Development of Crash Modification Factors for Comparing Standard Diamond Interchange to Other Common Interchange Designs

NCDOT Project 2023-19
FHWA/NC/2023-19
July 2025

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RESEARCH & DEVELOPMENT

Development of Crash Modification Factors for Comparing Standard Diamond Interchange to Other Common Interchange Designs

FINAL REPORT

Submitted to:
North Carolina Department of Transportation
Office of Research
(Research Project No. RP2023-19)

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July 2025

Technical Report Documentation Page

1. **Report No.** FHWA/NC/2023-19	2. **Government Accession No.**	3. **Recipient's Catalog No.**
4. **Title and Subtitle** Development of Crash Modification Factors for Comparing Standard Diamond Interchange to Other Common Interchange Designs		5. **Report Date** July 2025
		6. **Performing Organization Code**
7. **Author(s)** Meghna Chakraborty (https://orcid.org/0000-0002-8369-1198), Raghavan Srinivasan (https://orcid.org/0000-0002-3097-5154), Mike Vann (https://orcid.org/0000-0002-7535-883), Taha Saleem (https://orcid.org/0000-0003-4920-0698), and Bo Lan (https://orcid.org/0000-0002-7998-7252).		8. **Performing Organization Report No.**
9. **Performing Organization Name and Address** Highway Safety Research Center University of North Carolina 130 Mason Farm Rd. Campus Box 3430 Chapel Hill, NC 27514		10. **Work Unit No. (TRAIS)**
		11. **Contract or Grant No.**
12. **Sponsoring Agency Name and Address** North Carolina Department of Transportation Research and Development Unit 1549 Mail Service Center Raleigh, North Carolina 276699-1549		13. **Type of Report and Period Covered** Final Report (August 2022 to July 2025)
		14. **Sponsoring Agency Code** RP2023-19
15. **Supplementary Notes**		

16. **Abstract**

This study developed CMFs for comparing standard diamond interchange to other common interchange designs for total counts, fatal-injury (FI), and property damage only (PDO) crashes utilizing crash data from 2019 through 2023 from North Carolina. A total of 214 interchanges were evaluated, including diamond, PARCLO A, PARCLO B, PARCLO AB, single-point, complex-multi, and partial interchanges. The CMFs were developed for different interchange types, considering the baseline as diamond interchanges, utilizing cross-sectional models with negative binomial technique. The results of the cross-sectional analysis revealed that among all interchange types, compared to diamond interchanges, single-point interchanges were shown to have the greatest crash likelihoods for all crash severities, followed by complex interchanges. Also, PARCLO A interchanges were associated with greater crash likelihoods for all crash severities compared to diamond interchanges, but lower likelihoods with respect to single-point and complex interchanges. Partial interchanges had lower likelihoods for all crash severities compared to diamond interchanges, while PARCLO AB was found to be associated with lower likelihood for only PDO crashes. Furthermore, while PARCLO B was associated with slightly higher crash likelihoods for total and FI crashes, it showed a lower likelihood for PDO crashes, compared to diamond interchanges. Additionally, a manual review of a sample of 526 crashes revealed that K crashes, and KA crashes were most common at the diamond interchanges, while crashes at different locations of entry and exit ramps were more common for partial cloverleaf interchange types, except for those occurring at on-ramp terminals on crossroads, which were most common at diamond interchanges. Similarly, crash types, including angle, sideswipe same direction, rear-end, and backing up, head-on, and right-turn crashes, were more common for partial cloverleaf interchange types.

17. **Keywords** Crash modification factors (CMFs), diamond interchange, partial cloverleaf (PARCLO) interchange, single-point urban interchange (SPUI), complex interchange, partial interchange, Safety Performance Functions (SPFs)	18. **Distribution Statement**		
19. **Security Classif. (of this report)** **unclassified**	20. **Security Classif. (of this page)** **unclassified**	21. **No. of Pages** 86	22. **Price**

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

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ACKNOWLEDGEMENTS

This project was funded by the North Carolina Department of Transportation. The research team wishes to thank the many individuals of the North Carolina Department of Transportation who contributed to the project. Special appreciation is also given to the Steering and Implementation Committee for their valuable support of the study.

EXECUTIVE SUMMARY

In order to understand the safety implications of various design alternatives and engineering treatments at interchanges, it is imperative that decisions are made based on the best information available. The NCDOT Transportation Improvement Program (TIP) prioritization process continues to produce many interchange improvement projects, showing that there are significant operational and safety problems at many interchanges across North Carolina (NC) and that potential cost-effective solutions exist for those problems. However, there is a lack of information on the safety performance of rival interchange design concepts, leading to choices based on factors other than safety.

To that end, this study developed crash modification factors (CMFs) for comparing standard diamond interchange to other common interchange designs for total counts, fatal and injury (FI), and property damage only crashes (PDO) utilizing 5 years of crash data from 2019 through 2023, and the interchange inventory developed and maintained by NCDOT. A total of 214 interchanges were evaluated, including diamond, partial cloverleaf A (PARCLO A), PARCLO B, PARCLO AB, single-point, complex-multi, and partial interchanges. The CMFs were developed for different interchange types, considering the baseline as diamond interchanges, utilizing cross-sectional models with negative binomial regression technique.

The results of the cross-sectional analysis revealed that both single-point and complex interchanges were consistently shown to have higher crash likelihoods compared to diamond interchanges for all crash severities. While both PARCLO A and PARCLO B were shown to have a higher likelihood for FI crashes, PARCLO AB did not have any statistically significant impacts on FI crashes. In fact, PARCLO AB was found to be associated with a lower likelihood of PDO crashes. Also, partial interchanges were associated with lower crash likelihoods for all crash severities compared to diamond interchanges. Overall, the effects of interchange type were more pronounced for FI crashes. Table 1 below summarizes the effects of different interchange types analyzed compared to the baseline of diamond interchanges for total, FI, and PDO crashes.

Table 1. Summary of effects of interchanges compared to diamond interchange

Interchange Type	Total Crashes	FI Crashes	PDO Crashes
Diamond	Baseline		
Complex	Higher (130.4%)*	Higher (176.3%)*	Higher (111.7%)*
PARCLO A	Higher (9.3%)*	Higher (16.8%)*	Higher (6%)
PARCLO B	Higher (2.9%)*	Higher (26.7%)*	Lower (4.3%)
PARCLO AB	Lower (9.2%)*	Higher (4.3%)	Lower (13.7%)*
Partial	Lower (57.2%)*	Lower (53.8%)*	Lower (57.3%)*
SPUI	Higher (138.6%)*	Higher (186.7%)*	Higher (122.4%)*

** Denotes the statistically significant associations*

A follow-up descriptive analysis involved manual review of a sample of 526 crashes occurring at 12 interchanges of 5 different types, including diamond, PARCLO A, PARCLO B, PARCLO AB, and single-point interchanges. This review revealed that almost 6 percent of crashes occurred outside of the interchange influence area, and their spatial locations were miscoded in the original crash data utilized in the cross-sectional analysis. The results revealed that the proportions of fatal (K) crashes and fatal and incapacitating injury (KA) crashes combined were the highest at the diamond interchanges. However, for non-incapacitating injury (B) and possible injury (C) crashes, the proportions were the highest at PARCLO B interchange type. Additionally, PARCLO A interchanges experienced the highest proportions of crashes occurring on shoulders and roadside, while single-point interchanges had the highest proportion of crashes occurring on medians. The proportion of crashes occurring at on-ramp terminals on crossroads was the highest at diamond interchanges, followed by PARCLO AB interchanges, while that for crashes occurring at “on-ramp proper” was higher at PARCLO A and PARCLO B interchanges, compared to diamond interchanges. The proportions of crashes at off-ramp entries, “off-ramp proper”, and merge lane between on- and off-ramps were the highest for PARCLO A, single-point, and PARCLO AB interchanges, respectively. PARCLO B interchanges experienced the highest proportions of crashes occurring both at off-ramp terminals on crossroads and on-ramp entries. Besides, the proportions of angle crashes, sideswipe same direction crashes, and crashes with pedal-cyclists were the highest for PARCLO B interchanges, while rear-end and backing up crashes, and crashes with pedestrians were the highest for PARCLO AB interchanges. Finally, PARCLO A interchanges showed the highest proportions of head-on, right-turn, and fixed-object crashes, while single-point interchanges had the highest proportion of run-off-road crashes. Among all these crash types and locations, crashes at median (highest occurrence at SPUI), head-on crashes (highest occurrence at PARCLO A), angle crashes and crashes with pedal-cyclists (highest occurrence at PARCLO B), and rear-end crashes and crashes with pedestrians (highest occurrence at PARCLO AB) might need to be prioritized by practitioners and decision makers owing to higher severities of these crashes.

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Chapter 1. Introduction

1.1 Background

It is undebatable that one of the objectives of state agencies is to reduce the number and severity of crashes within the limits of available resources, science, technology, and legislatively mandated priorities. In order to achieve the greatest return on the investment of limited budgets, it is imperative that decisions are made based on the best information regarding the safety implications of various design alternatives and engineering treatments. The NCDOT Transportation Improvement Program (TIP) prioritization process continues to produce many interchange improvement projects, showing that there are significant operational and safety problems at many NC interchanges and that potential cost-effective solutions exist for those problems. One difficulty faced by NCDOT throughout the early project development stages, however, is the lack of information on the safety performance of rival interchange design concepts, leading to choices based on factors other than safety.

The Crash Modification Factor (CMF) Clearinghouse, a repository of CMFs from studies all over the world, only contains high-quality interchange CMFs (rated 3-star or better) for conversion of a standard diamond to a diverging diamond or to a roundabout interchange. University of North Carolina Highway Safety Research Center (UNC HSRC) has also recently developed CMFs for converting from an at-grade intersection to a diamond interchange as part of NCDOT Project 2022-14. Having reliable interchange CMFs would allow NCDOT to compare the potential safety impacts of various common interchange designs and help ensure that the decisions on interchange design concepts get closer to the optimum. Thus, with the completion of this project, NCDOT would have access to various CMFs that can inform the safety benefits of converting many intersection designs to many interchange designs.

1.2 Research Objective and Scope

The objective of this effort was to develop a set of crash modification factors (CMFs) for comparing standard diamond interchange to other common interchange designs to be used by NCDOT at a planning level. The goal was to estimate CMFs for total, fatal and injury, and property damage only crashes.

1.3 Research Approach

In this study, the development of CMFs was carried out using cross-sectional regression methods with negative binomial regression technique for total, fatal and injury, and property damage only crashes. The CMFs developed will provide valuable information to NCDOT regarding the safety effects of various interchange conversions and are expected to be used as part of the safety management process and for alternative analysis.

1.4 Report Organization

The remainder of this report consists of the following sections. Chapter 2 outlines the review of existing research. Chapter 3 describes the data collection and compilation procedures. Chapter 4 provides the details of the analysis methodologies this study has adopted. Finally, Chapter 5 provides the details of the findings of this research along with conclusions and future research needs.

Chapter 2. Literature Review

Transportation agencies are incorporating data-driven safety benefits of roadway design elements and safety countermeasures into their project screening and evaluation decision processes. This section is organized into three subsections to provide the background on this project. The first subsection briefly discusses the safety aspect of transportation project evaluation of the North Carolina Department of Transportation (NCDOT) and other state transportation agencies. The second subsection provides the literature review on the safety benefit evaluation of interchange design, and the last subsection includes a description of project objectives.

2.1 Data-driven framework to incorporate safety in decision-making

The Strategic Transportation Investment (STI) law was established in 2013 to systematically allocate transportation funding in North Carolina which includes the Strategic Mobility Formula for data-driven scoring and inputs from regional and local governments. The North Carolina Department of Transportation Strategic Prioritization Office (SPOT) oversees the implementation of this law by identifying projects that are likely to improve transportation infrastructure while supporting economic growth, creating jobs, and improving quality of life. Safety is one of the key components of the STI scoring process. NCDOT uses Safety Benefit Factors (SBFs) to quantify the expected safety benefits (or crash reductions) if specific project types with particular characteristics are implemented. A brief description of SBFs, along with an explanation of other terminologies, is included in the following section.

The state of practice for incorporating safety into project identification and evaluation from state and regional transportation agencies could help NCDOT inform best practices on transportation safety decision-making. The research team incorporates the findings of the state of practice from a similar completed project, which developed Safety Benefit Factors for a new location and widening projects to incorporate in the Strategic Transportation Investment (STI) scoring process of NCDOT (*1*). This study interviewed representatives of transportation agencies from five states as follows: Virginia, Colorado, Kentucky, Ohio, and the North Central Texas Council of Governments.

The report highlighted two key lessons from these interviews as follows: 1) Almost all these states implemented extensive methods to determine the safety impact of transportation projects; 2) some of the states included Crash Modification Factors (CMFs) or Safety Performance Functions (SPFs) to incorporate safety benefits during the project screening process. For example, the Colorado Department of Transportation (CDOT) is implementing a framework to evaluate and prioritize safety countermeasures, such as rumble strips, median barriers, and fully protected left-turn phases, using CMFs. A summary of key lessons learned from each state is summarized as follows. It is worth noting that these evaluations did not particularly have any quantitative safety scores or ratings for different interchange designs.

2.1.1 Virginia

Virginia House Bill 2, defined in § 33.2-214.1, requires the Commonwealth Transportation Board (CTB) to develop a prioritization process to select transportation projects by July 2016 based on the following factor areas: congestion mitigation, economic development, accessibility, safety, environmental quality, and land use coordination (for project area with a population over 200,000). These factor areas can be weighted differently across the commonwealth as well as within each district, and the projects are scored based on statewide objective analysis. Candidate projects are screened if they meet the eligibility requirements and objectives of the long-range transportation plan of VTrans and the Commonwealth.

CTB requires projects to evaluate project benefits relative to the total project cost using SMART SCALE and also estimate the final SMART SCALE based on funding requests from the state. The General Assembly adopted HB2241/SB1331 (as defined in § 33.2- 214.2) in 2017, updating several SMART SCALE items. The Office of Intermodal Planning and Investment reports to the Secretary of Transportation, who also acts as the Chairman of the CTB, and is responsible for implementing the SMART SCALE process. The scores are required to be released at least 150 days before the CTB decides to include evaluated projects in the Six-Year Improvement Program or January of odd-numbered years, always ensuring five months of public discussion on project evaluation (*2*).

