th	collector	35	12000	2.3	20	8	5.5	5.5	24
	IRT & Withrow	collector	35	5400	7.9	13	7	5	5	18
No Markings	IRT & North Oak	local	20	5000	6.1	14	7	8.5	3	18
	IRT & Highway 64	arterial	35	4300	9.2	2	8.5	8	5.5	36
	WCT & Lake Johnson South	collector	35	8400	2.8	14	7	4.5	5	15

The likelihood score is maximized when no pavement markings are present. The mean and median likelihood scores are also highest when no markings are present. The mean and median likelihood scores are actually lowest when refuge islands are present, with traffic control and supplemental yielding associated with the second lowest likelihood scores.

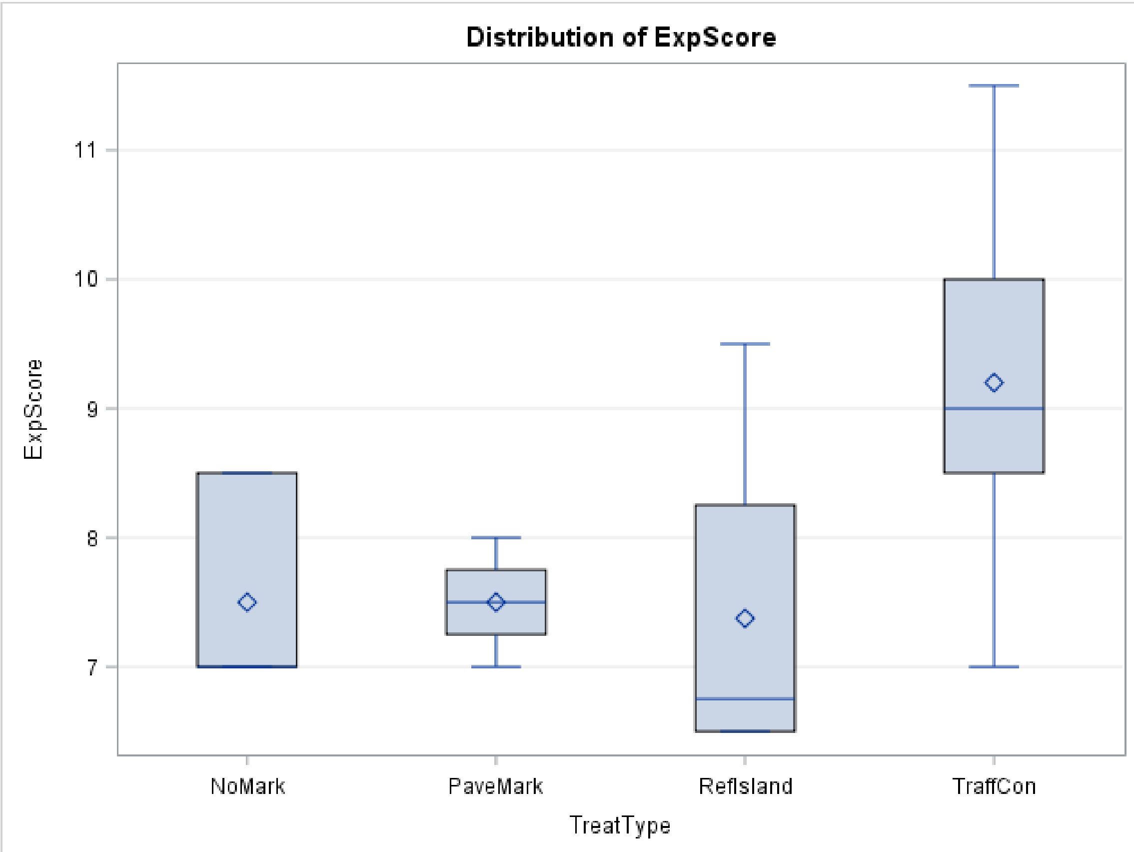

Figure 10. Distribution of Exposure Score by Treatment Group

The severity score is maximized at sites with traffic control or supplemental yielding sites. However, the mean severity scores are highest at sites with only pavement markings, and the median severity scores are highest at sites with no markings or only pavement markings. The mean and median severity scores are minimized at sites with traffic control and supplemental yielding.