2.1.2 Colorado

The Safety and Analysis Program group of the Colorado Department of Transportation (CDOT) is leading and supporting the ongoing statewide efforts to quantify the benefits of safety improvements. CDOT has developed the 2020-2023 Colorado Strategic Transportation Safety Plan to establish a statewide collaborative shared vision and mission for transportation safety (*3*). This initiative addresses both severe and all crash types and includes components like intersections and roadway departures and programmatic elements like data, law enforcement, and coordination. Like the Virginia Department of Transportation (VDOT), CDOT is applying a ranked approach to identify and implement the most effective systemic safety mitigation strategies along with hotspot safety improvement projects.

Additionally, CDOT uses two key methods to identify locations to reduce crashes as a part of the Highway Safety Impact Program. They are as follows: 1) Level of Service of Safety (LOSS), which is based on the concept of Safety Performance Functions (SPF); 2) Diagnostic Analysis, which is based on statistical pattern recognition. CDOT has also calibrated and deployed SPFs for all public roadways in their jurisdiction, stratified by the number of lanes, terrains, environmental, and functional classification of all roadways and intersections, including ramp terminals at interchanges (*4*). CDOT maintains and refines SPFs for intersections which include ramp intersections at interchanges. The intersection facility type is classified by location (rural, urban, rural-urban), number of lanes, traffic control (signalized or unsignalized), and the number of legs. The score is based on the level of service of safety (LOSS), and is classified into four categories which CDOT has developed maps of (*5*). These four categories are i) LOSS 1 defined as low potential for crash reduction, ii) LOSS 2 defined as low to moderate potential for crash reduction, iii) LOSS 3 defined as moderate to high potential for crash reduction, and iv) LOSS 4 defined as high potential crash reduction. CDOT can systematically evaluate roadway facilities' safety performance using these three approaches and identify locations for safety improvements. CDOT's ST&E branch develops a statewide summary of locations, stratified by region for high-potential crash reduction and crash hotspots, and distributed to the regional agencies for project identification consideration (*3*, *6*).

2.1.3 Kentucky

The Kentucky Transportation Cabinet (KYTC) implemented the Systematic Safety Project Selection Tool (*7*) for the roadway departure crashes on horizontal curves of the local road system based on the findings of their previous efforts of conducting systematic planning on the state highway through the Federal Highway Administration Focus State Initiative. Using crash data between 2007 and 2011 and roadway attribute of a total of 217 miles segment from photo logs, KYTC identified five risk roadway attribute factors as follows: 1) horizontal curve density defined as the number of curves per mile with a radius between 500 and 1200 feet; 2) lane width less than 10.5 ft; 3) shoulder width less than 10 feet; 4) unpaved shoulder pavement type; 5) posted speed limit greater than 30 mph. The study, however, did not analyze or suggest any improvement strategies for rural county roads, but not for interchanges. KYTC also has a separate effort to support five to six county agencies annually by reviewing corridors and identifying specific safety-related improvements based on the crash data.

2.1.4 Ohio

The Ohio Department of Transportation (ODOT) takes a data-driven approach to identify, screen, and prioritize potential highway safety improvement projects. ODOT typically analyzes crash data, roadway design, and traffic data of up to 300 crash locations yearly to identify safety issues and develop targeted countermeasures. The ODOT District offices develop funding applications for these safety-related projects and submit them to the Central Office, where multidisciplinary committees review and evaluate applications based on several factors, including crash analysis, state, regional, and project priority, matching funds, and cost-benefit analysis.

To support their highway safety prioritization process, ODOT has developed an Economic Crash Analysis Tool (ECAT) that automates the safety benefit analysis and allows people with various skill set levels to make informed decisions (*8*, *9*). ECAT estimates the safety performance of existing or proposed facilities including signalized Single-Point Urban Interchanges (SPUI) and tight diamond interchanges (TDI) (*10*), conducts alternative analyses, and produces cost-benefit analyses. ECAT also includes an additional module to incorporate annual predicted and estimated crashes with the following inputs: the number of fatal and incapacitating injury crashes, the number of injury crashes, and the total number of crashes.

2.1.5 North Central Texas Council of Governments

At the time of the interview by Davis et al. (2021), the North Central Texas Council of Governments (NCTCOG) was developing safety benefits factors for scoring transportation projects using crash rate data as a part of its Regional Safety Plan (*1*, *11*). NCTCOG prioritizes project funding based on the number of crashes weighted by the total vehicle miles traveled in the corroding roadway facilities. These scores could be adjusted based on how projects rank within the NCTCOG region based on the expected crash reduction and treatment types. Additionally, the NCTCOG Safety Program prepares county-level crash rates on specific access facilities of 12 County Metropolitan Planning Area (MPA) to compare with the regional crash rate for that specific year. Note that these facilities did not include interchange ratings.

2.2 Safety evaluation of interchange design

Common measures of quantifying crash reduction benefits are using Crash Modification Factors (CMFs) and Safety Benefit Factors (SBFs) or also known as Safety Performance Functions (SPFs). CMFs are a multiplicative factor to express the estimated number of crashes after implementing a specific countermeasure for a given site condition. A CMF greater than 1 indicates an expected increase in crashes after applying countermeasures, while a value less than 1 suggests a reduction in crashes. CMF values can also be interpreted in the expected percentage reduction in crashes. For example, a CMF value of 0.8 indicates a 20 percent reduction in crashes, while a CMF value of 1.2 indicates a 20 percent increase after countermeasure implementation.

CMF is multiplied by the expected crash frequency without the treatment to obtain the expected crash frequency with countermeasures. If multiple countermeasures are applied to a specific site, the crash reduction might not be to the full extent when implemented concurrently. For example, countermeasures targeting the same crash types, such as street lighting and enhancing pavement marking for nighttime crashes, will not add up because the effects of these treatments overlap with each other. Therefore, multiplying several CMFs is likely to overestimate the combined effect. The net CMF of the combined treatment should be ideally estimated through rigorous analysis, whereas caution and engineering judgment should be exercised without such data. Furthermore, the safety effect of countermeasures is influenced by several factors, including geometric configuration and usage rates. SBFs or SPFs are mathematical equations to incorporate such effects and provide estimates of crash reductions as a function of these factors.

The remainder of the section provides a brief literature review of the safety evaluation of interchange design types and is organized into four subsections. The first subsection provides an overview of existing studies assessing the safety impacts, and the second subsection summarizes the safety impacts by segmentation of crash severity, crash types, and other factors. The third subsection includes literature related to the SBFs or SPFs of interchange designs, and the last subsection provides an overview of the Enhanced Interchange Safety Analysis Tool (ISATe) to estimate the safety benefits of roadway facilities.

2.2.1 Existing studies on evaluating safety impacts of interchange designs

Several studies have compared the safety effects of interchange designs, and most of them focused on evaluating the safety benefits of converting conventional diamond interchange into a Diverging Diamond Interchange (DDI). These studies focused on a single site to assess site-specific safety effects or multiple sites across single and several states to evaluate state-wide or national-level safety effects of DDI. Previous studies implemented various analytical methods, including naïve, comparison group (CG), and empirical Bayes (EB), to incorporate biases like the regression-to-the-mean, temporal, and spatial trends.

A relatively recent study by Claros et al. (2018) evaluated 1,681 crash reports for 13 interchange roundabout terminals in Missouri. Using the Empirical Bayes (EB) method, the researchers found that single-lane roundabouts replacing stop-controlled ramp terminals reduced fatal and injury (FI) crashes by 33 percent, property damage only (PDO) crashes by 23 percent, and total crashes by 25 percent. However, dual-lane roundabout terminals showed an aggregate increase of 29 percent in FI crashes, 34 percent in PDO crashes, and 33 percent in total crashes, respectively (*12*).

State Department of Transportation (DOT) agencies have assessed the safety benefits of DDI based on the data from a single site to evaluate the cost-benefit of implementing DDI designs for future projects. Chilukuri et al. (2011) evaluated the safety benefits of the first DDI constructed in Missouri using the before-and-after comparison group method and found a 46 percent reduction in total crashes. The study also found a 72 percent reduction in left-turn crashes due to the elimination of left-turn conflicts in the DDI interchange design. Although the findings from a single site can inform safety-related decisions, more than these results are needed for transportation agencies to make statewide or nationwide policy decisions (*13*).

A few studies have evaluated interchange design safety performance based on data from multiple sites within a single state. Claros et al. (2015) assessed the safety benefits of six DDIs in Missouri using naïve, CG, and EB methods. They found 41 percent to 48 percent reduced crashes depending on the evaluation method. The authors also found a 34 percent decrease in fatal and injury crashes involving left-hand turns (*14*). Zlatkovic (2015) implemented EB methods to evaluate the safety performance of three DDIs in Utah and found a 25 percent reduction in total crashes. The statewide analysis could better incorporate driving behavior and other biases; however, the limited number of interchange sites and shorter study duration constrained the robustness of the safety evaluation (*15*).

Many researchers have evaluated sites across states to overcome the data limitations of a single site and improve the safety assessment of interchange designs. Hummer et al. (2016) evaluated seven DDIs across four states using naïve and CG methods to conclude a 32 percent reduction in total crashes based on the results of the CG method (*16*). In another study, Nye et al. (2019) found a 37 percent reduction in total crashes using CG methods, evaluating 26 DDIs from 11 states (*17*). The authors of these studies argued that the regression-to-the-mean bias is not likely present in the analysis for the following reasons: 1) transportation agencies had constructed DDI for operational improvement and not safety considerations; 2) Claros et al. (2015) found no significant effect of regression-to-the-mean on their analysis (*14*). However, Abdelrahman et al.

(2021) found higher estimates of crash reduction from the CG method than the EB method indicating the possible presence of the regression-to-the-mean effect in the recent study evaluating 80 DDIs from 24 states (*18*).

A few studies have evaluated the safety performance of ramp terminals and adjacent roadway facilities of DDI design. A study focusing on the safety impacts of DDI on ramp terminals in Missouri found a 55 percent reduction in fatal and injury crashes and a 31 percent reduction in PDO crashes (*19*). In another study, the authors found no significant safety effects (both positive and negative) of DDI on adjacent intersections and speed-change lanes (*20*).

A recent FHWA study (2023) developed a planning-level safety prediction model to assess the predicted safety performance of interchange configurations in a manner consistent with those developed for the HSM (*21*). The CPM predicts KABC and PDO crash frequency separately at the interchange level for different interchange types including diamond interchange, compressed diamond (CD), tight diamond interchange (TDI), diverging diamond interchange (DDI), roundabout diamond, single-point diamond interchange (SPDI), partial cloverleaf A2 or A4 (Parclo type A), partial cloverleaf B2 or B4 (Parclo type B), and parclo AB2 or AB4 (Parclo type AB). The study found that there was no safety performance difference between a diamond and CD interchange. These two configurations combined were assumed to be the base condition. As the results the crash prediction model for KABC crash frequency showed lower crash likelihoods for all other interchange type to have a lower crash likelihood, except for Parclo interchanges, compared to the baseline condition of diamond or CD interchange. On the other hand, the crash prediction model for PDO crash frequency exhibited higher crash likelihoods for DDI and Parclo interchange, but lower likelihoods for SPDI, TDI, and roundabout interchanges. It is to note that the effects of these interchange types were only statistically significant for SPDI and TDI for FI crashes, and SPDI for PDO crashes, respectively.

Most recently, an NCDOT study by Srinivasan et al. (2024) conducted an empirical Bayes before-and-after evaluation of the conversion of at-grade intersections to diamond interchanges (*22*). The data included 20 intersections that were converted in Minnesota and North Carolina. Before conversion, 6 of the intersections in Minnesota were stop-controlled, and 4 were signalized. In North Carolina, all 10 intersections were stop-controlled before conversion. The combined results from the two States including all 20 sites indicated that fatal and injury crashes decreased by about 30 percent, PDO crashes increased by about 11 percent, and total crashes decreased by about 8 percent. For the 16 sites that were stop-controlled before conversion and had stop-controlled ramp terminals after conversion, injury and fatal crashes decreased by about 12 percent, PDO crashes increased by about 156 percent, and total crashes increased by about 60 percent. The 4 sites (all from Minnesota) that were signalized before conversion experienced significant reductions in crashes, but the sample size is probably not sufficient to provide a reliable finding for this group.

2.2.2 Safety evaluation by crash severity, crash types, and other factors

Previous studies evaluating the safety effects of interchanges have examined crash reduction by crash severity, segmenting crashes by fatal and injury, and property damage only (PDO) crashes.

Claros et al. (2015) found that DDI design in Missouri had the highest reduction of fatal or injury crashes, between 59 percent and 63 percent. The authors also found a 34 percent to 45 percent reduction in PDO crashes (*14*). In a study of DDIs in Missouri, Kentucky, New York, and Tennessee, Hummer et al. (2016) found a 41 percent reduction in fatal and injury crashes. The authors did not include PDO crashes in their analysis (*16*). Nye et al. (2019) found a 54 percent reduction in fatal and injury crashes and a 31 percent reduction in PDO crashes in a national-level safety evaluation of DDI design (*17*). In a recent nationwide study, Abdelrahman et al. (2021) found a 44 percent reduction in fatal and injury and an 8 percent reduction in PDO crashes (*18*). Most studies have found a significantly higher percentage reduction in fatal and injury crashes than PDO crashes due to DDI design.

A few studies have examined the safety effects of interchange designs based on crash types. Abdelrahman et al. (2021) found a decrease in rear-end collisions by 11 percent and angle/left-turn collisions by 55 percent in the recent nationwide study of DDI design (*18*). Nye et al. (2019) also found that angle and rear-end crashes decreased by 56 percent and 45 percent, respectively, whereas sideswipe crashes increased by 14 percent in an analysis of 26 DDIs from 11 states (*17*). Most studies have found a significant reduction in crashes involving left-turn movement. DDI design reduces eight out of ten crossing conflict points of a conventional diamond interchange design, typically resulting in high-severity right-angled collisions (*14*, *23*).