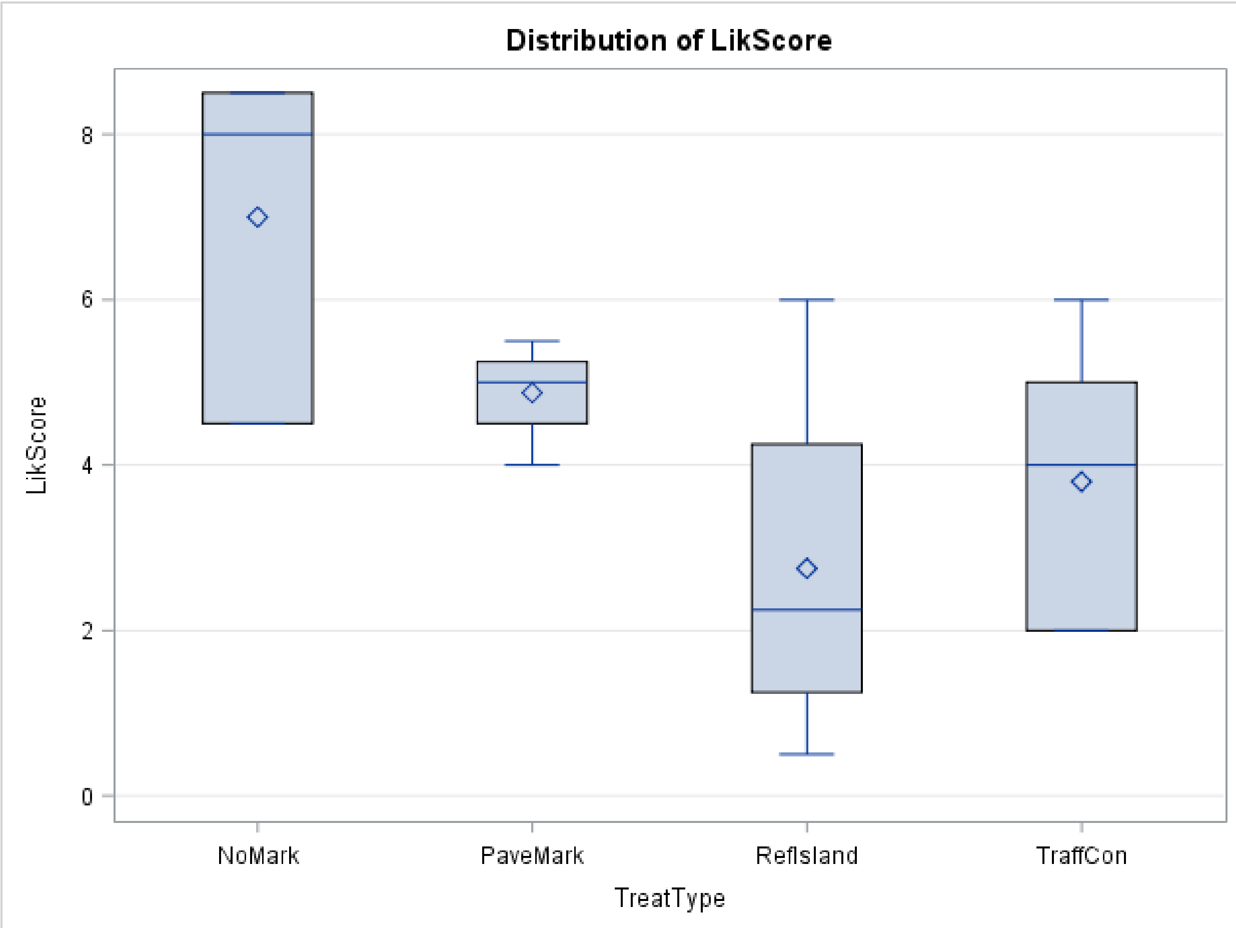

Figure 11. Distribution of Likelihood Score by Treatment Group

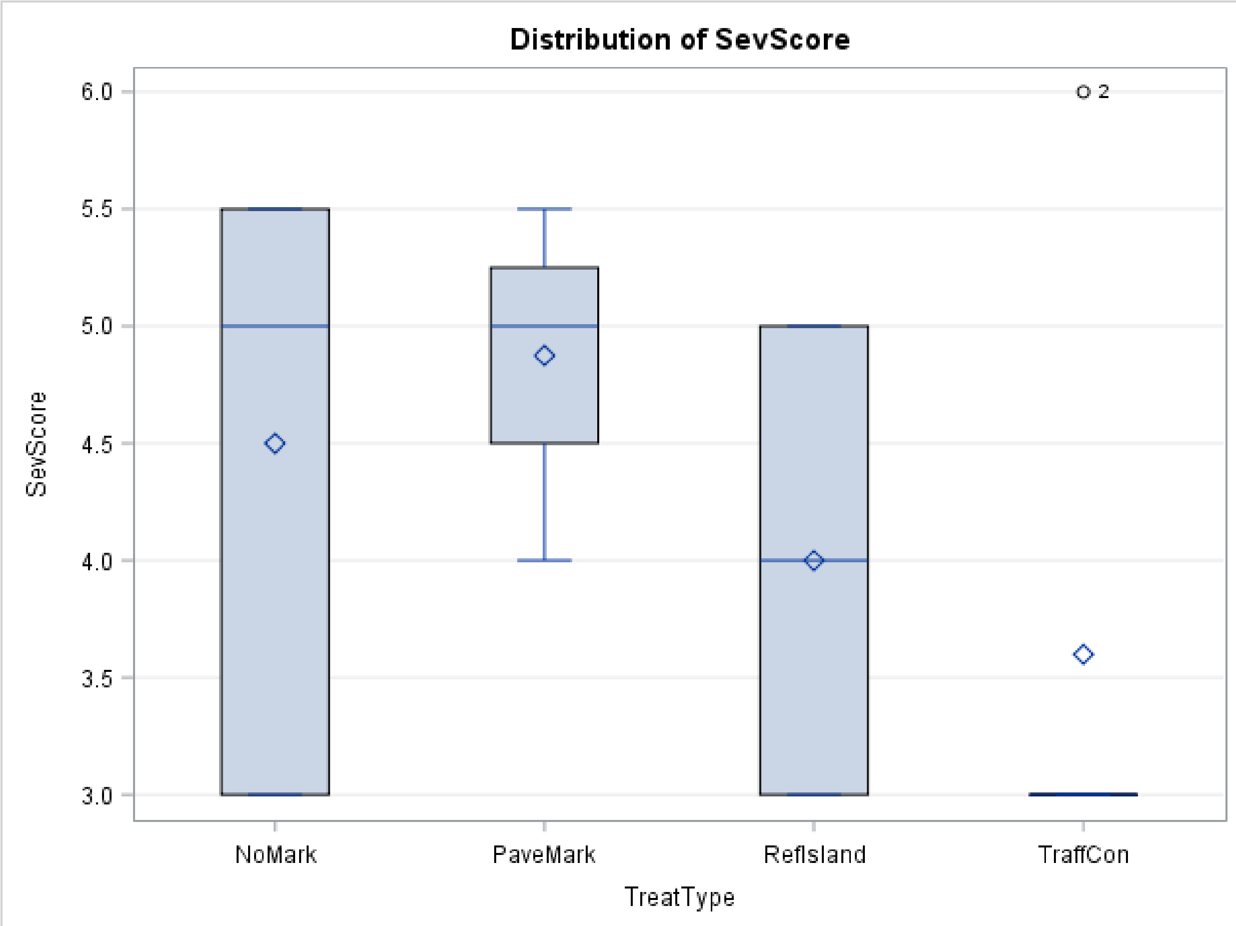

Figure 12. Distribution of Severity Score by Treatment Group

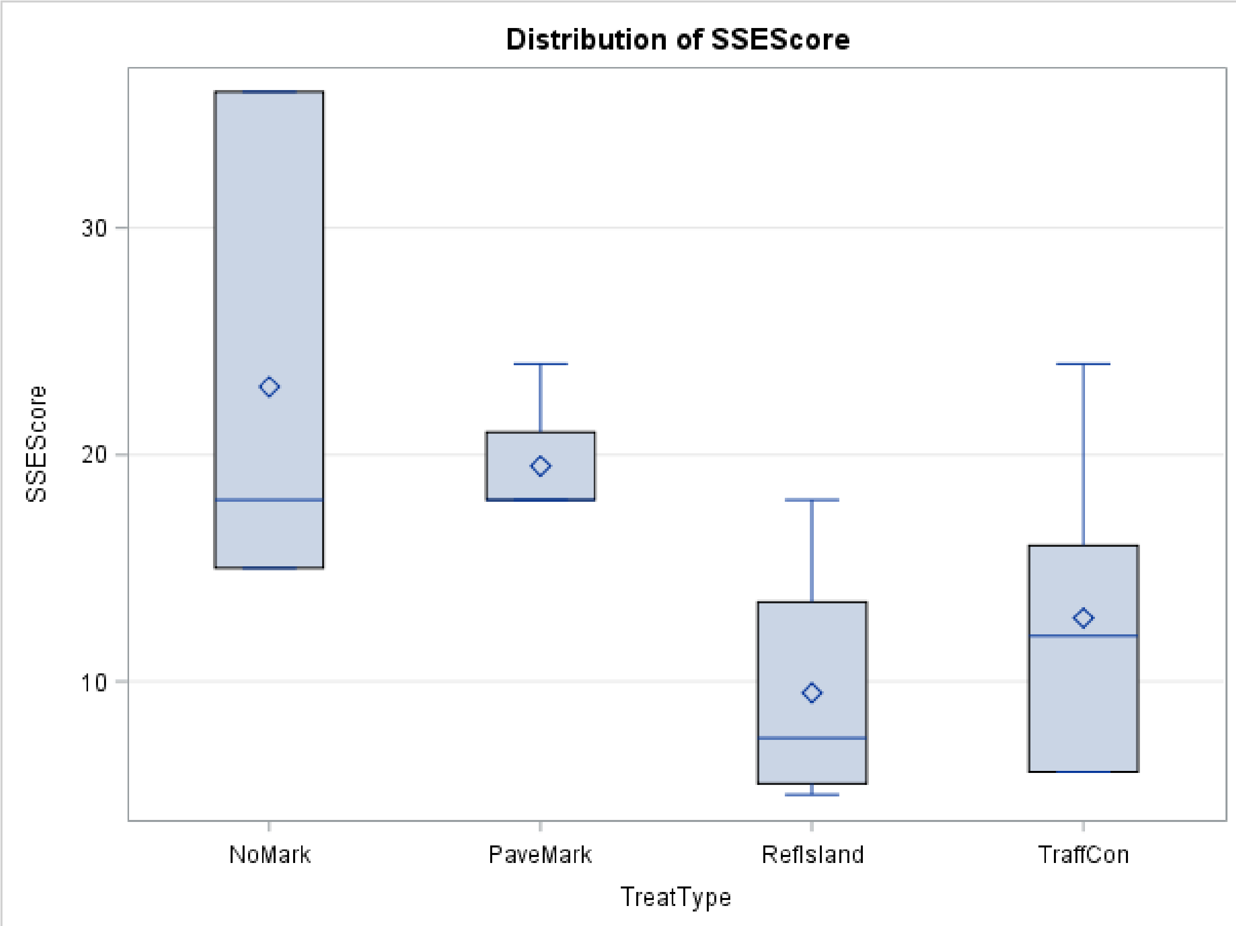

Figure 13. Distribution of Safe System Score by Treatment Group

7 Recommendations and Guidance

This section provides potential guidelines practitioners may consider when identifying the most appropriate SUP crossing treatments to reduce risks and align with the Safe System Approach. Unique cross sections may exist that make some crossing treatments difficult to install, but to the extent possible, practitioners should consider how the suggested treatments reduce the exposure to, likelihood of, and severity of conflicts for pedestrians and bicyclists. Recommendations based on the analysis of the exposure scores discussed in Section 6 may indicate that when exposure is high, traffic control and supplemental yielding mitigate the risks to pedestrians and bicyclists. Therefore, some potential guidelines for installing traffic control and supplemental yielding may include:

- When AADT exceeds 8,500 vpd, install traffic control or supplemental yielding, regardless of other site attributes.
- When pedestrians or bicyclists must cross more than one lane on each side, install traffic control or supplemental yielding, regardless of other site attributes.

Given that the mean and median exposure scores are lowest for sites with refuge islands, a potential guideline to consider for installing a refuge island might be:

- Where AADT is less than 8,500 vpd and there is only one lane per direction, but the average lane width is 12 ft or greater, consider installing a refuge island.

On-street parking may contribute to increased exposure if vehicles are interacting with pedestrians and bicyclists. However, the type of on-street parking and site access requirements may make it difficult to install a refuge island. Practitioners are encouraged to consider accessibility and local conditions when parking is present to select the most appropriate crossing treatment.

The likelihood scores discussed in Section 6 seem to be related to clear expectations and visibility at crossing locations. Considering these factors, it may be worth taking treatment visibility and speed limit into consideration, as speed limit dictates the distance at which signs need to be placed and how clear sight triangles need to be. Some potential guidelines that may be derived based on the likelihood results include:

- When speed limit is 20 mph, no markings are required but pavement markings are encouraged.
- When speed limits are below 35 mph but above 20 mph, provide pavement markings or a higher order crossing treatment.
- If bicycle lanes intersect the crossing location, install a refuge island or traffic control/supplemental yielding.

On-street parking may contribute to increased exposure if vehicles are interacting with pedestrians and bicyclists, but on-street parking may also relate to whether or not the crossing is clear of sight obstructions. For example, the Blue Line Trail at New Bern intersection has a 20 mph speed limit, but the on-street parking obstructs views from the start of the crossings and may contribute to the high number of critical events at that site. Therefore, a potential rule for treatment types based on the relationship between parking and sight triangles includes:

- If on-street parking exists, install a refuge island.

If for some reason the recommended treatment is not feasible within the cross section, the Safe System SUP Evaluation tool's scores may indicate other potential changes to the roadway environment that may lower the scores and improve safety. For example, if a refuge island cannot be installed because of on-street parking access requirements, practitioners may examine the speed limit, signs, and other criteria to assess if other changes can be made.

Severity is most connected to speed and vehicle mass. Considering these factors, the following guidelines may be derived:

- If there are three or more access points within the stopping sight distance radius of the crossing location, install a refuge island or traffic control/supplemental yielding.
- If speed limits are 35 mph or above, install a refuge island or traffic control/supplemental yielding.
- If speed limits are above 35 mph, install traffic control/supplemental yielding.

- If the commuting traffic is composed of at least 20% larger vehicles (i.e., SUVs, pickup trucks, or larger), install a refuge island or traffic control/supplemental yielding.
- If the commuting traffic is composed of at least 30% larger vehicles, install traffic control/supplemental yielding.