Existing studies have also evaluated the safety improvement of interchange designs by other factors, such as daytime vs. nighttime. Nye et al.(2019) found that 35 percent reduction in all crashes of DDI during daylight conditions and a 36 percent crash reduction for nighttime (*17*).

2.2.3 Safety Performance Functions (SPFs) to estimate safety impacts

Several geometric and road characteristics factors impact the safety of interchanges, and safety performance functions (SPFs) incorporate the effects of these factors to estimate the safety benefits. One approach is to develop a site or project-specific SPFs to evaluate the safety impacts of geometric, road characteristics, and driving behavior. Claros et al. (2017a) used Exploratory Data Analysis (EDA) and VIEDA (Variable Introduction Exploratory Data Analysis) to identify key variables influencing SPF and develop the functional form (*19*). The authors found Annual Average Daily Traffic (AADT) and the number of through or shared lanes of the crossroad to develop the SPFs of fatal injury and PDO crashes. In another study, Abdelrahman et al. (2021) used a cross-sectional method to develop SPFs by including AADT of adjacent arterial, the speed limit of arterial and freeway, the distance between crossroad/ramps, and interchange configuration (underpass/overpass) (*18*).

Another approach uses the Highway Safety Manual (HSM) to calibrate for driving behavior, crash reporting practices, and climate conditions (*24*). Claros et al. (2016) calibrated and used the SPF from HSM to analyze the safety of 20 ramp terminals in Missouri (*25*). However, a limitation of this approach is that SPF developed in HSM is based on data from Maine, California, and Washington (*26*), and the accuracy of the SPF calibrated from other study areas is generally lower than site-specific calibration (*19*, *27*).

2.2.4 Brief overview of the Enhanced Interchange Safety Analysis Tool (ISATe)

The Enhanced Interchange Safety Analysis Tool (ISATe) is a spreadsheet tool based on the HSM's predictive methods to evaluate the safety of freeways, including main freeway lanes, interchanges, and ramps (*28*). ISATe implements a disaggregate safety evaluation approach to quantify the relationship between design elements (e.g., lane width), design components (e.g., left-turn bay), and average crash frequency. Some of the applications of the ISATe are to evaluate the safety performance of an interchange or freeway with various design elements, including barrier-separated managed lanes and toll facilities. ISATe includes an optional feature of calibrating the evaluation results to the local conditions based on the crash severity and crash type, although the default parameters result in satisfactory outcomes. Some state agencies have also calibrated the HSM predictive method calculation of freeways and ramps to approximate the local freeway conditions of their jurisdiction (*29*).

ISATe requires a sequence of steps to complete the safety evaluation of a freeway facility or site, resulting in an estimate of the average crash frequency of all severity and crash types for the project and each site within the project limit. A brief description of these steps is as follows:

Step 1 — Define Project Limits: This step identifies the physical extent of the roadway facility being evaluated and could include multiple sites connected to form a functioning roadway.

Step 2 — Define Study Period: This step defines the consecutive past or future period for safety evaluation. ISATe defines three time periods for the analysis as follows: 1) "study period," defined as consecutive years for which an estimate of average crash frequency is desired; 2) "crash period," defined as consecutive years for which observed crash data are available; 3) "evaluation period" defined as the combined set of years represented by the study period and crash period. All periods are measured in years, and the predictive method evaluates every year in the evaluation period.

Step 3 — Acquire Traffic Volume and Observed Crash Data: This step entails obtaining the traffic volume data measured in annual average daily traffic (AADT) for the project limits and study period. The observed crash data should also be obtained if the site-specific or project-level EB Method is to be applied.

Step 4 — Acquire Geometric Design and Traffic Control Data: Geometric design features, traffic control features, and traffic demand characteristics data required are collected in this step.

Step 5 — Divide Project into Individual Sites: The project limit is segmented into individual sites consisting of homogeneous freeway segments, ramp segments, C-D road segments, or crossroad segments using information from previous steps. The data obtained in Steps 3 and 4 are assigned to each site and entered into the ISATe spreadsheet site-by-site.

Step 6 — Assign Observed Crashes: This step is required if a decision to use the EB Method is taken in Step 3; else this step can be skipped. The crash data needs to be aggregated at the site-level or project-level, depending on the scope of analysis.

Step 7 — Initiate Calculations and Review Results: ISATe Excel tool includes 11 safety evaluation worksheets. They are as follows:

- **Welcome:** includes a foreword, acknowledgments, and disclaimer.
- **Introduction:** a brief overview of ISATe and this user manual.
- **Main:** input data to describe evaluation and start calculations.
- **Input Freeway Segments:** input data describing freeway segments and speed-change lanes.
- **Input Ramp Segments:** input data describing ramp and C-D road segments.
- **Input Ramp Terminals:** input data describing crossroad ramp terminals.
- **Output Summary:** summary of analysis results.
- **Output Freeway Segments:** detailed listing of analysis results for freeway segments.
- **Output Ramp Segments:** detailed ramp and C-D road segments analysis results.
- **Output Ramp Terminals:** detailed analysis results for crossroad ramp terminals.
- **Calibration Factors:** calibration factors for predictive models and crash-type distributions.

The analysis may use one or multiple input worksheets depending on the evaluation scope. For example, a freeway section evaluation will use *Input Freeway Segments* only, while an interchange evaluation will use *Input Ramp Segments* and *Input Ramp Terminals* worksheets. Table 2 lists the site characteristics data needed for the analysis in ISATe. The required column indicates the needed data, while the desired column indicates a recommendation to use the data if available. The assumption column provides suggestions if the data is not available.

Table 2. Data needed for calibration of ISATe (*28*)

Predictive Method	Data Element	Data Need		Default Assumption
		Required	Desirable	
ROADWAY SEGMENTS				
Freeways	Area type (rural or urban)	X		Need actual data
	Number of through lanes	X		Need actual data
	Segment length	X		Need actual data
	Length and radii of horizontal curves	X		Need actual data
	Lane width	X		Need actual data
	Inside and outside shoulder width (paved)	X		Need actual data
	Median width	X		Need actual data
	Length of rumble strips on inside and outside shoulders		X	Base default on agency policy
	Length of (and offset to) median barrier	X		Need actual data
	Length of (and offset to) outside barrier	X		Need actual data
	Clear zone width		X	Base default on agency policy
	AADT volume of (and distance to) nearest upstream entrance ramp	X	X	Need actual data
	AADT volume of (and distance to) nearest downstream exit ramp	X	X	Need actual data
	Presence of speed-change lane	X		Need actual data
	Presence and length of Type B maneuver sections	X		Need actual data
	Proportion of AADT that occurs during hours where lane volume exceeds 1,000 veh/h/ln		X	Table 4 of User Manual
	Average annual daily traffic (AADT) volume	X		Need actual data
Ramps	***For ramps and collector-distributor (C-D) roads:***			
	Area type (rural or urban)	X		Need actual data
	Number of through lanes	X		Need actual data
	Segment length	X		Need actual data
	Average annual daily traffic (AADT) volume	X		Need actual data
	Length and radii of horizontal curves	X		Need actual data
	Lane width	X		Lane width
	Left and right shoulder width (paved)	X		Left and right shoulder width (paved)
	Length of (and offset to) right side barrier	X		Length of (and offset to) right side barrier
	Length of (and offset to) left side barrier	X		Length of (and offset to) left side barrier
	Presence of lane add or drop		X	Presence of lane add or drop
	Presence of speed-change lane	X		Presence of speed-change lane
	For C-D roads only:			
	Presence and length of maneuver section	X		Presence and length of maneuver section

Table 2. Data needed for calibration of ISATe (*28*)

Predictive Method	Data Element	Data Need		Default Assumption
		Required	Desirable	
INTERSECTIONS				
Freeways	***For freeway speed-change lanes:***			
	Area type (rural or urban)	X		Need actual data
	Number of through lanes	X		Need actual data
	Segment length	X		Need actual data
	Length and radii of horizontal curves	X		Need actual data
	Lane width	X		Need actual data
	Inside shoulder width (paved)	X		Need actual data
	Median width	X		Need actual data
	Presence of rumble strips on inside shoulder		X	Base default on agency policy
	Length of (and offset to) median barrier	X		Need actual data
	AADT volume of ramp in speed-change lane		X	Need actual data
	Presence and length of Type B maneuver sections	X		Need actual data
	Proportion of AADT that occurs during hours where lane volume exceeds 1,000 veh/h/ln		X	Table 4 of User Manual
	AADT of freeway adjacent to speed-change lane	X		Need actual data
Ramps	***For all crossroad ramp terminals:***			
	Area type (rural or urban)	X		Need actual data
	Ramp terminal configuration	X		Need actual data
	Type of traffic control	X		Need actual data
	Control for exit ramp right-turn movement	X		Need actual data
	AADT for inside and outside crossroad legs	X		Need actual data
	AADT volume for each ramp leg	X		Need actual data
	Number of through lanes on each crossroad approach	X		Need actual data
	Number of lanes on the exit ramp	X		Need actual data
	Number of crossroad approaches with left-turn lanes	X		Need actual data
	Number of crossroad approaches with right-turn lanes	X		Need actual data
	Number of unsignalized public street approaches to the crossroad leg outside of the interchange		X	Assume no public street approaches present
	Distance to next public street intersection		X	Assume 0.15 mi for urban areas, assume 0.20 mi for rural areas
	Distance to adjacent crossroad ramp terminal		X	Based default on terminal configuration and area type[a]
	Crossroad median width and left-turn lane width	X		Need actual data

Table 2. Data needed for calibration of ISATe (*28*)

Predictive Method	Data Element	Data Need		Default Assumption
		Required	Desirable	
INTERSECTIONS				
Ramps	***For signal-controlled crossroad ramp terminals only:***			
	Number of unsignalized driveways on the crossroad leg outside of the interchange		X	Assume no driveways present
	Number of crossroad approaches with protected-only left-turn operation	X		Need actual data
	Number of crossroad approaches with right-turn channelization	X		Need actual data
	Presence of exit ramp right-turn channelization	X		Need actual data
	Presence of a non-ramp public street leg		X	Assume leg not present
	For one-way stop-controlled crossroad ramp terminals only:			
	Skew angle	X		Need actual data

ISATe tool has several limitations: 1) the safety evaluation of freeways and ramps is not available for all designs. For example, ISATe does not account for the analysis of freeways with more than 11 or more through lanes in an urban area and nine or more through lanes in a rural area and does not incorporate effects of features like ramp metering. The upper range of AADT also limits the application of ISATe; 2) ISATe spreadsheet can only accommodate data for 20 freeway segments, 40 ramps or C-D road segments, and six crossroad ramp terminals. It allows the evaluation of two interchanges and corresponding freeway sections. The developers advise subdividing projects if the analysis exceeds the workbook limits; 3) the spreadsheet can accommodate evaluation of a crash period that is between 1 and 5 years and an evaluation period between 1 to 24 years in duration.

Chapter 3. Compilation of Data

Recently, an inventory of all interchanges in North Carolina (NC) was compiled by NCDOT's Traffic Safety Unit and the GIS Unit. The inventory showed that there are many different interchange designs across NC with sample sizes large enough for CMF development. The research team initially reviewed 1,035 interchanges in the interchange inventory file as below in Table 3. This initial review included collection of data including presence of frontage roads., presence/number of driveways within 250 ft of the interchange, ramp intersection control type (signalized/stop-controlled), type of interchange, presence of lighting at ramp terminal intersections, ramp loop radius, intersecting "direction" of travel – "single-direction" when they intersect the cross-street (i.e., there is only one option of a direction) vs. "multi-direction" (i.e., an exiting vehicle could turn left or right from the ramp onto the cross-street; an entering vehicle could turn left or right from the cross-street into the entrance ramp), overpass/underpass, and skew angles. Appendix A provides visual examples of different interchange types that were initially considered and reviewed to identify the analysis sample.

Table 3. Distribution of interchanges based on their type and count in the initial review

Interchange Type	Count of Interchanges
Diamond	418
Partial cloverleaf	357
PARCLO A	*111*
PARCLO AB	*141*
PARCLO B	*98*
Partial interchange	50
Trumpet	39
Complex multi-interchange	38
Semi-directional	36
Other	20
Full cloverleaf	18
Three-leg directional	17
Single point urban interchange (SPUI)	16
Diverging diamond	14
Double roundabout interchange	11
Four-leg all-directional	1
Grand Total	**1,035**

However, for the cross-sectional regression model development, a modified list of interchanges of highest priority to NCDOT, comprising a total of 214 interchanges, was included. This process involved randomly selecting interchanges based on interchange type, in addition to the following filtering criteria, and the resulting set includes interchanges across the state in both rural and urban areas. Particularly, DDI interchanges were not included in this analysis because they had already been studied earlier. Additionally, some other interchange types including trumpet, semi-directional, full cloverleaf, three-leg and four-leg directional, and double roundabout were also excluded from this analysis owing to their small sample sizes. Moreover, five years of crash data were analyzed from 2019 through 2023. The distribution of these 214 interchanges is shown in Table 4. The following information is reviewed to finalize the data for analysis.

- Interchange characteristics including on- and off-ramp attributes.
- Crossroad characteristics.
- Construction years – The interchanges with three years of construction period were excluded, as only two years of data would be inadequate for analysis (a total of five years of crash data were analyzed).
- AADT information – Missing observations with AADT data were excluded.
- Sample size for each interchange type - Interchanges with very small counts were eliminated (semi-directional, three-leg directional, and trumpet).