Considering all of these potential guidelines, the following upgrade matrix shown, the Safe System SUP Crossing Treatment Matrix, in Table 30, can be derived. The criteria specified in Table 30 generally follow the distributions of site data as correspond to treatment group and Safe System Scores. These criteria include:

- AADT: The thresholds for traffic volume were derived by identifying the median traffic volume for treatment groups. For no crossings, the median AADT was 5,900 vpd, so a rounded up AADT equal to 6,000 vpd was used as the lower volume threshold. The median AADT of all sites was 8,600 vpd, so a rounded down AADT equal to 8,500 vpd was used as the upper volume threshold.
- Speed limit: physical separation is less important when speed limits are low, so the 20 mph speed limit was set as the threshold for unmarked crossings. When speed limits exceed 35 mph, the potential crash severity is high, so the highest form of treatment should be considered.
- Maximum number of lanes per direction: more lanes result in more potential exposure for crossing pedestrians or bicyclists, so the highest form of treatment should be considered when there are multiple lanes per direction to cross.
- Average lane width per direction: a lane width equal to 12 ft should be considered as the criterion for physical separation, as discussed in Table 11.
- Intersection bicycle lanes: the presence of a bicycle lane potentially increases the crossing distance for pedestrians and bicyclists and therefore increases potential exposure, so physical separation should be considered.
- On-street parking: on-street parking may contribute to increased exposure if vehicles are interacting with pedestrians and bicyclists, so physical separation should be considered.
- Access points: the median number of access points across all sites was 2.5, so a rounded up number of three access points was set as the threshold for physical separation.
- Percentage of large vehicles: the median number of large vehicles observed across all sites was 32%, so a rounded down value of 30% was set as the threshold for physical separation.

Note that the pedestrian and bicyclist volume inputs that are part of the evaluation tool are not required to use the Safe System SUP Crossing Decision Tool.

Table 30. Safe System SUP Crossing Treatment Matrix

Criteria	No Markings	Pavement Markings	Refuge Islands	Traffic Control/ Supplemental Yielding
Annual Average Daily Traffic	<=6,000 vpd	<=8,500 vpd	<=8,500 vpd	>8,500 vpd
Speed Limit	20 mph	20-30 mph	20-35 mph	>35 mph
Maximum Number of Lanes per Direction	1	1	1	> 1
Average Lane Width per Direction	<12 ft	<12ft	>=12ft	>=12ft
Intersecting Bicycle Lanes	No	No	Yes	Yes
On-Street Parking	No	No	Yes	Yes
Access Points	<3	<3	>=3	>=3
Percentage of Large Vehicles	<20%	<20%	20%-30%	>=30%

Researchers built these decision guidelines into the Safe System SUP Crossing Decision tool (a screenshot of which is shown in Figure 14) to support practitioners and facilitate scenario testing.

AADT (vpd)	Speed limit (mph)	Max lanes per direction	Average lane width (feet)	Intersecting bicycle lanes	On-street parking	Access points	% of large vehicles	Recommended minimum treatment
<6000	20	1	<12	no	no	<3	<20	none
<6000	<=30	1	<12	no	no	<3	<20	pavement markings
6000-8500	<=35	1	<12	yes	no	>=3	20-30	refuge island
>8500	>35	>1						traffic control
<6000	>35	1	<12	no	no	>=3	<20	traffic control
<6000	<=35	1	<12	no	no	>=3	<20	refuge island

Figure 14. Safe System SUP Crossing Decision Tool

However, to simplify the decision process and to provide an alternative to using a separate spreadsheet tool to select an appropriate SUP crossing treatment, researchers prepared the flowchart shown in Figure 15. This flowchart is also included in a separate sheet. The flowchart uses all the input from Table 30, starting with traffic volume, and allows practitioners to arrive at a SUP crossing treatment decision using only the input data and a series of yes or no decisions.

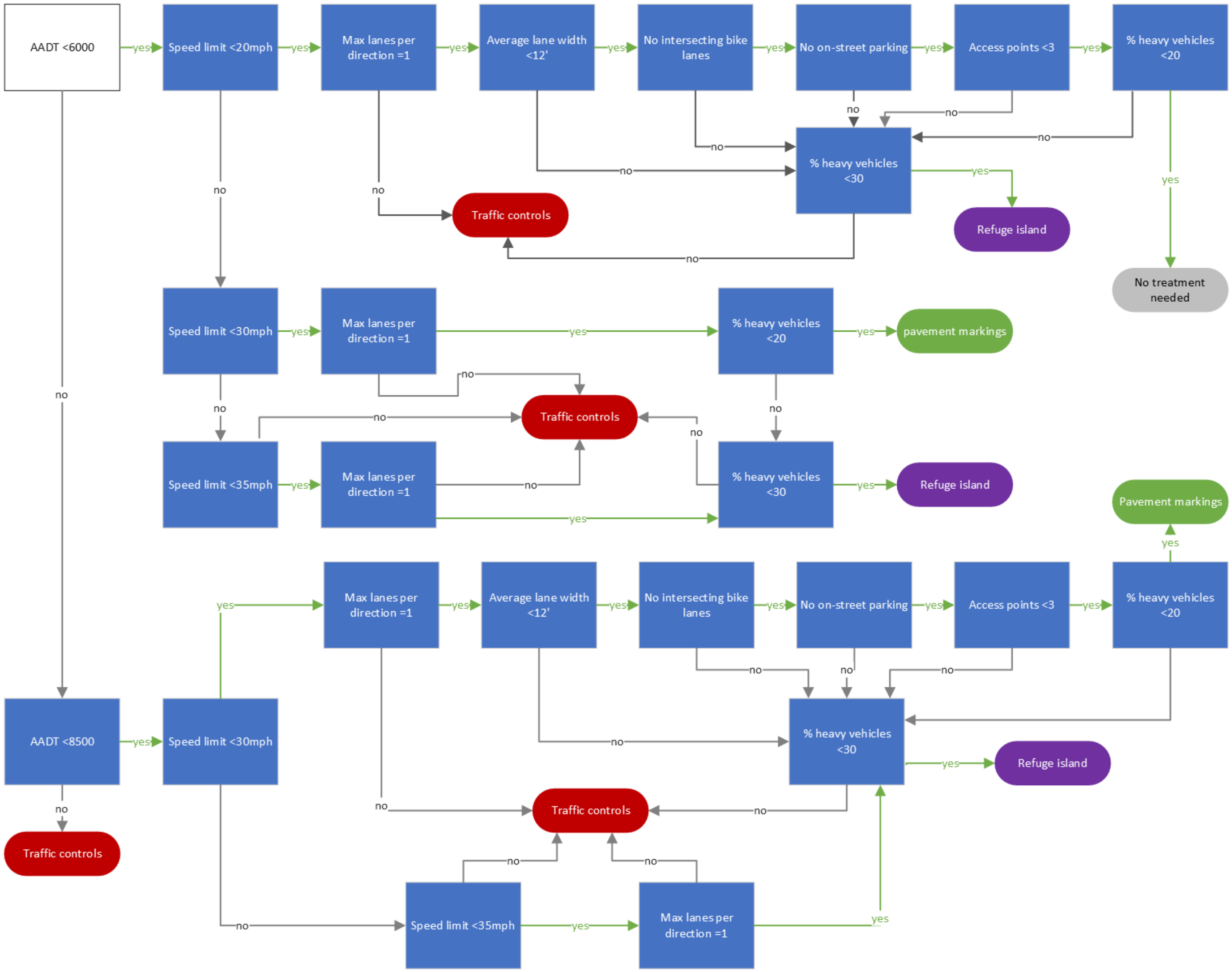

Figure 15. Safe System SUP Crossing Decision Flowchart

7.1.1 Case Studies

To demonstrate the utility of the Safe System tools developed as part of this project for identifying the effects of improving site characteristics on risks to crossing pedestrians and bicyclists, three case studies showing nominal base conditions and improved conditions are shown below. For each of the three case studies, one of the sample sites in a lower treatment category will be described, and then the effect of a treatment upgrade will be demonstrated through changes to the four Safe System criteria.

No Pavement Markings

The intersection of the American Tobacco Trail and Wimberly Road serves as an effective base condition for a site without pavement markings. This site has a standard crossing with no additional treatments and no refuge island. Wimberly Road is a two-way road that serves as a collector facility for nearby local roads that access Sunnybrook Farms and Amity Fields. The average lane width on either side of the crossing is 10 feet. There is no on-street parking. The AADT at this site is 1,600 vpd. Because this site is not one of the study locations, some assumptions need to be made about pedestrian and bicyclist volumes. Two of the other three ATT sites in the study sample had low hourly bicyclist demand, so a low bicyclist volume will be assumed. Conversely, there is a trail parking lot adjacent to this site, so pedestrian volume can be assumed to be high. Since conflicts were observed at every crossing location in the study sample, critical conflicts can be assumed to occur at this site.

There was no obvious source of light visible from either approach when examining the site. However, there is adequate signage within the stopping sight distance radius, the sight triangles are clear, and there are no obvious obstructions for crossing pedestrian and bicyclist visibility. There is no intersecting bicycle facility.

The posted speed limit on both approaches for this site is 45 mph. There is a total of three access points within the stopping sight distance radius of the crossing, and there is only one, non-crossing related sign visible on approach (there are two no-parking signs placed at the crossing, but these appear to only be visible to traffic accessing the parking lot). Based on the traffic composition for the other ATT sites, it can be assumed that this site does not see a high percentage of larger vehicles.

The corresponding Safe System criteria scores based on these site characteristics include:

- Exposure Score = 7.5/14
- Likelihood Score = 5/12
- Severity Score = 3/7
- Safe System Evaluation Score = 12/64

Based on the criteria in Table 30, the lack of pavement markings would not be adequate because of the speed limit. Because the site has otherwise adequate visibility and few complexities that may cause drivers to inadequately slow at the site, the likelihood, severity, and translated Safe System scores are below the median values for this treatment group (8, 5, and 18, respectively). However, the exposure score is above the median (7) for this treatment group. This exposure score, considered alongside the 45 mph speed limit, may indicate a need for additional treatment.