Table 4. Distribution of interchanges based on their type and count included in the analysis

Interchange Type	Count
Diamond	69
Complex_multi_interchange	18
PARCLO_A	36
PARCLO_AB	52
PARCLO_B	24
Partial_interchange	6
SPUI	9
Grand Total	**214**

Ultimately, for these 214 interchanges, the collected data that were aggregated and analyzed included interchange types, AADT on freeway ramps, AADT on crossroads, number of freeway through lanes, lengths of whole segments as well as speed change lanes, freeway median and shoulder widths, freeway median barrier lengths and their offset distances, proportion of rumble strips on freeways, proportion and length of Type B maneuver at off-ramps, proportion of 4- and 5-leg intersections at crossroad terminals, proportion of signalized intersections at crossroad terminals, number of lanes at crossroad terminals by direction, distance to next intersection, and left-turn lane width at crossroad terminals, along with crash data. The summary statistics including minimum, maximum, mean, and standard deviation (S.D.) of this data are shown below in Table 5 in the forms they were included in the analysis.

Table 5. Descriptive statistics of the variables of interest

Variable	Units	Min.	Max.	Mean	S.D
Diamond Interchange Type	Binary indicator for presence (Yes=1, No=0)	0	1	0.32	0.47
Complex interchange type	Binary indicator for presence (Yes=1, No=0)	0	1	0.08	0.28
Partial Cloverleaf (PARCLO) A interchange type	Binary indicator for presence (Yes=1, No=0)	0	1	0.17	0.37
Partial Cloverleaf (PARCLO) B interchange type	Binary indicator for presence (Yes=1, No=0)	0	1	0.11	0.32
Partial Cloverleaf (PARCLO) AB interchange type	Binary indicator for presence (Yes=1, No=0)	0	1	0.24	0.43
Partial interchange type	Binary indicator for presence (Yes=1, No=0)	0	1	0.03	0.17
Single-point urban interchange (SPUI) type	Binary indicator for presence (Yes=1, No=0)	0	1	0.04	0.20
Maximum number of freeway through lanes	Count	2	6	2.96	0.99
Minimum number of freeway through lanes	Count	2	5	2.65	0.78
Average length of freeway speed change lanes	Miles	0	0.34	0.10	0.05
Average freeway segment lengths	Miles	0	1.21	0.27	0.19
Average freeway lane width	Feet	0	16	10.849	1.88
Average freeway inside shoulder width	Feet	0	17	6.12	3.43
Average freeway median width	Feet	0	394	42.66	34.84
Proportion of rumble strips on freeways	Proportion	0	1	0.86	0.30
Average freeway median barrier length	Feet	0	1	0.24	0.18
Average freeway median barrier offset distance	Feet	0	37	10.49	7.87
Average length of Type B maneuver	Miles	0	0.45	0.06	0.09
Average AADT on freeways	Vehicles per day	7,450	148,500	65,149.97	33,632.79
Average length of Type B maneuver on-ramps	Miles	0	0.47	0.05	0.10
Average AADT on freeway on ramps	Vehicles per day	7,450	148,500	65,009.62	33,550.31
Proportion of Type B maneuver off ramps	Proportion	0	1	0.20	0.29
Average length of Type B maneuver off-ramps	Miles	0	0.48	0.06	0.10
Average AADT on freeway off ramps	Vehicles per day	7,450	148,500	65,325.31	33,846.03

Table 5. Descriptive statistics of the variables of interest

Variable	Units	Min.	Max.	Mean	S.D
Proportion of 3-leg intersection at crossroad terminal	Proportion	0	1	0.26	0.35
Proportion of 4-leg intersection at crossroad terminal	Proportion	0	1	0.61	0.40
Proportion of 5-leg intersection at crossroad terminal	Proportion	0	1	0.01	0.07
Proportion of merge at crossroad terminal	Proportion	0	1	0.08	0.19
Proportion of single-point urban interchange (SPUI) at crossroad terminal	Proportion	0	1	0.05	0.22
Proportion of signalized intersection at crossroad terminal	Proportion	0	1	0.83	0.26
Proportion of stop-controlled intersection at crossroad terminal	Proportion	0	0.33	0.04	0.09
Proportion of yield-controlled intersection at crossroad terminal	Proportion	0	1	0.02	0.08
Average AADT on crossroad terminal	Vehicles per day	3,200	54,500	17,714.79	9,761.49
Average AADT on crossroad terminal ramps	Vehicles per day	600	11,250	4,399.82	2,060.75
Maximum number of through lanes in one direction at crossroad terminal	Count	2	9	3.89	1.10
Minimum number of through lanes in one direction at crossroad terminal	Count	1	8	3.44	1.07
Maximum number of through lanes in opposite direction at crossroad terminal	Count	0	9	3.86	1.16
Minimum number of through lanes in opposite direction at crossroad terminal	Count	0	7	3.41	1.06
Maximum number of left-turn lanes at crossroad terminal	Count	0	3	1.35	0.52
Minimum number of left-turn lanes at crossroad terminal	Count	0	2	0.47	0.58
Maximum number of right-turn lanes at crossroad terminal	Count	0	3	1.22	0.47
Minimum number of right-turn lanes at crossroad terminal	Count	0	1	0.51	0.50
Average distance to next intersection	Miles	0	1.03	0.13	0.09
Average median width at crossroad terminal	Feet	0	70	11.89	9.51
Average left-turn lane width at crossroad terminal	Feet	0	7	4.38	1.81
Total crash	Count/year	0	732	54.31	63.36
Fatal-Injury (FI) crash	Count/year	0	158	13.30	16.07
Property damage only (PDO) crash	Count/year	0	574	41.01	48.75

NCDOT provided the research team with a GIS polygon shapefile of all interchanges in NC. Along with the interchange itself, the polygon includes the ramps, ramp terminals, crossroads, and acceleration/deceleration lanes on the access-controlled roadway. NCDOT also provided the research team with a GIS point shapefile of geolocated crashes that includes the attributes of crash severity, crash type, and the crash date. The research team added the interchange and crash shapefiles to ArcGIS Pro to create a map, as shown in Figure 1, where the yellow dots depict the locations of crashes that occurred within the interchange influence area polygons. Crashes within the interchange influence areas were then merged with the site characteristics data and aggregated for individual sites to carry out the cross-sectional modeling in Phase 1. It is to be noted that the initial crash locations the research team received are determined by law enforcement officers on the scene and may not represent the actual location of the crash. The research team used Google Earth when reviewing variables in the crash reports in Phase 2 to compare the locations of crashes between those in the original spatial data from NCDOT and the crash reports.

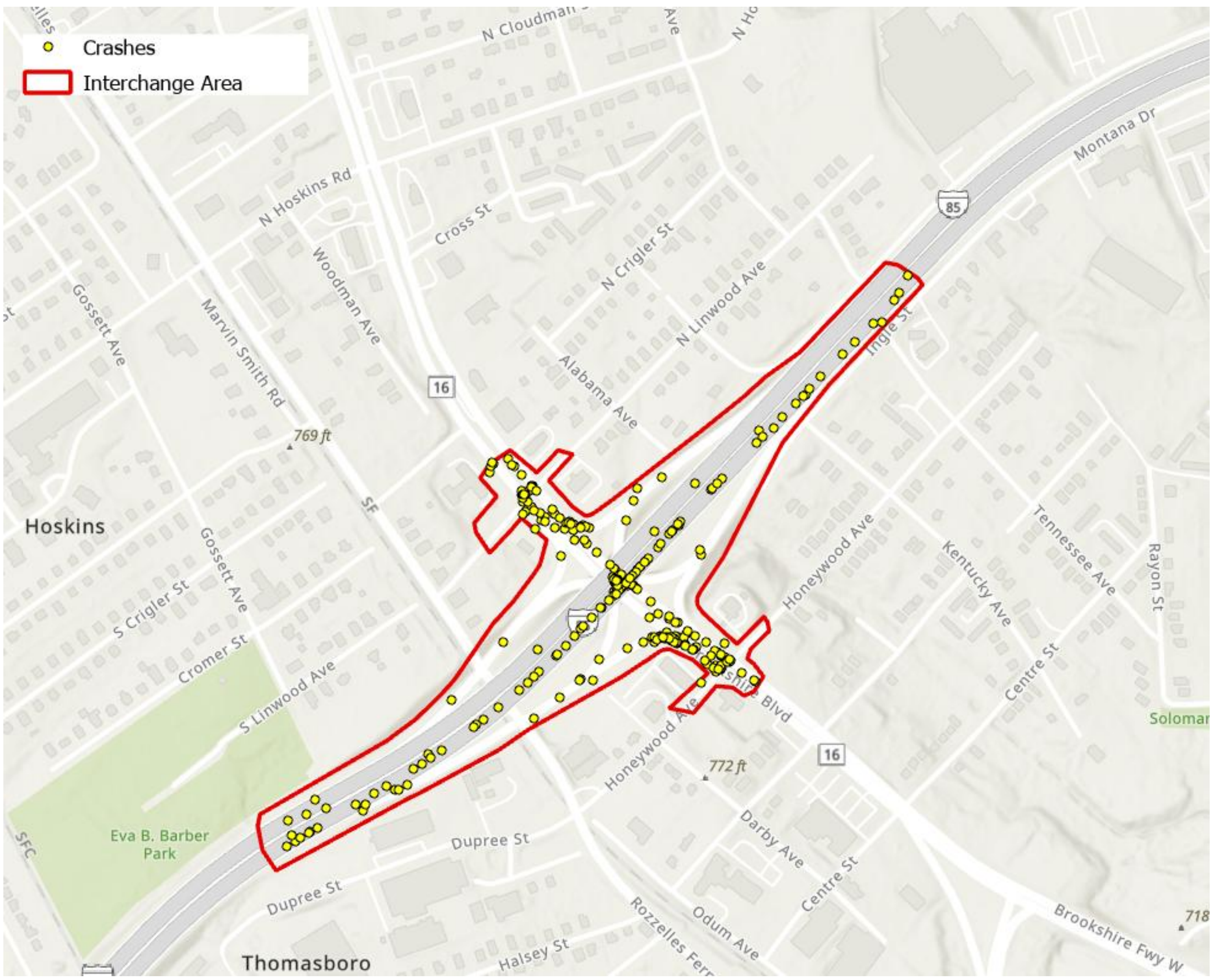

Figure 1. Example map of the interchange influence area and spatial locations of crashes within the polygon

Chapter 4. Analysis Methodology

The analysis of this project was carried out in two phases. Phase 1 involved the development of cross-sectional models using negative binomial regression technique. Thereafter, based on feedback from NCDOT, in Phase 2, crash reports of a selected sample of crashes that have already been included in the Phase 1 analysis were manually reviewed to:

- Compare the accuracy of data between that directly obtained from the NCDOT database and individual crash reports (including the crash diagrams in the reports), and
- Have a more granular understanding of crash locations with respect to the interchange influence area.

Based on the research team’s discussion with NCDOT, it was decided to include only 5 interchange types in Phase 2 analysis including diamond, SPUI, PARCLO A, PARCLO B, and PARCLO AB interchanges. Ultimately, a total of 526 crashes were sampled, and their respective crash reports were reviewed in Phase 2.

4.1 Negative binomial models for crash frequency

Traditional linear regression techniques are generally inappropriate as crash data are comprised of non-negative integers. As an alternative, the Poisson distribution provides a starting point for the analyses. In the Poisson model, the probability of site *i* experiencing y_i crashes in one year can be expressed as

$$P(y_i) = \frac{exp(-\lambda_i)\lambda_i^{y_i}}{y_i!} \qquad (1)$$

where P(y_i) is the probability of site *i* experiencing y_i crashes, and λ_i is the Poisson parameter or the expected number of annual crashes for site *i,* E[y_i]. The Poisson regression model relates the expected number of crashes on a site, λ_i , to a function of explanatory variables, expressed as

$$\lambda_i = exp(\beta X_i) \qquad (2)$$

where X_i is a vector of explanatory variables and β is a vector of estimable parameters. A limitation of the Poisson distribution is the assumption that the mean and variance are equal, which often is not the case with crash data. Commonly with crashes, variance exceeds mean, leading to "overdispersion”. The negative binomial model addresses this overdispersion by adding an unobserved heterogeneity term as,

$$\lambda_i = exp(\beta X_i + \varepsilon_i) \qquad (3)$$

where $exp(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The inclusion of this term essentially allows the variance to differ from mean as

$$VAR[y_i] = E[y_i] + \alpha E[y_i]^2 \qquad (4)$$

This α is termed as the overdispersion parameter. In the safety analysis, negative binomial regression models have been widely used (*30–36*) and accepted as the current practice for modeling crashes, as such models account for overdispersion. The negative binomial models in this analysis are used to develop crash modification factors (CMFs). CMFs represent the change in crashes associated with a unit change in a predictor variable. These factors are typically the ratio of the expected values of crashes with and without the change. The CMFs can be expressed as

$$CMF = \exp(\beta_j) \qquad (5)$$

where β_j is the regression coefficient associated with the variable j. In this study, the CMFs were developed directly from the coefficients of the negative binomial models. CMF values less than 1.0 indicate that alternative treatment reduces the estimated average crash frequency compared to the base condition and vice versa.

4.1.1 Cross-sectional regression model development

Cross-sectional regression models were developed separately for total, fatal-injury (FI), and property damage only (PDO) crashes. Several different models were developed initially with varying combinations of predictor variables. Ultimately, based on the p-values of the parameter estimates, AIC, and log-likelihood information, the best fit models were finalized as shown below (Table 6 through Table 8), considering the correlations between independent variables, and excluding the strongly correlated variables in the models simultaneously. A significance level of 0.1 (α = 0.1) was used in this analysis. While the significance level of 0.05 is more commonly used, a higher alpha level (0.1) allows for more sensitivity to detect possible effects. This is particularly true for smaller samples, where achieving significance at 0.05 may be too strict. Our literature review also revealed some studies did not find any statistically significant effects of interchange types at α = 0.05. Using α = 0.1 can help compensate for smaller sample sizes or low-frequency outcomes, and increases sensitivity, implying it is more likely to detect potential safety issues, even at the risk of a false positives.

The models included interchange type as a variable, with the diamond interchange serving as the baseline condition. Traffic volumes in the form of AADT were included in natural log form and, as such, its parameter estimate reflects an elasticity. Several other site characteristics were aggregated by individual site and included in the analysis. The regression analyses in this study were conducted using R statistical software version 4.3.1.