If continental markings were added at this site, the exposure score would not be meaningfully reduced. However, if supplemental yielding were added alongside a refuge island to meet the 45-mph criteria in Table 30, the exposure score of 6.5 would drop below the median for the traffic control group (9.0), and the likelihood score of 1.0 would drop below the median for that treatment group (4.0), resulting in a low translated Safe System score of 5/64.

Pavement Markings Only

The intersection of the American Tobacco Trail and Scott King Road may serve as a useful example for when to upgrade a site with only marked crossings. This site has a marked crossing with a painted median (i.e., not a real median) in the center of the road. It is a bi-directional roadway with only one lane in each direction at the crossing location, although there is a turn lane just past the crosswalk in the westbound direction. The roadway appears to serve as a collector road between nearby arterials, although the AADT is relatively low. The average lane width in either direction is approximately 11 feet, ignoring the shoulder space and painted median section. There is no on-street parking at this site, and the AADT is only 2,000 vpd.

There are no apparent streetlights at the crossing location. There are multiple warning signs for the crossing within the stopping sight distance radius of the crossing in both locations. The sight triangles for approaching vehicles are clear, although there is a slight grade to the location. There are no evident obstructions for crossing pedestrians or bicyclists to look down the road. On the eastbound approach, there is a shoulder facility that may serve as a temporary bike lane, given the bicycle traffic at the nearby Herndon Park, so there may be conflicts with bicyclists on this side of the road.

The posted speed limit is 45 mph in each direction, although there are advisory speed limit of 35 mph signs in either direction. There are no access points within the stopping sight distance on the westbound approach, and there are only two access points on the eastbound approach. There are no additional traffic control devices within the stopping sight distance, although there are two additional “No Parking” signs on the eastbound approach.

As with the intersection of the ATT and Wimberly Road, some assumptions can be made about this crossing site to facilitate completion of the Safe System scoring sheet. Given the proximity to Herndon Park and the other observed volumes at ATT sites in this study, the crossing pedestrian and bicycle activity can be assumed to be high. Traffic conflicts and noncompliant yielding were observed at every other site in the sample, so these can be assumed for this case study site as well. It is assumed that there are fewer than 30% larger vehicles at this site.

The corresponding Safe System scores based on these site characteristics include:

- Exposure Score = 6/14
- Likelihood Score = 6/12
- Severity Score = 3/7
- Safe System Evaluation Score = 8/64

The exposure, severity, and Safe System evaluation scores are all in line with the median values for marked only sites. However, the likelihood score of 6.0 exceeds the median value (5.0) for marked crossing sites. This consideration, taken together with the 45 mph speed limit, may be grounds for an upgrade. If it can be assumed that most motorists are abiding by the 35 mph advisory speed limit, a refuge island would reduce the exposure score to 5.0, the likelihood score to 23.0, and the total Safe System score to 4/64. These values are all below the median values for refuge island sites. If the 45 mph speed limit is not complied with, the addition of supplementary traffic control would also bring the site into compliance with Table 30.

Refuge Island

The intersection of the Blue Line Trail and East Boulevard in Charlotte may be a useful case study for a refuge island site that may benefit from improvement. This road likely serves as an arterial through Charlotte. There is a marked crosswalk that crosses two lanes in each direction, and the refuge island is approximately 10 feet wide. The average lane width is approximately 12 feet wide because of the sharrows/wide outside lanes used on either side. There is no on-street parking at this location. The AADT at this site is 6,250 vpd in each direction. Based on the other BLT sites in Charlotte in the sample, it can be assumed that there is high pedestrian crossing traffic but low bicyclist crossing traffic at this site, with some conflicts observed.

Lights are apparent on either side of the trail, and there are crossing signs posted to be seen at an adequate stopping sight distance for the posted speed limit. However, the two-lane traffic and general complexity of the rail crossing make it so that drivers may not have clear sight triangles, and crossing pedestrians may not be able to see all vehicular traffic. Although sharrows are painted on the outside lanes, there are no bicycle lanes present.

The posted speed limit, based on the signs on the northwest approach, is 30 mph. There are several signs for transit services, the rail line, and the intersection with Camden Road that may increase the complexity in either direction. There are two access points visible in each direction, assuming the possibility of two-way traffic flow (i.e., unrestricted right turns on red) on Camden Road. Based on the other Charlotte BLT sites, it can be assumed that there are over 30% larger passenger vehicles and noncompliant yielding behaviors.

The corresponding Safe System scores based on these site characteristics include:

- Exposure Score = 8.5/14
- Likelihood Score = 4/12
- Severity Score = 6/7
- Safe System Evaluation Score = 24/64

These scores are above the median scores for exposure (6.8), likelihood (2.3), severity (4.0), and the Safe System total (7.5), respectively, for refuge island sites in the sample. Although the introduction of additional traffic control may not actually reduce the scores in the spreadsheet, the median values for exposure and likelihood would be at or below those for other traffic control/supplemental yielding sites. Based on Table 30, supplemental yielding would ideally provide an additional degree of separation, in this case separation in time, for crossing pedestrians, thereby likely reducing the number of critical events observed. Therefore, supplemental yielding or traffic control would bring this site closer to compliance with the Safe System Approach and would be expected to improve safety at this location.

8 Conclusions

This report presented the results of a Safe System-based analysis of SUP crossings in North Carolina. The goal of this project was to derive simple guidance aligned with Safe System principles that practitioners may consider when assessing the risks to pedestrians and bicyclists at crossing sites and selecting appropriate treatments to mitigate those risks. The guidance provided in this report is based on an evaluation of 16 different crossing sites, a Safe System evaluation of those sites, statistical analysis of the relationship between those sites' Safe System compliance and their treatment groups, an assessment of the log odds of critical conflicts occurring at different types of treatments, and case studies of other crossing sites not used in the statistical analysis.

The project produced several key findings. First, the statistical analysis showed that, generally, as speed limits and traffic volumes increase, the post-encroachment time decreases and the log odds of a critical event occurring on the SUP crossing increases. Second, the treatment groups tended to perform as expected and in a manner aligned with Safe System principles; the sites that tended to provide greater separation in time (through the addition of supplemental yielding or traffic control) tended to have higher PETs and fewer critical events, while the sites that provided separation in space (through the addition of refuge islands) tended to have the lowest Safe System risk. Third, the different Safe System criteria (exposure, likelihood, and severity) tended to act as expected (i.e., as the level of treatment improved, the lack of compliance or risk to pedestrians and bicyclists decreased) except in the case of the traffic control/supplemental yielding group, which tended to have higher exposure scores than the other sites, though this may be a function of the interaction recording method used in this study. A potential explanation for this finding could be that the sites with supplemental yielding/traffic control in the sample were generally larger facilities with higher speed limits and more daily traffic, so the traffic control devices were already installed at sites where exposure was high. Finally, the case studies demonstrated how the project results could be used to identify suitable locations for improvement.

A key benefit of the proposed Safe System assessment framework is that users can quickly identify potential risks to pedestrians and bicyclists and thereby identify relevant countermeasures to those risks beyond the crossing treatments identified. For example, at some sites in the sample, researchers identified limited sight triangles due to on-street parking or visual obstructions. After performing the evaluation, a user could then recommend parking restrictions or the removal of trees that block sight triangles. The user would then be able to see how changing this site obstruction would improve Safe System compliance. Given that there are few Safe System-aligned assessment tools like this in use in the United States, the researchers believe there is value in the process of using the tool itself.

Despite the intuitive results of the project and the benefits discussed above, there are some limitations to this project. First and foremost is the fact that the Safe System evaluation tool is qualitative in nature. Further validation and calibration are likely needed to ensure that the various risk factors are properly weighted and capturing the effects of different roadway elements on actual crashes. Second, the true link between surrogate safety measures like PET and crashes involving pedestrians and bicyclists is unknown. A critical PET may indicate that a site has some amount of risk, but it is difficult to translate these results to broader conclusions about crash prevention. Some research has claimed that surrogate safety studies validate crash analyses[34], but further research on the relationship between surrogate measures and crashes is needed. Third, the site pool was limited, so statistical analyses on the means and variance of the Safe System scores per treatment group could not be performed. More data may allow additional methods to be tested so that statistical differences between treatment groups by Safe System compliance could be found. Finally, the methods used to calculate exposure based on the observed interactions may require refinement to better accommodate total road user volumes rather than focusing solely on those interactions between SUP users and motor vehicles; this type of refinement may provide a better understanding of the exposure score. This study did include total pedestrians and total bicyclists in the evaluation, but because crossings were only recorded until 50 interactions were observed, the evaluation is focused entirely on interactions with the potential to become crashes.

Researchers also noticed other noteworthy findings that do not easily fall into the analysis performed for this project. At one site, it was noticed that a school crossing and a SUP crossing were in close proximity to each other; researchers assumed that the pedestrian crossing signs were intended to account for both crossings, but it is possible that drivers may need extra signage to watch for crossing pedestrians if multiple crossings are in close proximity. Researchers also noticed that features visible in Google Maps® may differ from those visible in Google Streetview®, so field visits may provide more accurate data than can be found through desk reviews. Finally, researchers recommend a Delphi process to further calibrate the qualitative Safe System tool.