4.2 Identification of the sample representative for manual crash report review

Phase 2 of this project reviewed the crash reports for selected crashes occurring at some of the interchanges that were included in the analysis of Phase 1 (cross-sectional models). In this regard, the research team came up with a methodology that might reasonably work for sampling of crashes closely representing the population crashes by crash severity and crash types for Phase

2. The research team shared this methodology with NCDOT and received their feedback prior to conducting Phase 2 analysis.

- First, the research team focused on the interchanges of the following types out of all 214 interchanges analyzed in Phase 1, as suggested by NCDOT:
    - Diamond
    - PARCLO A
    - PARCLO B
    - PARCLO AB
    - SPUI
- This filtering criterion (i.e., specific interchange type) reduced the number of relevant interchanges for Phase 2 analysis to a total of 199.
- Then we ranked the interchanges based on the crash counts (total, FI, and PDO crashes as well as different crash types) in descending order. It is to note that, crashes with “U” or unknown severity were previously removed from the crash data at hand.
- Ultimately, the research team identified a total of 12 interchanges with the highest crash occurrences of various crash severity and type, which also represented different interchange design configurations that are of priority to NCDOT, as shown below in Figure 2.

Interchnge Name	Total_Crash	Interchange Name	FI_Crash	Interchange Name	O_Crash
TSUINTC00098	1138	TSUINTC00340	265	TSUINTC00098	896
TSUINTC00340	1156	TSUINTC00098	239	TSUINTC00291	857
TSUINTC00291	1097	TSUINTC00623	235	TSUINTC00340	843
TSUINTC00346	1019	TSUINTC00291	229	TSUINTC00325	811
TSUINTC00325	1033	TSUINTC00346	209	TSUINTC00346	806
TSUINTC00206	755	TSUINTC00617	209	TSUINTC00061	577
TSUINTC00061	712	TSUINTC00338	199	TSUINTC00206	566
TSUINTC00338	682	TSUINTC00206	180	TSUINTC00299	516
TSUINTC00299	657	TSUINTC00112	155	TSUINTC00275	473
TSUINTC00295	555	TSUINTC00201	140	TSUINTC00338	465

Figure 2. Sample of 12 interchanges with highest crash occurrences of various crash severity and types

- These selected interchanges were
    - TSUINTC00036 (PARCLO B): *I-277, NC-27, SR-4798, S Davidson St, South Bv, E Brooklyn Village Ave*
    - TSUINTC00098 (PARCLO AB): *I-440, US-70, Ridge Rd, Ridge Rd To I-440 Ramp EB, Varnell Ave, Arrow Dr*
    - TSUINTC00201 (PARCLO A): *I-40, NC-68, SR-1607, SR-1681, SR-1695, SR-1882, SR-1883*
    - TSUINTC00205 (SPUI): *I-77, SR-1138, W Arrowood Rd, Arrowridge Blvd*
    - TSUINTC00206 (PARCLO A): *I-77, SR-1128, SR-1382, Westinghouse Blvd*
    - TSUINTC00254 (Diamond): *I-85, SR-2200, Remount Rd*
    - TSUINTC00295 (PARCLO AB): *I-485, SR-3998, SR-4982, Rodney St, Packard St*

- TSUINTC00325 (Diamond): *I-77, Atando Av, Lasalle St*
- TSUINTC00336 (Diamond): *I-85, SR-2480, SR-2619, SR-2620, SR-2621, SR-2622, Cannon Av, Tom Hunter Rd*
- TSUINTC00338 (PARCLO B): *I-77, US-21, SR-2108, SR-2110, Hamilton Cr*
- TSUINTC00340 (SPUI): *I-85, NC-16, SR-1811, SR-1812, SR-2179, SR-2180, Tennessee Av, N Linwood Av, Honeywood Av, Darby Av, Kentucky Av, Rozzelles Ferry Rd, Alabama Av*
- TSUINTC00617 (PARCLO B): *I-40, SR-1541, On Ramp I-40e, Lanada Rd, River Oaks Dr*

- Then the proportion of severity and type of crashes in the distribution of all crashes occurring at these 12 interchanges was computed (as shown in Figure 3). It is to note that, at this stage, we excluded animal crashes, and crash types coded as “other” that do not fall within the most commonly occurring crash types included in this phase of analysis.

```
=COUNTIFS('Crashes@top12'!S$1:S$8138,"Angle")/COUNTIFS('Crashes@top12'!S$1:S$8138,"*")
```

Crash_Type	Proportion
Angle	0.0892
Bike	0.0005
BU	0.0063
FO	0.0568
HDON	0.0048
JK	0.0010
LT_DR	0.0151
LT_SR	0.0305
OT_RO	0.0038
Ped	0.0037
RE	0.4757
ROR_L	0.0154
ROR_R	0.0155
ROR_S	0.0017
RT_DR	0.0059
RT_SR	0.0066
SSO	0.0027
SSS	0.2648

Crash_Severity	Proportion
K	0.002
A	0.005
B	0.048
C	0.200
O	0.745

Angle=angle crashes, Bike=crashes involving bikes, BU=backing up crashes, FO=crashes with fixed objects, HDON=head-on crashes, JK=jackknife crashes, LT_DR=left-turn crashes on different roadways, LT_SR=left-turn crashes on same roadways, OT_RO=overturn/rollover crashes, Ped=crashes involving pedestrians, RE=rear-end crashes, ROR_L=run-off-road crashes on the left, ROR_R= run-off-road crashes on the right, ROR_S= straight run-off-road crashes, RT_DR=right-turn crashes on different roadways, RT_SR= right-turn crashes on same roadways, SSO=sideswipe crashes in opposite direction, SSS=sideswipe crashes in same direction.

Figure 3. Proportions of crash severities and types at the sample interchanges

- Then the joint proportion of each combination of crash severity and crash type was computed by multiplying the individual proportion of crash severity and crash type, as shown below in Crash_Sev_Typ_Com = joint combination of crash severity and type
- **Figure 4**.

Crash_Sev_Typ_Comb	Proportion
O_RE	0.4
O_SSS	0.2
C_RE	0.1
O_Angle	0.1
A_Angle	0.0
A_FO	0.0
A_LT_SR	0.0
A_Ped	0.0
A_RE	0.0
A_ROR_L	0.0
A_ROR_R	0.0
A_SSS	0.0
B_Bike	0.0
B_FO	0.0

Crash_Sev_Typ_Com = joint combination of crash severity and type

Figure 4. Joint proportion of crash severity and type in the sample

- Then, with a rough estimate of 500 crashes for manual review of crash reports, the count of each crash severity-type combination in the distribution was computed as shown below in Crash_Sev_Typ_Com = joint combination of crash severity and type
- **Figure 5**.

Crash_Sev_Typ_Comb	Proportion	Sample_Size
O_RE	0.4	177.1
O_SSS	0.2	98.6
C_RE	0.1	47.6
O_Angle	0.1	33.2
A_Angle	0.0	0.2
A_FO	0.0	0.1
A_LT_SR	0.0	0.1
A_Ped	0.0	0.0
A_RE	0.0	1.1
A_ROR_L	0.0	0.0
A_ROR_R	0.0	0.0
A_SSS	0.0	0.6
B_Bike	0.0	0.0
B_FO	0.0	1.4

Crash_Sev_Typ_Com = joint combination of crash severity and type

Figure 5. Sample size for each crash severity-type combination

- Then, for practical purposes, as crash counts are integers, the sample size for each combination of crash severity-type was rounded to the nearest integer, where the sample sizes were greater than 1. Sample sizes smaller than 1 were rounded up to 1 in the revised sample size, as shown below in Figure 6.

D2 =ROUND(C2,0)

	A	B	C	D
1	Crash_Sev_Typ_Comb	Proportion	Sample_Size	Rev_Count_Crash_Sample
2	O_RE	0.4	177.1	177
3	O_SSS	0.2	98.6	99
4	C_RE	0.1	47.6	48
5	O_Angle	0.1	33.2	33
25	A_Angle	0.0	0.2	1
26	A_FO	0.0	0.1	1
27	A_LT_SR	0.0	0.1	1
28	A_Ped	0.0	0.0	1
29	A_RE	0.0	1.1	1
30	A_ROR_L	0.0	0.0	1
31	A_ROR_R	0.0	0.0	1
32	A_SSS	0.0	0.6	1
33	B_Bike	0.0	0.0	1
34	B_FO	0.0	1.4	1
35	B_HDON	0.0	0.1	1

Crash_Sev_Typ_Com = joint combination of crash severity and type

Figure 6. Final crash sample size computation

- The resultant total sample size was 526 crashes for the previously identified 12 interchanges.
- Then the random sampling was done on R Studio using the sample() function for each of the combinations of crash severity-type based on the number of crashes for each combination as identified in the previous step (as shown below in Figure 7). The column titled "In_Sample" is a binary indicator (Y=yes vs N=no) to show whether a crash is within the identified sample (crashes that are within the sample are also highlighted in green).

Crash_ID	Interchange_Name	CrSeverity	Crash_Type_Rec_Rev	Crash_Sev_Typ	CS_Pr	CT_Pr	CS_CT_Pr	In_Sample
107298218	TSUINTC00340	O	Angle	O_Angle	0.74	0.09	0.07	Y
107309466	TSUINTC00340	B	Ped	B_Ped	0.05	0.00	0.00	N
107431819	TSUINTC00340	C	RE	C_RE	0.20	0.48	0.10	N
107352913	TSUINTC00340	O	RE	O_RE	0.74	0.48	0.35	N
107243924	TSUINTC00340	O	LT_SR	O_LT_SR	0.74	0.03	0.02	N
107481928	TSUINTC00340	O	RE	O_RE	0.74	0.48	0.35	N
107464489	TSUINTC00340	C	RE	C_RE	0.20	0.48	0.10	N
107419927	TSUINTC00340	O	RE	O_RE	0.74	0.48	0.35	N
107260605	TSUINTC00340	O	SSS	O_SSS	0.74	0.26	0.20	N
107204008	TSUINTC00340	C	RE	C_RE	0.20	0.48	0.10	N
107307698	TSUINTC00340	O	RE	O_RE	0.74	0.48	0.35	N
107387307	TSUINTC00340	O	SSS	O_SSS	0.74	0.26	0.20	N
107381893	TSUINTC00340	O	RE	O_RE	0.74	0.48	0.35	N
107288256	TSUINTC00340	O	SSS	O_SSS	0.74	0.26	0.20	N
107368337	TSUINTC00340	O	SSS	O_SSS	0.74	0.26	0.20	N
107448632	TSUINTC00340	O	SSS	O_SSS	0.74	0.26	0.20	N
107289062	TSUINTC00340	O	Angle	O_Angle	0.74	0.09	0.07	Y
107325235	TSUINTC00340	O	SSS	O_SSS	0.74	0.26	0.20	N

Crash_Sev_Typ_Com = joint combination of crash severity and type, CrSeverity: crash severity, Crash_Typ_Rec_Rev= crash types, Crash_Sev_Typ: combination of crash severity and type, CS_Pr= crash severity proportion in the sample, CT_Pr= crash type proportion in the sample, CS_CT_Pr= proportion of each crash severity and type combination in the whole sample, In_Sample= indicates whether the observation is within the identified sample.

Figure 7. Random sampling of crashes

The finally identified sample of a total of 526 crashes represented the population of crashes (i.e., all crashes occurring at the 12 interchanges as stated above) well, in terms of crash severity and crash type proportions in the sample vs population. This additional effort also helped identify the mismatches between the crash spatial locations in the original cash data and crash locations as provided by the crash reports and their diagrams, for about 6 percent of crashes in the sample. This implies, the spatial coordinates might not always be optimal to designate the crash location accurately. Moreover, this additional effort involving the review of individual crash reports and their associated crash diagrams helped identify the specific crash locations in relation to the interchange geometry (i.e., on-ramp, off-ramp, ramp terminals, and crossroads etc.) and different crash types and provided with a comparative understanding of these crash occurrences on different interchange types including PARCLO A, PARCLO B, PARCLO AB, and SPUI, relative to diamond interchange.

Chapter 5. Results and Conclusions

5.1 Phase 1: Cross-sectional negative binomial regression modeling

The results of the analysis, as presented in Table 6 through Table 8, revealed several interesting findings. This section provides details of the model results for individual predictors in the final models developed and comparisons between the effects of these predictors across the three models. For Table 6 through Table 8, implications of each column are as below:

- Estimate (β): These are the log of the expected count ratio for each predictor variable. When we exponentiate a coefficient (*exp(β)*), we get the Incidence Rate Ratio (IRR). For example, if $\beta = 0.5$, then IRR = $exp(0.5) \approx 1.65$, meaning a one-unit increase in the predictor increases the expected count by ~65%.
- S.E (Standard error): It measures the uncertainty or variability of the estimated coefficient. Smaller standard errors indicate more precise estimates.
- z-value: It is used to test the null hypothesis that the coefficient is zero. It is ccomputed as:

$$z = \frac{Estimate\ (\beta)}{Standard\ error}$$

- p-value: This indicates whether a predictor is statistically significant. A small p-value (e.g. < 0.05, or 0.10) suggests strong evidence against the null hypothesis (i.e., the coefficient is not zero).
- Exp(β): This represents the crash modification factors (CMFs), which depicts the change in crashes associated with a unit change in a predictor variable. CMF values less than 1.0 indicate that a treatment of interest reduces the estimated average crash frequency compared to the base condition and vice versa.

The model results, as presented in Table 6 through Table 8 can be summarized as follows:

- Several interchange types were shown to have statistically significant associations with crash frequency. Below are these details.
    - Complex interchanges – Statistically significant positive associations for all crash severities. Particularly, this interchange type is associated with approximately 130 percent (Table 6, Row# 1), 176 percent (Table 7, Row# 1), and 112 percent (Table 8, Row# 1) higher crash likelihood for total, FI, and PDO crashes, respectively.
    - PARCLO A – Statistically significant positive associations for total and FI crashes, but not PDO crashes. Particularly, this interchange type is associated with approximately 9.3 percent (Table 6, Row# 2) and 16.8 percent (Table 7, Row# 2) higher crash likelihood for total and FI crashes, respectively.