9 Implementation & Technology Transfer Plan

This project produced a number of resources that NCDOT and municipality staff can use to collect relevant data on SUP crossing sites, evaluate those sites for potential risk factors, evaluate those sites for compliance with Safe System principles, and identify the most appropriate SUP crossing treatments for use at these sites. The resources include Microsoft Excel spreadsheets that link a checklist that can be filled out during a site visit (or desk review) to produce a Safe System score based on the Safe System SUP Crossing Evaluation spreadsheet, as well as a Safe System SUP Crossing Decision tool that takes the recommendations shown in Table 30 and generates recommendations based on user input, as shown in Figure 14 and Figure 15. Figure 15 is a flowchart that allows users to work through Table 30 with data inputs by answering a series of yes or no questions. The flowchart is also included as a separate document.

Engineers and planners can use these tools for scenario testing similarly to the case studies presented in Section 7. Both the process of tabulating risk factors to fill out the checklist and an assessment of the Safe System scores can be valuable for determining if additional treatments are needed. The Safe System SUP Crossing Evaluation tool itself can be calibrated to local conditions if different weighting criteria are determined.

Researchers are able to support and train NCDOT and local staff in the use of these tools. Researchers are also able to host and facilitate a Delphi-style consensus building exercise to finetune the weights in the Safe System SUP Crossing Evaluation tool. The calibrated tool may facilitate both identifying the most appropriate treatments for planned SUP crossings as well as identifying countermeasures that may mitigate risks at existing crossings.

Researchers are also able to share insights into the video data collection process and offer feedback on how best to calculate PET and the other observed behaviors. These data are valuable in themselves for capturing elements of local driving culture, but they can also directly feed into the Safe System SUP Crossing Evaluation tool.

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11 Appendices

A. Additional Literature Review

A.1. Crash Prediction Models Found in the Literature

Additional SPFs or other models that can be used for predicting pedestrian and bicycle crashes include:

- Total number of pedestrian crashes at intersections[39]
- Number of pedestrian crashes on principal arterials[40]
- Number of pedestrian crashes on road segments with 5 or more lanes[40]
- Number of pedestrian crashes where the pedestrian was struck by a through vehicle while crossing at an intersection[39]
- Number of pedestrian crashes where the vehicle was traveling straight and a pedestrian was struck while walking along or crossing a segment (i.e., not at an intersection) [9,41,42]
- Number of pedestrian crashes where the pedestrian was struck by a vehicle while crossing at night[9,41]
- Number of pedestrian and bicycle crashes at the census block level[43]
- Number of bicycle crashes at intersections[44]
- Number of non-fatal bicyclist crashes on road segments per mile[45]
- Number of bicycle crashes at unsignalized intersections[46]
- Number of pedestrian crashes on uncontrolled midblock segments[18]
- Number of bicyclist crashes at signalized intersection on low-speed roadways[18]
- Number of pedestrian crashes where speed limits are 35mph or greater[40]
- Number of pedestrian crashes where medians are present[40]

A.2. Safety Treatments at Typical Intersections and Other Crossing Locations

Using literature synthesis and stakeholder interviews, Thomas et al. (2015) identified treatments commonly used in 11 different countries that may be viable for addressing bicyclist safety problems in the United States. These solutions include[47]:

- Overpasses, underpasses, and grade separated junctions for when bicycle traffic intersects with major roadways
- At-grade roundabouts when bicycle traffic intersects lower-speed roadways
- Path and lane-lighting to illuminate road users at night at crossing locations
- Signal prioritization, such as "green waves" or leading bicycle intervals (LBIs), when bicycle traffic intersects significant motor vehicle traffic

Kwigizile et al. (2016) examined the efficacy of pedestrian count-down signals at intersections in Michigan.[48] The researchers collected data on several variables, including traffic volumes (AADT), median type, roadway division, and adjacent land use on all intersection legs. They then calculated expected crashes (a type of crash prediction developed through an Empirical Bayes equation that weights SPF-predicted crashes against historical crashes) and a crash modification function (CMF) (a unitless number that indicates the efficacy of a treatment) for pedestrian countdown signals. They found that this treatment type reduces all pedestrian crashes by 32% (and pedestrian crashes involving those aged 65 and older by 65%). They also found that pedestrians had a strong preference for pedestrian countdown signals compared to no pedestrian countdown features.

Zegeer et al. (2017) developed SPFs using an Empirical Bayes before-after analysis method to evaluate the efficacy of four types of pedestrian crossing treatments: rectangular rapid flashing beacons (RRFBs), pedestrian hybrid beacons (PHBs), pedestrian refuge islands, and advance YIELD or STOP markings and signs. By analyzing 1,000 treatment sites in 14 U.S. cities, they determined the following CMFs shown in Table 31.[49]

Table 31. Estimated CMFs from Before-After Evaluation of Pedestrian Crossing Treatments[49]

Table 4-4. Estimated crash modification factors from the before-after evaluation.

Treatment and number of sites	Crash type	# of crashes per year (before)	# of crashes per year (after)	# of crashes (before)	# of crashes (after)	EB estimates (before)	Variance of EB (before)	EB estimates (after)	Variance of EB (after)	CMF	S.E. of CMF	p-value
Refuge island: 68 sites	Pedestrian	2.53	2.23	6	13	7.9	2.0	18.8	11.2	0.671	0.215	0.126
Advanced YIELD or STOP markings and signs: 69 sites	Total	163.16	148.78	310	671	304.6	233.7	754.7	2254.5	0.886	0.065	0.079
	Rear-end and Sideswipe	83.68	74.28	159	335	155.5	101.0	416.2	1068.8	0.800	0.076	0.008
	Pedestrian	9.47	4.66	18	21	14.3	5.4	32.2	27.4	0.636	0.169	0.031
Pedestrian hybrid beacons & Advanced YIELD or STOP markings and signs: 27 sites	Total	87.73	63.03	286	341	275.1	232.3	413.2	1078.5	0.820	0.078	0.021
	Rear-end and Sideswipe	38.65	33.64	126	182	117.5	84.0	205.4	460.9	0.876	0.111	0.264
	Pedestrian	3.07	0.74	10	4	8.0	2.9	15.6	13.3	0.244	0.128	<0.001

Stapleton et al. (2017) examined driver yielding compliance (a type of surrogate safety measure similar to deceleration) at uncontrolled midblock crosswalks.[50] The researchers conducted field studies at 31 low-speed crossings and measured driver yielding compliance in relation to unmarked crossings, continental crossings, and additional treatments (PHBs, RRFBs, or in-street R1-6 signs) using a mixed effects logistic regression model. The researchers found that compared to unmarked crossings, the highest driver yielding compliance corresponded to those facilities with additional treatments, especially PHBs. Their results indicate that treatments like PHBs or RRFBs may improve pedestrian safety by improving driver yielding.

Lu et al. (2018) studied bicyclist safety at intersections using surrogate measures (braking and conflicting traffic) similar to deceleration.[51] The researchers evaluated the efficacy of signal timing treatments at a case study intersection and found that the adaptive signal timing plan provided improved throughput for bicyclists. However, the connections to safety in this analysis are abstract, and the results may not be readily applicable to shared use path crossings.

A.3. Other Crossing Guidance

Birmingham, Alabama

Birmingham, AL uses only the very extreme of the figure, requiring a vehicles per hour (vph) volume of 2,000 and a pedestrians per hour (PPH) volume of at least 20.[52]

Ireland

In Ireland, most midblock crossings are Pelican Crossings. Pelican Crossings are a type of PHB. However, midblock crossings which cross only one lane, and which have speeds under 50kph, may use Zebra Crossings instead, which are defined as a crosswalk with a flashing amber beacon.[53]

Australia and New Zealand

Austroads is the collective of all levels of transport agencies for both Australia and New Zealand. Austroads offers an online tool where users can input a variety of details about a midblock crossing and the tool will assess the viability of a crossing.[54] A summary of guidelines is provided in Table 32.

Table 32. Austroads Guidelines for Traffic Devices Depending on Street Type[54]

Table 8.5: Guideline for selection of facilities according to road classification

Facility	Freeway/ motorway	Primary arterial urban/(rural)	Secondary arterial	Collector road	Local street
Refuge/traffic island, median	X	O	O	A	A
Kerb extension	X	X/(O)[(3)]	O	A	A
Road narrowing, indented parking	X	X	X	A	A
Pedestrian fencing[(1)]	X[(2)]	O	O	O	X
Speed control device	X	X	X	O	A
Pedestrian (Zebra) crossing	X	X	O	O	A
Children's crossing	X	X	X	O	A
Pedestrian traffic signals	X	A/(X)	A	O	X
Grade separated	A	O	O	X	X
Mall	X	X	X	O	O
Integrated	X	X	X	X	O

A.4. Examples of Traffic Control Devices

Table 33. Examples of Common Traffic Control Devices

Municipality	Traffic Device	Example
Cary, North Carolina	Rectangular Rapid Flash Beacon	 Black Creek Greenway 35°48'05.0"N 78°47'29.9"W

Municipality	Traffic Device	Example
Beaverton, Oregon	Signalized Shared Use Path Crossing	 Water House Trail 45°31'07.9"N 122°50'45.2"W
Orlando, FL	Signalized Shared Use Path Crossing	 Little Econ Greenway 28°34'27.0"N 81°16'10.6"W
Dublin, Ireland	Signalized Shared Use Path Crossing	 Unnamed SUP 53°19'55.2"N 6°20'46.9"W

Municipality	Traffic Device	Example
Vancouver, British Columbia	Rectangular Rapid Flash Beacon	 Arbutus Greenway 49°14'31.2"N 123°08'49.2"W
Tokyo, Japan	Signalized Shared Use Path Crossing	 Unnamed SUP 35°38'56.4"N 139°39'06.3"E
Vancouver, British Columbia	Signalized Shared Use Crossing	 Arbutus Greenway 49°15'49.9"N 123°09'08.4"W
Prague, Czech Republic	Speed Bumps	 Unnamed SUP 50°05'51.2"N 14°27'23.3"E