- PARCLO B – A statistically significant positive association for only FI crashes, but not total or PDO crashes. Particularly, this interchange type is associated with approximately 26.7 percent (Table 7, Row# 3) higher crash likelihood for FI crashes.
    - PARCLO AB – Statistically significant negative association for total and PDO crashes, but not FI crashes. Particularly, this interchange type is associated with approximately 9.2 percent (Table 6, Row# 4) and 13.7 percent (Table 8, Row# 4) lower crash likelihood for total and PDO crashes, respectively.
    - Partial – Statistically significant negative associations for all crash severities. Particularly, this interchange type is associated with approximately 57.2 percent (Table 6, Row# 5), 53.8 percent (Table 7, Row# 5), and 57.3 percent (Table 8, Row# 5) lower crash likelihood for total, FI, and PDO crashes, respectively.
    - SPUI – Statistically significant positive associations for all crash severities. Particularly, this interchange type is associated with approximately 139 percent (Table 6, Row# 6), 187 percent (Table 7, Row# 6), and 122 percent (Table 8, Row# 6) higher crash likelihood for total, FI, and PDO crashes, respectively.
    - To summarize, SPUIs were shown to have the greatest crash likelihoods for all crash severities, followed by complex interchanges. Also, PARCLO A interchanges were associated with greater crash likelihoods for all crash severities compared to diamond interchanges, but lower likelihoods with respect to SPUIs and complex interchanges. Partial interchanges had lower likelihoods for all crash severities compared to diamond interchanges, while PARCLO AB was found to be associated with a lower likelihood for only PDO crashes. Furthermore, while PARCLO B was associated with slightly higher crash likelihood for total and FI crashes, it showed a lower likelihood for PDO crashes, compared to diamond interchanges.
    - Overall, the effects of interchange type are more pronounced for FI crashes, except for partial interchange type.
- Traffic volumes were also shown to have statistically significant associations with crash occurrence, as below (see Table 6 through Table 8 from Row# 7 through 10).
    - On-ramp AADTs – Statistically significant negative associations for all crash severities.
    - Off-ramp AADTs – Statistically significant positive associations for all crash severities.
    - Crossroad AADTs – Statistically significant positive associations for all crash severities.
    - Overall, the effects of AADTs are more pronounced for total and PDO crashes.
- Average freeway inside shoulder width (see Table 6, Row# 11, Table 7, Row# 14, and Table 8, Row# 11, respectively) – Statistically significant positive associations for all crash severities. Although this may seem counterintuitive, a closer look at the association between shoulder width and traffic volume on ramps (both on and off) reveals that, while the average traffic volume for all shoulder width is approximately

65,000 vehicles per day (vpd), when it comes to shoulder width wider than 6 feet, the average traffic volume is almost 30 percent higher, approximately 84,000 vpd.

- Freeway median width (see Table 6, Row# 12, and Table 8, Row# 12, respectively) – Statistically significant negative associations for total and PDO crashes, but not FI crashes.
- Proportion of rumble strips on freeways (see Table 6, Row# 13, and Table 7, Row# 15, respectively) – Statistically significant negative associations for total and FI crashes, but not PDO crashes. Also, the effect of this variable is more pronounced for FI crashes.
- Average median barrier length (see Table 6, Row# 14, Table 7, Row# 16, and Table 8, Row# 13, respectively) – Statistically significant positive associations for all crash severities. Also, the effect of this variable is more pronounced for FI crashes.
- Average median barrier offset distance (see Table 6, Row# 15, and Table 8, Row# 14, respectively) – Statistically significant negative associations for only total and PDO crashes, but not FI crashes.
- Proportion of Type B maneuver off ramps (see Table 6, Row# 16, Table 7, Row# 17, and Table 8, Row# 15, respectively) – Statistically significant positive associations for all crash severities. Also, the effect of this variable is more pronounced for FI crashes.
- Minimum number of freeway through lanes (see Table 7, Row# 11) – A statistically significant positive association for only FI crashes.
- Average length of freeway speed change lanes (see Table 7, Row# 12) - A statistically significant negative association for only FI crashes.
- Average freeway segment lengths (see Table 7, Row# 13) - A statistically significant negative association for only FI crashes.
- Average length of Type B maneuver off-ramps (see Table 7, Row# 18) - A statistically significant negative association for only FI crashes.
- Proportion of 4-leg intersection at crossroad terminal ramps (see Table 6, Row# 17, Table 7, Row# 19, and Table 8, Row# 16, respectively) - Statistically significant positive associations for all crash severities. Also, the effect of this variable is more pronounced for FI crashes.
- Proportion of 5-leg intersection at crossroad terminal (see Table 7, Row# 20) - A statistically significant positive association for only FI crashes.
- Proportion of merge at crossroad terminal (see Table 6, Row# 18, Table 7, Row# 21, and Table 8, Row# 17, respectively) - Statistically significant positive associations for all crash severities. Also, the effect of this variable is more pronounced for FI crashes.
- Proportion of SPUI at crossroad terminal (see Table 6, Row# 19, Table 7, Row# 22, and Table 8, Row# 18, respectively) - Statistically significant negative associations for all crash severities. Also, the effect of this variable is more pronounced for FI crashes.
- Proportion of signalized intersection at crossroad terminal (see Table 6, Row# 20, Table 7, Row# 23, and Table 8, Row# 19, respectively) - Statistically significant positive associations for all crash severities.

- Minimum number of through lanes in one direction at crossroad terminal (see Table 7, Row# 24) – A statistically significant negative association for only FI crashes.
- Minimum number of through lanes in opposite direction at crossroad terminal (see Table 7, Row# 25) – A statistically significant positive association for only FI crashes.
- Maximum number of through lanes in opposite direction at crossroad terminal (see Table 6, Row# 21, and Table 8, Row# 20, respectively) – Statistically significant negative association for only total and PDO crashes, but not FI crashes.
- Maximum number of left-turn lanes at crossroad terminal (see Table 6, Row# 22, Table 7, Row# 26, and Table 8, Row# 21, respectively) – Statistically significant negative association for all crash severities.
- Minimum number of left-turn lanes at crossroad terminal (see Table 6, Row# 23, Table 7, Row# 27, and Table 8, Row# 22, respectively) – Statistically significant positive association for all crash severities.
- Maximum number of right-turn lanes at crossroad terminal (see Table 6, Row# 24, Table 7, Row# 28, and Table 8, Row# 23, respectively) – Statistically significant positive association for all crash severities. Also, the effect of this variable is more pronounced for total and PDO crashes.
- Average distance to next intersection (see Table 6, Row# 25, Table 7, Row# 29, and Table 8, Row# 24, respectively) – Statistically significant positive association for all crash severities. Also, the effect of this variable is more pronounced for total and PDO crashes.
- Average left-turn lane width at crossroad terminal (see Table 6, Row# 26, Table 7, Row# 30, and Table 8, Row# 245, respectively) - Statistically significant positive association for all crash severities. Also, the effect of this variable is more pronounced for FI crashes.

In addition to the model results, cumulative residual (CURE) plots are provided for each of these final models (Figure 8 through Figure 10). The CURE plots are a valuable tool in safety performance analysis for assessing the goodness-of-fit of statistical models and help assess how well a covariate is captured in a generalized linear regression model, such as negative binomial or Poisson regression models. By and large, a well-fitting model's CURE plot should show the cumulative residuals fluctuating around zero, within the lower and upper boundaries. In the CURE plots below, the cumulative residuals of the crash frequency (y-axis) are plotted against the predicted crash frequency (x-axis). As can be seen from Figure 8 through Figure 10, the CURE plots show good prediction performance and model fits, especially for total and PDO crashes, with an exception of a slightly higher underprediction of total crashes for the highest predicted values. This is not particularly of concern, as they are not typical scenarios representing most of the predicted values, and generally indicate that the model predictions might be less reliable in those highest ranges of predicted values and might warrant localized or contextualized analysis in future. In case of the CURE plot for FI crashes in Figure 10, while we see, for the most part, the CURE plot lies within the boundaries, we observe a larger underprediction where the cumulative residuals go beyond the upper bounding limit for a small range of predicted values (between approximately 42 to 55 crashes per year in the x-axis). This could be due to several reasons, including nonlinearity, heteroscedasticity (as defined by the phenomenon where the variance of errors changes with the level of prediction), and interaction among the predictor variables. As FI crashes are rarer event than PDO crashes, issues like these might be more likely, and could be tackled in future research utilizing different analysis approaches.

Table 6. Cross-sectional model results for total crashes

Parameters	Row#	Estimate (β)	S.E	z-value	p-value	Exp(β)
Intercept		-10.650	0.464	-22.927	<0.001****	
Diamond interchange type		Baseline				
Complex interchange type	1	0.835	0.066	12.717	<0.001****	2.304
PARCLO A interchange type	2	0.089	0.051	1.749	0.080*	1.093
PARCLO B interchange type	3	0.028	0.061	0.466	0.641	1.029
PARCLO AB interchange type	4	-0.097	0.058	-1.652	0.099*	0.908
Partial interchange type	5	-0.849	0.114	-7.472	<0.001****	0.428
SPUI type	6	0.870	0.206	4.224	<0.001****	2.386
Natural log of average AADT on freeway on ramps	7	-2.223	0.324	-6.868	<0.001****	0.108
Natural log of average AADT on freeway off ramps	8	2.894	0.323	8.973	<0.001****	18.065
Natural log of average AADT on crossroad terminal	9	0.280	0.044	6.374	<0.001****	1.323
Natural log of average AADT on crossroad terminal ramps	10	0.425	0.060	7.072	<0.001****	1.530
Average freeway inside shoulder width	11	0.024	0.006	3.653	<0.001****	1.024
Average freeway median width	12	-0.001	0.000	-2.244	0.025**	0.999
Proportion of rumble strips on freeways	13	-0.101	0.056	-1.798	0.072*	0.904
Average freeway median barrier length	14	0.409	0.098	4.154	<0.001****	1.505
Average freeway median barrier offset distance	15	-0.005	0.002	-2.160	0.031**	0.995
Proportion of Type B maneuver off ramps	16	0.297	0.058	5.087	<0.001****	1.345
Proportion of 4-leg intersection at crossroad terminal	17	0.257	0.065	3.945	<0.001****	1.293
Proportion of merge at crossroad terminal	18	0.899	0.133	6.752	<0.001****	2.458
Proportion of SPUI at crossroad terminal	19	-0.507	0.202	-2.512	0.012**	0.602
Proportion of signalized intersection at crossroad terminal	20	0.226	0.097	2.338	0.019**	1.253
Maximum number of through lanes in opposite direction at crossroad terminal	21	-0.044	0.018	-2.440	0.015**	0.956
Maximum number of left-turn lanes at crossroad terminal	22	-0.159	0.038	-4.171	<0.001****	0.853
Minimum number of left-turn lanes at crossroad terminal	23	0.103	0.040	2.583	0.010***	1.108
Maximum number of right-turn lanes at crossroad terminal	24	0.185	0.039	4.808	<0.001****	1.203
Average distance to next intersection	25	0.722	0.182	3.975	<0.001****	2.058
Average left-turn lane width at crossroad terminal	26	0.038	0.012	3.136	0.002***	1.039
Dispersion parameter		4.792	S.E.	0.237		
AIC		9223.8				
2 x log-likelihood		-9167.849				