A.5. Other Markings Guidance

Indianapolis, Indiana

Indianapolis, Indiana requires that SUP crossings must include high visibility markings that follow the MUTCD for all but residential roads. The city also requires that the width of the crossing be the same width of the trail. The city recommends that crossings happen at 90 degrees whenever possible and, if the crossing should include a pedestrian refuge, the crossing on either side of the refuge should be offset as to orient bicyclists and pedestrians towards oncoming traffic.[55]

British Columbia, Canada

At SUP midblock crossings, British Columbia requires that combined crosswalks and cross-rides be used. The stop lines should be set six to fifteen meters on the road from the pathway if the path users have the right of way. If road users have the right of way, then stop lines should be set six to fifteen meters on the pathway from the road. They also specify that yield lines can be used on either the road or the path to indicate right of way.[56]

A.6. Examples of Markings

Table 34. Examples of Common Markings

Municipality	Markings	Example
Cary, North Carolina	No markings	 Speight Branch Greenway 35°44'54.8"N 78°44'46.8"W
Vancouver, British Columbia	Combined crosswalk and cross-ride	 Arbutus Greenway 49°14'31.2"N 123°08'49.2"W

Municipality	Markings	Example
Cary, North Carolina	Continental Crossing	 White Oak Greenway 35°46'37.9"N 78°51'35.7"W
Cary, North Carolina	Continental Crossing with Yield Lines	 Black Creek Greenway 35°48'05.0"N 78°47'29.9"W
Essex, Ontario	Standard Crossing	 Chrysler Greenway 42°10'57.1"N 82°57'34.8"W
Birmingham, Alabama	Ladder Crossing	 Shades Valley Greenway 33°27'56.9"N 86°46'54.9"W

Municipality	Markings	Example
Beaverton, Oregon	Alternative Pavement Surface	 Burntwood West Trail 45°28'22.1"N 122°50'58.2"W
Beaverton, Oregon	Standard Crossing with Two Sets of Checked Lines	 Waterhouse Trail 45°31'22.9"N 122°50'45.9"W
Vitoria-Gasteiz, Spain	Continental Crossing with Stop Lines	 Belate Kalea 42°51'48.0"N 2°42'05.3"W

Municipality	Markings	Example
Annandale, New South Wales, Australia	Continental Crossing with Two Green One-Way Cross-Rides	 Unnamed SUP 33°52'56.5"S 151°10'34.7"E

A.7. Other Signage Guidance

Minnesota

The Minnesota Department of Transportation recommends that speeds, relative volumes, and relative importance should be the most crucial factors when choosing whether to use a stop or yield sign on a SUP; the MDOT also specifies a stop sign should never be used when a yield line would suffice. Another recommendation is that the mixing of yellow and fluorescent yellow-green signs should be avoided. Lastly, it is required that bicycle warning signs must be accompanied by a diagonal downward pointing arrow to indicate the location of the crossing.[57,58]

Central Ohio

High visibility signs should call attention to a SUP crossing and must follow the MUTCD.[59]

Indianapolis, Indiana

Warning and stop signs should be placed on SUPs when approaching local or major roads and vehicular scaled greenway identification signage should be placed adjacent to the crossing. Additionally, high visibility signage should call attention to the crossing and must follow the MUTCD.[55]

British Columbia, Canada

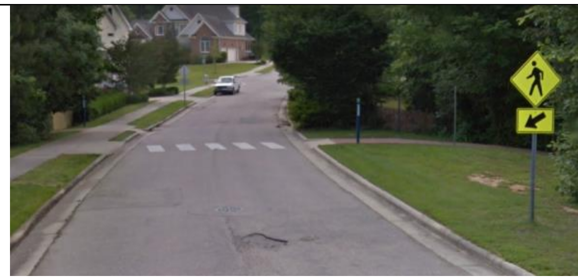
Midblock crossings for SUPs must include a Shared Pathway Sign (RB-93 in the MUTCD-C) on pathway leading up to the crossing. For all ages and abilities facilities, vehicular traffic should be stopped at minor road crossings and signalized at major road crossings. A Pedestrian and Bicycle Crossing Ahead sign (MUTCD-C WC-46) should be used to indicate to motorist that they are approaching a SUP crossing.[56]

A.8. Examples of Signage

Table 35. Examples of Common Signage

Municipality	Signage	Example
Cary, North Carolina	Crossing with Stop Signs on Path	 Speight Branch Greenway 35°44'54.8"N 78°44'46.8"W
Beaverton, Oregon	Yellow Bike/Ped Warning with Downwards Diagonal Arrow and Stop Sign on Path	 Westside Regional Trail 45°28'37.4"N 122°50'26.9"W
Birmingham, Alabama	Yellow Pedestrian Warning Sign On Road with Stop Sign on Path	 Shades Valley Greenway 33°27'56.9"N 86°46'54.9"W

Municipality	Signage	Example
Detroit, Michigan	Fluorescent Yellow-Green Pedestrian Warning Sign with Downwards Diagonal Arrow and Stop Sign on Road	 Shades Valley Greenway 33°27'56.9"N 86°46'54.9"W
Essex, Ontario	Yellow Pedestrian Warning Sign with Roadway Obstruction Sign	 Chrysler Greenway 42°10'57.1"N 82°57'34.8"W
Birmingham, Alabama	Stop Signs on Path with Small Yield to Pedestrian Sign on Road	 Dorothy Spears Greenway 33°31'26.7"N 86°50'27.0"W
Raleigh, North Carolina	Fluorescent Yellow-Green Bike/Ped Warning Sign with "Trail X-ING" Sign and Small Yield to Pedestrian Signs on Median	 Dorothy Spears Greenway 33°31'26.7"N 86°50'27.0"W

Municipality	Signage	Example
Cary, North Carolina	Fluorescent Yellow-Green Ped Warning Sign with Downward Diagonal Arrow in Advance of Crossing	 Green Hope School Greenway 35°47'44.5"N 78°52'53.8"W
Vancouver, British Columbia	Bike/Ped Warning Sign	 Arbutus Greenway 49°14'31.2"N 123°08'49.2"W
Vancouver, British Columbia	Bike/Ped Warning Sign with Stop Sign and Orange Reflector	 Arbutus Greenway 49°15'36.2"N 123°09'09.0"W

Municipality	Signage	Example
Vancouver, British Columbia	Pedestrian Warning Sign, Overhead Pedestrian Warning, Roadway Obstruction Sign	 BC Parkway 49°13'16.5"N 122°59'39.0"W
Vitoria-Gasteiz, Spain	Pedestrian Crossing Sign	 Unnamed SUP 42°52'04.9"N 2°41'51.7"W
Annandale, South New Wales	Give Way to Cyclist and Pedestrian Warning Sign	 Unnamed SUP 33°52'56.5"S 151°10'34.7"E

Municipality	Signage	Example
Raleigh, North Carolina	Fluorescent Yellow-Green Bike/Ped Warning Sign with Downwards Arrow and Yield Here to Pedestrians Sign	 Unnamed SUP 35°45'54.9"N 78°41'39.7"W

A.9. Other Grade Separation Guidance

Washington State

The Washington State Department of Transportation recommends that grade separated crossings provide the same minimum clear width as the approach paved SUP plus graded clear areas. In tunnels and undercrossings, it is also important to design a minimum vertical clearance such that maintenance and emergency services can access the tunnel or undercrossing. Additionally, expansion joints should be placed perpendicular to the SUP, with a maximum gap of 0.5" or covered with a slip resistant plate.[60]

Massachusetts

The Massachusetts Department of Transportation recommends the minimum clear width of both over passes and underpasses be the same as the approach of the SUP plus a minimum two feet of clear shoulder on either side of the path. Any slope greater than 5% must be treated as a ramp and any slope over 8.33% requires special approval from the Massachusetts Architectural Access Board. For overpasses, the railing should be at least 3.5 feet high. For underpasses, a vertical clearance of eight feet to twelve feet should be provided based on the anticipated users of the path.[61]

Promoting Cycling for Everyone as a Daily Transport Mode (PRESTO), EU

For tunnels, PRESTO recommends that the carriage way be raised two meters to decrease the depth of and the gradient entering the tunnel. The gradient should not exceed 5% and the tunnel itself should be 2.5 meters high by 3.5 meters wide, with separated bicycle and pedestrian paths. The entrance to the tunnel should be unobstructed and ideally the exit to the tunnel should be able to be seen from the entrance. Daylight gaps should be used whenever possible, and any lighting used should be vandal proof. Lastly, straight vertical walls should be avoided; walls should recede at the top to help prevent claustrophobic feelings.[62]

For bridges, the carriage way should be lowered to reduce the height necessary to climb. The bridge should be 3.5m wide with at least 4.5m of headroom and should have a handrail at least 1.2m high. There should be a max gradient of 5% and if there is no room for a ramp, stairs with bicycle channels should be implemented.[62]

A.10. Examples of Grade Separation

Many SUPs run alongside rivers and other waterways; for this reason, most underpasses are pre-existing as the bridge already runs over a river. Examples of purpose-built underpasses and tunnels specific to SUPs are rarer than underpasses which utilize existing bridges.

Table 36. Examples of Common Grade Separation

Municipality	Grade Separation Type	Example
Raleigh, North Carolina	SUP Underpass	 Mine Creek Trail 35°52'06.8"N 78°39'02.9"W
Raleigh, North Carolina	SUP Bridge	 Reedy Creek Trail 35°48'20.2"N 78°41'37.6"W

Municipality	Grade Separation Type	Example
Prague, Czech Republic	SUP Tunnel	 Unnamed SUP 50°06'12.2"N 14°27'51.3"E

A.11. Other SUP Crossing Considerations

The city of Toronto recommends a combined cross-ride configuration (one with cross-rides on either side of a crosswalk) for midblock locations with low to moderate volumes of trail users. A separated cross-ride (one cross-ride with crosswalks on either side) is recommended for midblock locations where trail user volumes are high. Separated cross-rides also have improved visibility, making them suitable for midblock crossings where the street has high-speed high-volume traffic. The asymmetric separated cross-ride (a cross-ride next to a crosswalk) is the most used crossing type in Toronto and is appropriate for many crossings.[63]

Table 37. Examples of Common Cross-Rides

Municipality	Cross-Ride Type	Example
Toronto, Ontario, Canada	Separated Cross-Ride	 Gatineau Hydro Corridor 43°45'55.0"N 79°14'17.7"W

Municipality	Cross-Ride Type	Example
Toronto, Ontario, Canada	Asymmetric Separated Cross-Ride	 Gatineau Hyrdo Corridor 43°45'36.5"N 79°14'48.8"W
Annandale, South New Wales	Combined Cross-Ride	 Unnamed SUP 33°52'56.5"S 151°10'34.7"E

Table 38. Examples of Common Trail Obstructions

Municipality	Obstruction Type	Example
Portland, Oregon	Intentional Trail Obstruction	 Fanno Creek Trail 45°28'15.2"N 122°46'11.1"W

Municipality	Obstruction Type	Example
Beaverton, Oregon	Intentional Trail Obstruction	 Burntwood West Trail 45°28'22.1"N 122°50'58.2"W
Deje, Sweden	Intentional Trail Obstruction	 Klarälvsbanan Greenway 59°36'35.1"N 13°28'04.1"E

B. Video Coding

Figure 16 is an example of how the codes were presented during the database collection process. Three interactions are shown in this figure. In the top left-hand corner is the time stamp that the interaction started. The columns labeled “Mode” and “Direction from” indicate the kind of road user and their trajectory through the crossing. The “Interaction” and “Reaction” columns indicate the type of interaction and reaction, and whether it was the vehicle that had the reaction. The PET is located in the top right-hand corner for each interaction.

Event	Time Stamp			Mode	Singleton/ Platoon	Direction From	Large Vehicle	Interaction	Reaction	Who Yielded?	Correct Yield?	PET
		Seconds in Trial	Comments									
E	15:03:56		1	Vehicle								7.8
X				Vehicle		Bottom						
C							Large					
Q				Pedestrian								
D				Pedestrian		Right						
U				Pedestrian				None	None			
N				Pedestrian							No	
E	15:07:04		2	Vehicle								9.4
X				Vehicle		Bottom						
W				Bike								
A				Bike	Platoon							
D				Bike		Right						
U				Bike				None	None			
N				Bike							No	
W	15:07:14		3	Bike								5.25
D				Bike		Right						
E				Vehicle								
A				Vehicle	Platoon							
S				Vehicle		Top						
O				Vehicle				Avoidance	Slow/ Brakes			
K				Vehicle						Vehicle		
M				Vehicle							Yes	

Figure 16. Example Interaction Coding from the intersection of the ATT & Cornwallis

C. Safe System SUP Crossing Evaluation Tool

In order to use the Safe System SUP Crossing Evaluation Tool, practitioners may work through the following steps.

1. Identify relevant sites for analysis (see Section 3).
2. Collect conflicting traffic stream volumes (see Section 4).
3. Collect geometric data and speed limit data or operational vehicle speed data using a desk review of site characteristics using Google Maps® and StreetView®.
4. Complete the Safe System SUP Crossing Checklist using the information collected in steps 2 and 3.
5. Identify relevant countermeasures—either full crossing treatment upgrades or other traffic safety countermeasures, like traffic calming devices—to reduce scores in each Safe System criterion included in the Safe System SUP Crossing Evaluation tool.

To fill out the checklist shown in Figure 6 and return the corresponding scores discussed in Section 5, the research team identified data sources for each element, as summarized in Table 39.

Table 39. Data Collected for Safe System Evaluation

Criteria	Parameter	Data Source
Geometry	Function classification (i.e., local, collector, arterial)	Google Maps/Streetview
	Number of lanes	Google Maps/Streetview
	Lane widths (average)	Calculated manually using Google Maps
	Presence of median	Google Maps/Streetview
	Width of median on each approach	Calculated manually using Google Maps
	Presence of bike lanes	Google Maps/Streetview
	Presence of crossing treatment	Google Maps/Streetview
	Type of crossing treatment	Google Maps/Streetview
	Sight distance	Calculated manually using Google Maps
Operations	Conflicts	Calculated from camera data
	Speed limit	Google Maps/Streetview
	Yielding behavior (surrogate for vehicle deceleration)	Calculated from camera data
	Volumes of each road user	Vehicles – NCDOT GIS Pedestrians – Calculated from camera data Bicycles – Calculated from camera data
	Traffic composition (i.e., percent of larger vehicles)	Calculated from camera data
	On-street parking	Google Maps/Streetview
	Roadway lighting	Google Maps/Streetview
	Signage	Google Maps/Streetview
	One-way or two-way flow of traffic	Google Maps/Streetview
	Access Points	Google Maps/Streetview

After the relevant data are collected, the exposure, likelihood, and severity table cells are filled out with either a 0, 1, or 2, using a the Safe System SUP Crossing Checklist, shown in Figure 17. Note that instructions for filling in each cell (e.g., case-sensitive responses and needed calculations) are shown to the right of the Direction 2 column in the Microsoft Excel sheet.

PLEASE ANSWER EACH QUESTION BELOW FOR BOTH ROADWAY DIRECTIONS AT THE SUP CROSSING				
Safe System Criterion	**Question Number**	**Safety Question**	**Direction 1**	**Direction 2**
Exposure	E-1	What is the functional classification of this roadway? (same answer per side)		
	E-2	Is traffic flow one-way or two-way? (1 or 2)		
	E-3	How many lanes must a pedestrian or bicyclist cross to be clear of this direction of traffic?		
	E-4	What is the average lane width (in ft) per direction?		
	E-5	Is there a raised median/pedestrian refuge at this crossing location? (yes or no)		
	E-6	If there is a median (E-5=yes), how wide (in ft) is it?		
	E-7	Is there on-street parking on this side of the street? (yes or no)		
	E-8	Are there are observed conflicts or near-misses between pedestrians/bicyclists and motor vehicles at this location? (yes or no)		
	E-9	What is the directional AADT at this crossing location?		
	E-10	Is the crossing pedestrian volume per hour high, low, or none? (same answer per side)		
	E-11	Is the crossing bicycle volume per hour high, low, or none? (same answer per side)		
		Exposure Criteria Average	**3**	
Likelihood	L-1	Is there a light source visible from the trail access point on this side of the street? (yes or no)		
	L-2	What is the posted speed limit (in mph) on this roadway?		
		Based on L-2, the necessary stopping sight distance (in ft) in each direction should be:	0	0
	L-3	Is there a trail crossing sign/warning sign placed far enough upstream of the crossing to allow a vehicle to stop? (yes or no)		
	L-4	Is there a clear sight triangle upstream of the crossing location that allows clear stopping sight distance? (yes or no)		
	L-5	Is the view from the trail approach clear of obstructions? (yes or no)		
	L-6	Does the crossing have any additional treatments beyond simple paint? (yes or no)		
	L-7	Does a bike facility intersect the SUP crossing at this location? (yes or no)		
		Likelihood Criteria Average	**0**	
Severity	S-1	Has hard braking or poor yielding behavior been reported at this site? (yes or no)		
	S-2	How many access points (e.g., private driveways) are there within the required stopping sight distance of the crossing location?		
	S-3	How many traffic control devices or signs are there within the required stopping sight distance of the crossing location?		
	S-4	Is the traffic composition at least 30% SUVs or pickup trucks? (yes or no)		
		Severity Criteria Average	**0**	
Safe System Compatibility Score		Exposure Translated Score	1	
		Likelihood Translated Score	1	
		Severity Translated Score	1	
		Total	1	/64

Figure 17. Checklist for Performing Safe System Scoring

D. Analytical Model Comparisons

Model sets and notes for which models were included in the report are presented in this Appendix.

D.1. Linear Regression Results

The Type III Statistical Significance column shows the p-values of individual variables and describes the overall significance of the variables in the model. For categorical variables, the Type III effects may indicate statistical significance, but not all variable levels may be statistically significant.

Table 40. Tested Linear Regression Models

Linear Regression Model Number	Variable Set	R^2	Type III Statistical Significance	Notes
1	TreatType	0.110999	<0.0001	This model shows that the variable for treatment type can be used to predict PET, although the variable explains very little of the variance in the model.
2	TreatType SpeedLim AADT AADT*SpeedLim	0.120304	0.0003 0.3149 0.5375 0.4431	Not all variables are statistically significant.
3	TreatType SpeedLim AADT*SpeedLim	0.120304	<.0001 0.3149 0.7227	Not all variables are statistically significant.