*p-value significance: '****'= <0.001; '***'= <0.01; '**'= <0.05; '*'= <0.1.*

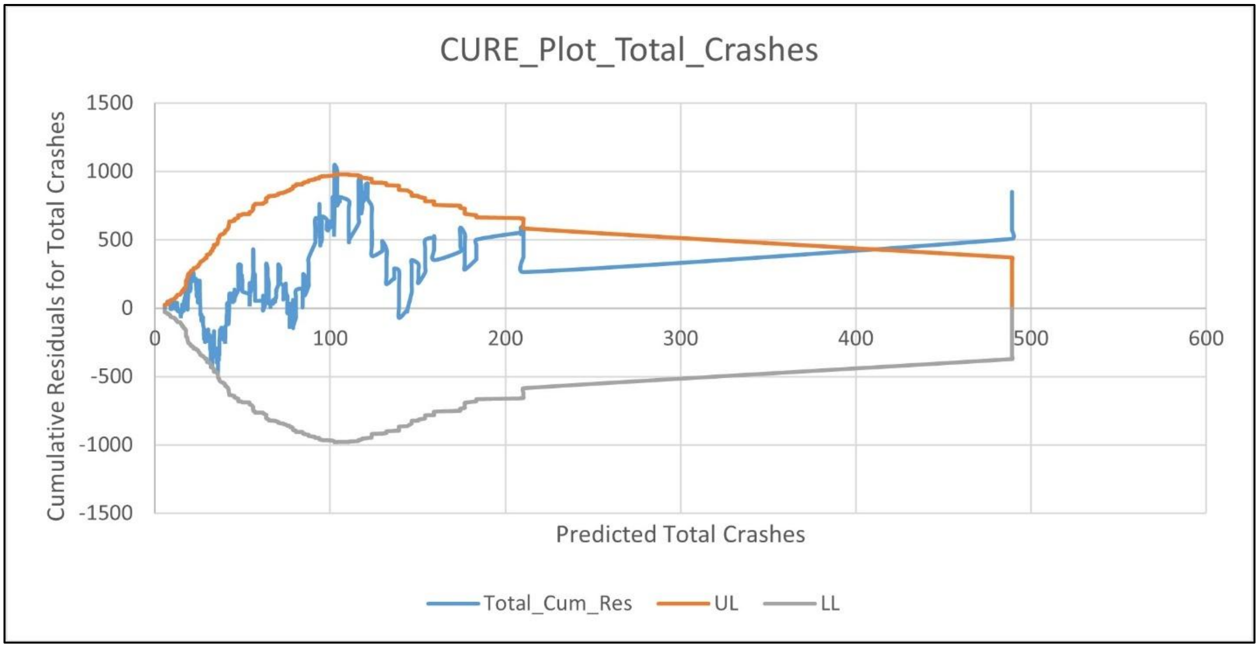

Figure 8. CURE plot for total crashes

Table 7. Cross-sectional model results for fatal-injury (FI) crashes

Parameters	Row#	Estimate (β)	S.E	z-value	p-value	Exp(β)
Intercept		-11.780	0.567	-20.775	<0.001****	-11.780
Diamond interchange type		Baseline				
Complex interchange type	1	1.016	0.077	13.186	<0.001****	2.763
PARCLO A interchange type	2	0.155	0.063	2.470	0.014**	1.168
PARCLO B interchange type	3	0.237	0.073	3.237	0.001***	1.267
PARCLO AB interchange type	4	0.042	0.073	0.568	0.570	1.043
Partial interchange type	5	-0.771	0.149	-5.185	<0.001****	0.462
SPUI type	6	1.053	0.252	4.183	<0.001****	2.867
Natural log of average AADT on freeway on ramps	7	-1.885	0.377	-4.993	<0.001****	0.152
Natural log of average AADT on freeway off ramps	8	2.619	0.375	6.980	<0.001****	13.720
Natural log of average AADT on crossroad terminal	9	0.253	0.058	4.372	<0.001****	1.288
Natural log of average AADT on crossroad terminal ramps	10	0.303	0.073	4.123	<0.001****	1.353
Minimum number of freeway through lanes	11	0.082	0.035	2.307	0.021**	1.085
Average length of freeway speed change lanes	12	-1.821	0.439	-4.146	<0.001****	0.162
Average freeway segment lengths	13	-0.539	0.230	-2.347	0.019**	0.583
Average freeway inside shoulder width	14	0.015	0.008	1.840	0.066*	1.015
Proportion of rumble strips on freeways	15	-0.363	0.064	-5.689	<0.001****	0.696
Average freeway median barrier length	16	0.822	0.236	3.479	<0.001****	2.276
Proportion of Type B maneuver off ramps	17	0.656	0.127	5.164	<0.001****	1.928
Average length of Type B maneuver off-ramps	18	-1.009	0.370	-2.726	0.006***	0.365
Proportion of 4-leg intersection at crossroad terminal	19	0.390	0.083	4.708	<0.001****	1.476
Proportion of 5-leg intersection at crossroad terminal	20	0.925	0.302	3.062	0.002***	2.521
Proportion of merge at crossroad terminal	21	1.035	0.160	6.473	<0.001****	2.816
Proportion of SPUI at crossroad terminal	22	-0.672	0.252	-2.661	0.008***	0.511
Proportion of signalized intersection at crossroad terminal	23	0.219	0.121	1.801	0.072*	1.245
Minimum number of through lanes in one direction at crossroad terminal	24	-0.087	0.040	-2.192	0.028**	0.917
Minimum number of through lanes in opposite direction at crossroad terminal	25	0.127	0.042	3.052	0.002***	1.136
Maximum number of left-turn lanes at crossroad terminal	26	-0.144	0.044	-3.251	0.001***	0.866
Minimum number of left-turn lanes at crossroad terminal	27	0.134	0.047	2.834	0.005***	1.144
Maximum number of right-turn lanes at crossroad terminal	28	0.098	0.044	2.230	0.026**	1.103
Average distance to next intersection	29	0.656	0.221	2.971	0.003***	1.927
Average left-turn lane width at crossroad terminal	30	0.051	0.015	3.423	<0.001****	1.052
Dispersion parameter		4.808	S.E.	0.326		
AIC		6526.9				
2 x log-likelihood		-6462.888				

*p-value significance: '****'= <0.001; '***'= <0.01; '**'= <0.05; '*'= <0.1.*

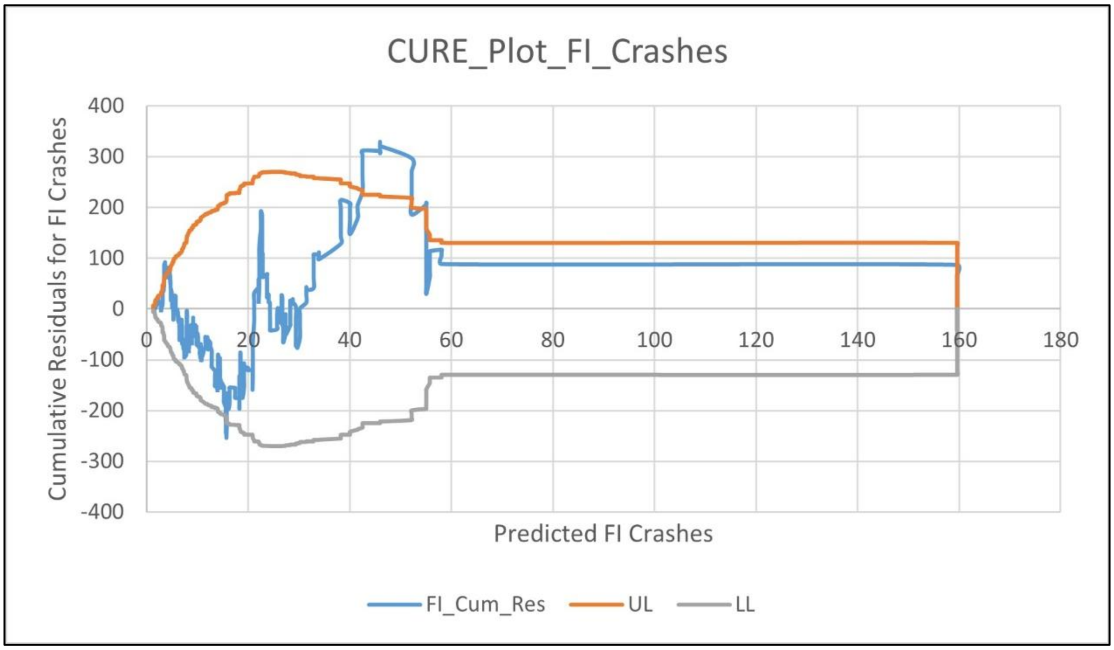

Figure 9. CURE plot for fatal-injury (FI) crashes

Table 8. Cross-sectional model results for PDO crashes

Parameters	Row#	Estimate (β)	S.E	z-value	p-value	Exp(β)
Intercept		-10.650	0.464	-22.927	<0.001****	
Diamond interchange type		Baseline				
Complex interchange type	1	0.835	0.066	12.717	<0.001****	2.304
PARCLO A interchange type	2	0.089	0.051	1.749	0.080*	1.093
PARCLO B interchange type	3	0.028	0.061	0.466	0.641	1.029
PARCLO AB interchange type	4	-0.097	0.058	-1.652	0.099*	0.908
Partial interchange type	5	-0.849	0.114	-7.472	<0.001****	0.428
SPUI type	6	0.870	0.206	4.224	<0.001****	2.386
Natural log of average AADT on freeway on ramps	7	-2.470	0.338	-7.317	<0.001****	0.085
Natural log of average AADT on freeway off ramps	8	3.124	0.336	9.286	<0.001****	22.737
Natural log of average AADT on crossroad terminal	9	0.289	0.046	6.299	<0.001****	1.335
Natural log of average AADT on crossroad terminal ramps	10	0.458	0.063	7.233	<0.001****	1.580
Average freeway inside shoulder width	11	0.021	0.007	3.171	0.002***	1.022
Average freeway median width	12	-0.001	0.001	-2.308	0.021**	0.999
Average freeway median barrier length	13	0.414	0.103	4.026	<0.001****	1.513
Average freeway median barrier offset distance	14	-0.005	0.002	-2.061	0.039**	0.995
Proportion of Type B maneuver off ramps	15	0.281	0.061	4.650	<0.001****	1.325
Proportion of 4-leg intersection at crossroad terminal	16	0.203	0.068	2.974	0.003***	1.225
Proportion of merge at crossroad terminal	17	0.823	0.139	5.904	<0.001****	2.278
Proportion of SPUI at crossroad terminal	18	-0.496	0.212	-2.346	0.019**	0.609
Proportion of signalized intersection at crossroad terminal	19	0.187	0.102	1.838	0.066*	1.206
Maximum number of through lanes in opposite direction at crossroad terminal	20	-0.051	0.019	-2.690	0.007***	0.950
Maximum number of left-turn lanes at crossroad terminal	21	-0.139	0.040	-3.467	<0.001****	0.870
Minimum number of left-turn lanes at crossroad terminal	22	0.107	0.042	2.579	0.010***	1.113
Maximum number of right-turn lanes at crossroad terminal	23	0.194	0.040	4.829	<0.001****	1.214
Average distance to next intersection	24	0.745	0.191	3.909	<0.001****	2.107
Average left-turn lane width at crossroad terminal	25	0.034	0.013	2.645	0.008***	1.034
Dispersion parameter		4.477	S.E.	0.227		
AIC		8715.6				
2 x log-likelihood		-8661.576				

*p-value significance: '****'= <0.001; '***'= <0.01; '**'= <0.05; '*'= <0.1.*

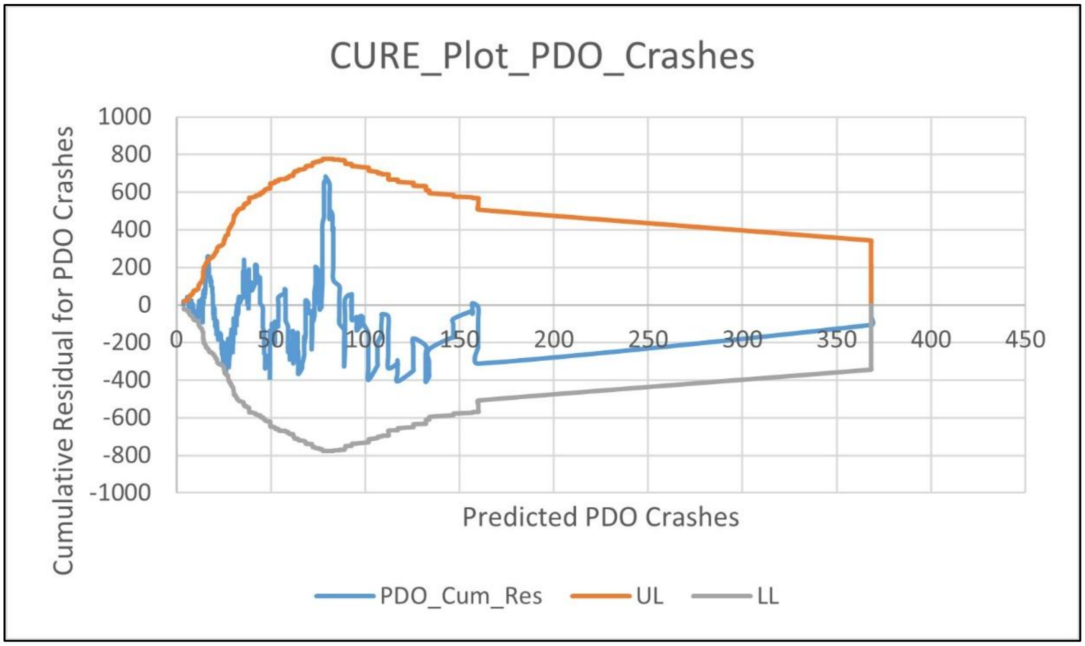

Figure 10. CURE plot for property damage only (PDO) crashes

Table 9 below summarizes the effects of different interchange types analyzed compared to the baseline of diamond interchanges for total, FI, and PDO crashes.

Table 9. Summary of effects of interchanges compared to diamond interchange

Interchange Type	Total Crashes	FI Crashes	PDO Crashes
Diamond	Baseline		
Complex	Higher (130.4%)*	Higher (176.3%)*	Higher (111.7%)*
PARCLO A	Higher (9.3%)*	Higher (16.8%)*	Higher (6%)
PARCLO B	Higher (2.9%)*	Higher (26.7%)*	Lower (4.3%)
PARCLO AB	Lower (9.2%)*	Higher (4.3%)	Lower (13.7%)*
Partial	Lower (57.2%)*	Lower (53.8%)*	Lower (57.3%)*
SPUI	Higher (138.6%)*	Higher (186.7%)*	Higher (122.4%)*

** Denotes the statistically significant associations*

5.2 Phase 2: Descriptive analysis from the manual review of crash reports

In the Phase 2 analysis, a total of 12 interchanges were considered as described in Section 5.3. The different types of interchanges included diamond, PARCLO A, PARCLO B, PARCLO AB, and SPUIs. Initially, a total of 558 crashes were sampled from the crashes that were originally included in the analysis in Phase 1. It is important to note that, as per the crash reports and their associated crash diagrams, it was found that a total of 32 out of 558 initially sampled crashes (approximately 5.7 percent) occurred outside of the interchange influence area. This implies that while all these crashes were included in Phase 1 analysis based on their geocoded location through spatial mapping, the crash report narrative and diagram of the crash location deviated from that. It is worth noting that the presence of these miscoded data is unlikely to significantly affect the quality and reliability of the CMFs developed using cross-sectional regression models, as the miscoding does not appear to be systematically biased. Ultimately, a total of 526 crashes (=558-32) occurring at these 12 interchange influence areas were manually reviewed in detail from the crash reports and their associated crash diagrams. The distribution of interchange type, their respective crash counts (with a total of 526 crashes), and corresponding crash rates (crash counts per interchange by interchange type) are shown below in Table 10. Also, a detailed crash severity distribution at each of these interchanges is provided in Table 15 in Appendix B. Additionally, Appendix C provides the Google Earth aerial images of 12 interchanges that were included in Phase 2 analysis.