Linear Regression Model Number	Variable Set	R^2	Type III Statistical Significance	Notes
4	TreatType SpeedLim	0.119522	<.0001 0.0698	Speed limit is still not statistically significant.
5	SpeedLim	0.018246	0.0036	Speed limit itself is statistically significant when TreatType is not included, but the fit (according to r^2) is not as good as TreatType alone.
6	AADT	0.002217	0.2007	AADT alone is not statistically significant.
7	Fun_Class	0.176923	<0.0001	Functional classification alone explains more variance in the model than treatment type, but this model is less useful for determining treatment guidance.
8	TreatType SpeedLim AADT AADT*SpeedLim Fun_Class	0.1225030	0.2002 N/A 0.0382 N/A <0.0001	The inclusion of functional classification obfuscates the effects of other site characteristics.
9	TreatType SpeedLim AADT AADT*SpeedLim MaxLWidth	0.124167	<.0001 0.9883 0.9569 0.7247 0.0732	Maximum lane width is not statistically significant.
10	TreatType AADT SpeedLim MaxLWidth	0.124018	<.0001 0.5011 0.1265 0.0551	Removing the interaction term does not make MaxLWidth statistically significant.
11	TreatType SpeedLim MaxLWidth	0.123475	<.0001 0.0674 0.0697	Removing AADT does not make MaxLWidth statistically significant.
12	TreatType SpeedLim AADT AADT*SpeedLim MaxLNum	0.120841	<.0001 0.9530 0.8418 0.8429 0.5047	Maximum number of lanes is not statistically significant, nor are other important explanatory variables.
13	TreatType AADT AADT*SpeedLim MaxLNum	0.120837	<.0001 0.2817 0.1693 0.2282	Removing SpeedLim does not make other variables statistically significant.
14	TreatType AADT*SpeedLim MaxLNum	0.120837	<.0001 0.1486 0.2282	Removing AADT does not make other variables statistically significant.
15	ExpScore	0.048451	<0.0001	This model shows that the variable for exposure can be used to predict PET, although the variable explains very little of the variance in the model.
16	LikScore	0.042873	<0.0001	Likelihood score is statistically significant, but the fit is not as good as Model 15.

Linear Regression Model Number	Variable Set	R^2	Type III Statistical Significance	Notes
17	SevScore	0.000042	0.8600	This model does not have a statistically significant independent variable.
18	SSEScore	0.042437	<0.0001	Safe System score is statistically significant, but the fit is not as good as Model 15.
19	ExpScore LikScore SevScore SSEScore	0.098350	0.0026 0.7902 <.0001 0.0004	The Likelihood score is not statistically significant in this model.
20	ExpScore SevScore SSEScore	0.098263	0.0026 <.0001 <.0001	Exposure, severity, and Safe System score are all statistically significant when included together.
21	ExpScore SevScore	0.048809	<.0001 0.5987	When the Safe System score is eliminated, the Severity score is no longer statistically significant.
22	TreatType SpeedLim AADT AADT*SpeedLim SevScore	0.136007	<.0001 0.0299 0.1419 0.1404 0.0003	The AADT variable and interaction term are not statistically significant in this model.
23	TreatType AADT*SpeedLim SevScore	0.130407	<.0001 0.0087 0.0021	All three independent variables have statistically significant relationships with PET.
24	TreatType SpeedLim AADT AADT*SpeedLim ExpScore	0.137053	<.0001 0.6995 0.8969 0.2930 0.0002	Three variables are not statistically significant, so this model is rejected.
25	TreatType SpeedLim AADT*SpeedLim ExpScore	0.137053	<.0001 0.6995 0.1086 0.0002	Speed limit is not statistically significant in this model.
26	TreatType AADT*SpeedLim ExpScore	0.136877	<.0001 0.0012 0.0001	All three independent variables have statistically significant relationships with PET, and the model fit is superior to Model 23.
27	TreatType AADT SpeedLim AADT*SpeedLim LikScore	0.152769	<.0001 0.7427 0.9155 0.7261 <.0001	Three variables are not statistically significant, so this model is rejected.
28	TreatType AADT*SpeedLim LikScore	0.152756	<.0001 0.0057 <.0001	All three independent variables have statistically significant relationships with PET, and the model fit is superior to Model 26.
29	TreatType AADT SpeedLim	0.180501	<.0001 0.2408 0.2361	Three variables are not statistically significant, so this model is rejected.

Linear Regression Model Number	Variable Set	R^2	Type III Statistical Significance	Notes
	AADT*SpeedLim SSEScore		0.7374 <.0001	
30	TreatType AADT SpeedLim SSEScore	0.180375	<.0001 0.0302 0.0010 <.0001	All independent variables have statistically significant relationships with PET, and the model fit is superior to Model 28.
31	TreatType AADT SpeedLim AADT*SpeedLim ExpScore SevScore LikScore SSEScore	0.188761	<.0001 0.2359 0.3335 0.3302 0.0187 0.0143 0.5985 <.0001	Four variables are not statistically significant, so this model is rejected.
32	TreatType AADT SpeedLim AADT*SpeedLim ExpScore SevScore SSEScore	0.188452	<.0001 0.2035 0.2430 0.3057 0.0195 0.0155 <.0001	Three variables are not statistically significant, so this model is rejected.
33	TreatType AADT SpeedLim ExpScore SevScore SSEScore	0.187281	<.0001 0.4268 0.0152 0.0356 0.0181 <.0001	AADT is not statistically significant, so this model is rejected.
34	TreatType SpeedLim ExpScore SevScore SSEScore	0.186576	<.0001 0.0111 0.0028 0.0066 <.0001	All independent variables have statistically significant relationships with PET, and the model fit is superior to Model 30.
35	TreatType SpeedLim AADT ExpScore SevScore	0.150612	<.0001 0.0003 0.0196 0.0001 0.0004	All independent variables have statistically significant relationships with PET, but the model fit is poorer than Models 30 and 34.
36	TreatType SpeedLim ExpScore SevScore	0.144242	<.0001 <.0001 0.0024 0.0012	All independent variables have statistically significant relationships with PET, but the model fit is poorer than Model 35.
37	TreatType ExpScore SevScore	0.116431	<.0001 0.1659 0.3217	This model does not work.

B.2. Logistic Regression Results

The Type III Statistical Significance column shows the p-values of individual variables and describes the overall significance of the variables in the model. For categorical variables, the Type III effects may indicate statistical significance, but not all variable levels may be statistically significant.

Table 41. Tested Logistic Regression Models

Logistic Regression Model Number	Variable Set	AIC	Type III Statistical Significance	Notes
1	TreatType	811.212	<0.0001	The results of this model show that TreatType can also be used to predict the log odds of an interaction being critical.
2	TreatType SpeedLim AADT AADT*SpeedLim	793.109	<.0001 0.0855 0.0465 0.9963	The interaction term between speed limit and AADT is not statistically significant and was excluded from further logistic regression analysis.
3	TreatType SpeedLim AADT	791.109	<.0001 0.0015 0.0409	With the exclusion of the interaction term, AADT is now statistically significant for predicting the log odds of a critical interaction.
4	TreatType SpeedLim AADT MaxLWidth	791.953	<.0001 0.0230 0.0232 0.2802	Adding the MaxLWidth variables causes the AADT variable to be statistically significant, but MaxLWidth is not.
5	TreatType SpeedLim AADT MaxLNum	792.983	<.0001 0.0023 0.0521 0.7232	When MaxLNum is included, AADT is not statistically significant, nor is MaxLNum.
6	TreatType SpeedLim	793.333	<.0001 0.0005	Both variables are statistically significant, but the model fit is not as good as that for Model 3, according to the AIC.
7	TreatType SpeedLim AADT Fun_Class	768.236	0.3430 0.0002 0.0052 <.0001	The functional classification variable obfuscates the effect of the treatment type variable, so further models with functional classification are rejected.
8	ExpScore	840.050	0.0104	Exposure score is statistically significant for determining the log odds of an interaction being critical.
9	LikScore	847.0111	0.8389	Likelihood score is not statistically significant for determining the log odds of an interaction being critical.
10	SevScore	842.467	0.0328	Severity score is statistically significant for determining the log odds of an interaction being critical, although the AIC indicates slightly worse model fit than the model with ExpScore alone.
11	SSEScore	846.908	0.7038	The Safe System score alone is not statistically significant for determining the log odds of an interaction being critical.

Logistic Regression Model Number	Variable Set	AIC	Type III Statistical Significance	Notes
12	ExpScore LikScore SevScore SSEScore	835.806	0.0671 0.1949 0.0018 0.0530	Only the severity score is statistically significant when comparing all of the Safe System criteria.
13	ExpScore SevScore SSEScore	835.477	0.0526 0.0045 0.1200	When the likelihood score is eliminated from model 12, the Safe System score is not statistically significant.
14	ExpScore LikScore SevScore	837.706	0.0112 0.6037 0.0151	Only the exposure score and severity score are statistically significant when comparing the components of a Safe System score.
15	ExpScore SevScore	835.979	0.0052 0.0145	After eliminating the non-statistically significant variables from Model 14, exposure score and severity score were retained.
16	TreatType SpeedLim AADT ExpScore LikScore SevScore SSEScore	781.178	<.0001 0.0011 0.0221 0.1415 0.0457 0.0465 0.0013	Not all of the Safe System variables are statistically significant.
17	TreatType SpeedLim AADT LikScore SevScore SSEScore	781.341	<.0001 0.0024 0.0032 0.0112 0.1487 0.0018	Note that severity score is no longer statistically significant after eliminating the exposure score.
18	TreatType SpeedLim AADT LikScore SSEScore	781.467	<.0001 0.0040 0.0044 0.0128 0.0018	All variables in the combined model are now statistically significant, including AADT.
19	TreatType SpeedLim AADT LikScore	792.898	<.0001 0.0018 0.0375 0.6458	The likelihood score is not statistically significant when the Safe System score is not included.
20	TreatType SpeedLim AADT SSEScore	786.117	<.0001 0.0051 0.0048 0.0115	The Safe System score is statistically significant when likelihood score is excluded, although this model has a slightly worse fit based on AIC than Model 18.