Table 10. Distribution of interchange type, crash counts, and crash rates

Interchange type (I-Typ)	Interchange type count	Crash count	Crash count%	Crash rate per interchange
Diamond	3	171	32.5	57.0
PARCLO A	2	62	11.8	31.0
PARCLO AB	2	80	15.2	40.0
PARCLO B	3	98	18.6	32.7
SPUI	2	115	21.9	57.5
Grand Total	**12**	**526**	**100.0**	**43.8**

Authorized speed limit 1 is for the roadway vehicle 1 is on, while authorized speed limit 2 would be for the roadway for vehicle 2. For 11 crashes, authorized speed limit 2 was higher than authorized speed limit 1. When the higher of the authorized speed limits 1 and 2 from the crash reports were compared against crash severity, as shown in Figure 11, it showed that overall, the speed distribution was comparable across all severity types. However, the median value was higher for incapacitating injury (A) crashes with a broader range (difference between maximum and minimum authorized speed limits values) indicated by longer whiskers and a larger box, suggesting a wider distribution/dispersion of the higher of the authorized speed limits 1 and 2 for incapacitating injury (A) crashes Also, there were a few outliers for non-incapacitating injury (B) crashes and property damage only (O) crashes, as shown in the figure.

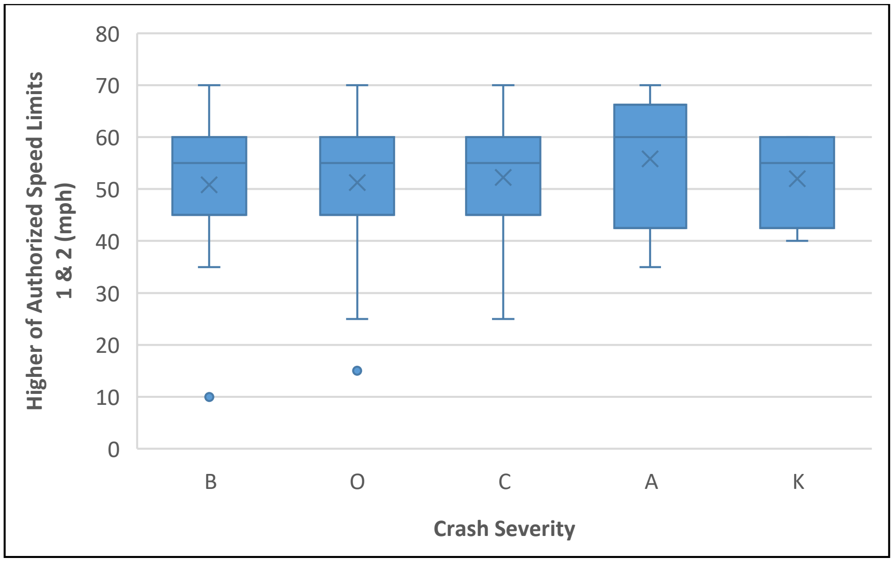

Figure 11. Authorized speed limit vs crash severity

The crash severity distribution across the 5 interchange types is provided in Table 11. As can be seen from Table 11, the proportion of fatal (K) crashes, as well as the proportion of fatal and incapacitating injury (KA) crashes combined were the highest at the diamond interchanges. However, for non-incapacitating injury (B) crashes and possible injury (C) crashes, the proportions were the highest at PARCLO B interchange type. Finally, the property damage-only (O) crashes were the highest at PARCLO AB interchanges.

Table 11. Crash severity distribution across interchange types

I-Typ	I-Typ count	K	K%	A	A%	B	B%	C	C%	O	O%	Grand Total
Diamond	3	3	1.75	3	1.75	9	5.26	28	16.37	128	74.85	**171**
PARCLO A	2	2	3.23	0	0.00	2	3.23	15	24.19	43	69.35	**62**
PARCLO AB	2	0	0.00	1	1.25	6	7.50	11	13.75	62	77.50	**80**
PARCLO B	3	0	0.00	2	2.04	8	8.16	27	27.55	61	62.24	**98**
SPUI	2	0	0.00	1	0.87	6	5.22	27	23.48	81	70.43	**115**
Grand Total	**12**	**5**	**0.95**	**7**	**1.33**	**31**	**5.89**	**108**	**20.53**	**375**	**71.29**	**526**

When the variable “Relation to Roadway” was assessed by the different interchange types, as shown in Table 12, it was found that the proportion of crashes occurring “on roadway” was the lowest for PARCLO A interchanges, while those for PARCLO B, PARCLO AB, and SPUIs were higher than that for diamond interchanges. Also, the proportions of crashes occurring on shoulders and roadside were the highest for PARCLO A interchange type. However, the proportion of crashes occurring on the median was the greatest for SPUIs.

Table 12. Crash location relation to roadways

I-Typ	On Roadway%	Shoulder%	Median%	Roadside%	Outside Trafficway%
Diamond	96.49	2.34	1.17	0.00	0.00
PARCLO A	90.32	4.84	1.61	3.23	0.00
PARCLO AB	97.50	1.25	0.00	0.00	1.25
PARCLO B	98.98	0.00	0.00	0.00	1.02
SPUI	98.26	0.00	1.74	0.00	0.00

In terms of the crash locations within the interchange influence area (“Road Feature” variable), as shown in Table 13, while the proportion of crashes at off-ramp entries was the highest for PARCLO A, the proportion of crashes occurring at “off-ramp proper” was the highest for SPUIs, and the lowest on diamond interchanges, respectively. Moreover, the proportions of crashes occurring at off-ramp terminals on crossroads and on-ramp entries were the highest for PARCLO B interchanges, and lowest for diamond interchanges, respectively. Also, the proportion of crashes occurring at “on-ramp proper” was higher at PARCLO A and PARCLO B interchanges, compared to diamond interchanges. The proportion of crashes occurring at on-ramp terminals on crossroads was the highest at diamond interchanges followed by PARCLO AB interchanges. Additionally, the proportions of crashes occurring at four-way and T-intersections on crossroads, and bridges and bridge approaches within the interchange influence areas were the highest for PARCLO B interchanges. Furthermore, while the proportions of crashes occurring at underpasses and merge lanes between on- and off-ramps were the highest for PARCLO AB interchanges, those at public driveways on crossroads within the interchange influence areas were higher for PARCLO A and PARCLO AB interchanges compared to diamond interchanges.

Table 13. Crash location with respect to road features

I-Typ	None %	Off RE%	Off RP %	OffR T%	OnR E%	OnR P%	OnR T%	Mrg On Off %	4wyI nt %	TInt %	IntR el%	Drv wy %	Brdg %	BrAp prch %	Up%
Diam ond	70.18	1.17	1.17	9.94	1.17	0.58	8.19	0.00	4.09	0.00	0.00	0.58	2.34	0.58	0.00
PAR CLO A	43.55	4.84	3.23	19.35	4.84	3.23	1.61	0.00	12.90	0.00	0.00	6.45	0.00	0.00	0.00
PAR CLO AB	58.75	2.50	6.25	17.50	2.50	0.00	6.25	1.25	0.00	0.00	0.00	1.25	0.00	0.00	3.75
PAR CLO B	32.65	0.00	4.08	24.49	6.12	1.02	4.08	0.00	17.35	2.04	1.02	0.00	5.10	1.02	1.02
SPUI	54.78	2.61	8.70	20.00	4.35	0.00	0.87	0.87	4.35	1.74	0.00	0.00	0.87	0.00	0.87

I-Typ=interchange type, None=no special feature, OffRE=off-ramp entry, OffRP=off-ramp proper, OffRT=off-ramp terminal on crossroads, OnRE=on-ramp entry, OnRP=on-ramp proper, OnRT=on-ramp terminal on crossroads, MrgOnOff= merge lane between on and off ramp, 4wyInt=four-way intersection on crossroads within interchange influence area, Tint=T-intersections on crossroads within interchange influence area, IntRel=related to other intersections on crossroads within interchange influence area, Drvwy=public driveways on crossroads within interchange influence area, Brdg=bridges, BrApprch=bridge approach, Up=underpasses.

Moving on to the distribution of most harmful crash type (variable titled "most harmful event" in the crash reports) as shown in Table 14, the proportions of angle, backing up, and fixed object crashes were the highest for PARCLO B, PARCLO AB, and PARCLO A interchanges, respectively. While the proportion of head-on crashes was the highest for PARCLO A interchanges, those of left-turn and overturn/rollover crashes were the highest for diamond interchanges. Additionally, while the proportion of rear-end crashes and crashes with pedestrians was the highest for PARCLO AB interchanges, those with pedal-cyclists were the highest for PARCLO B interchanges. Also, the proportions of run-off-road and right-turn crashes were the highest for SPUIs and PARCLO A interchanges, respectively. Lastly, sideswipe opposite direction crashes and crashes with parked vehicles in this sample occurred only at diamond interchanges, while the highest proportion of sideswipe same direction crashes was at PARCLO B interchanges.

Table 14. Crash types based on most harmful event

I-Typ	RE%	Angl %	BU %	FO%	HO %	LT %	RT %	OT %	ROR %	SSS %	SSO %	Ped %	Pcy %	Prk %	Oth %
Diamond	42.11	5.85	0.00	9.36	1.75	7.02	0.00	1.75	1.75	27.49	0.58	1.17	0.00	0.58	0.58
PARCLO A	37.10	14.52	0.00	14.52	3.23	6.45	3.23	1.61	0.00	17.74	0.00	0.00	0.00	0.00	1.61
PARCLO AB	60.00	5.00	2.50	8.75	1.25	1.25	1.25	0.00	0.00	17.50	0.00	1.25	0.00	0.00	1.25
PARCLO B	33.67	23.47	0.00	6.12	1.02	4.08	0.00	1.02	1.02	27.55	0.00	0.00	2.04	0.00	0.00
SPUI	53.91	3.48	0.87	6.96	1.74	1.74	2.61	1.74	2.61	23.48	0.00	0.87	0.00	0.00	0.00

I-Typ=interchange type, RE=all rear-end crashes, Angl=angle crashes, BU=backing-up crashes, FO=fixed-object crashes, HO=all head-on crashes, LT=all left-turn crashes, RT=all right-turn crashes, OT=overturn or rollover crashes, ROR=all run-off-road crashes, SSS=sideswipe same direction crashes, SSO=sideswipe opposite direction crashes, Ped=crashes with pedestrians, Pcy=crashes with pedalcyclist, Prk=crashes with parked motor vehicles, Oth=other crashes.

5.3 Conclusions and future research needs

This study developed CMFs for comparing standard diamond interchange to other common interchange designs for total, fatal and injury, and property damage only crashes, utilizing 5 years of crash data from 2019 through 2023 from North Carolina. A total of 214 interchanges were evaluated including diamond, PARCLO A, PARCLO B, PARCLO AB, SPUI, complex-multi, and partial interchanges. Phase 1 (cross-sectional models) findings of this research can be summarized as below.

Different interchange types were shown to have safety impacts, considering diamond interchanges as the baseline. Complex interchanges were consistently shown to have higher crash likelihoods compared to diamond interchanges for all crash severities. In case of partial cloverleaf (PARCLO) interchanges, while PARCLO A was found to be associated with higher crash likelihoods for total, fatal and injury (FI) crashes, PARCLO B was found to be impacting only FI crashes with a higher crash likelihood. However, PARCLO AB did not have any significant safety effects for total and FI crashes and was associated with lower crash likelihood only for property damage only (PDO) crashes. Additionally, partial interchanges were associated with lower crash likelihoods for all crash severities. Conversely, SPUIs were found to be associated with higher crash likelihoods for all crash severities. Overall, the effects of interchange type were more pronounced for FI crashes. In summary, SPUIs were shown to have the greatest crash likelihoods for all crash severities, followed by complex interchanges. Also, PARCLO A interchanges were associated with greater crash likelihoods for all crash severities compared to diamond interchanges, but lower likelihoods with respect to SPUIs and complex interchanges. Partial interchanges had lower likelihoods for all crash severities compared to diamond interchanges, while PARCLO AB was found to be associated with a lower likelihood for only PDO crashes. Furthermore, while PARCLO B was associated with slightly higher crash likelihood for total and FI crashes, it showed a lower likelihood for PDO crashes, compared to diamond interchanges.

In terms of traffic volumes, on-ramp AADTs showed associations with lower crash likelihoods for all crash severities. Conversely, off-ramp AADTs and crossroad AADTs resulted in higher crash occurrences for all crash severities. Overall, the effects of AADTs were more pronounced for total and PDO crashes.

Among other interchange characteristics, while the average length of Type B maneuver at off-ramps was found to lower FI crash likelihood, the proportion of Type B maneuver at off-ramps increased the crash likelihoods for all crash severities, with a greater effect for FI crashes. Some other attributes including the proportion of 4- leg intersections (for all crash severities) and 5-leg intersections (for only FI crashes) at crossroad terminals, proportion of merging at crossroad terminals (for all crash severities), minimum number of through lanes in opposite direction at crossroad terminals (for only FI crashes), and maximum number of right-turn lanes at crossroad terminals (for all crash severities) were associated with higher crash likelihoods to varying extents. Conversely, other factors such as maximum number of left-turn lanes at crossroad terminals (for all crash severities), and proportion of SPUI at crossroad terminals (for all crash severities) seemed to be associated with lower crash likelihoods by differing magnitudes.

While the Phase 2 analysis did not directly address the primary research objective, as part of this effort, a deeper dive into a sample of crashes with manual crash report review was carried out. These crashes occurred at 5 different interchange types, including diamond, PARCLO A, PARCLO B, PARCLO AB, and SPUIs with a total count of 12 interchanges. This review revealed that almost 6 percent of crashes occurred outside of the interchange influence area, and their spatial locations were miscoded in the original crash data utilized in Phase 1 analysis. Excluding those crashes, ultimately, a total of 526 crashes were included in this phase of analysis. The descriptive analysis revealed that the median value and range of the higher of authorized speed limits 1 and 2 were the greatest for incapacitating injury (A) crashes, although the overall speed distribution was comparable across all severity types. Also, the proportions of fatal (K) crashes and fatal and incapacitating injury (KA) crashes combined were the highest at the diamond interchanges. However, for non-incapacitating injury (B) and possible injury (C) crashes, the proportions were the highest at PARCLO B interchange type. Additionally, the proportions of crashes occurring "on roadway" were the lowest for PARCLO A interchanges, and those of crashes occurring on shoulders and roadside were the highest for PARCLO A interchanges, while SPUIs had the highest proportion of crashes occurring on medians. Moreover, while the proportion of crashes at off-ramp entries was the highest for PARCLO A, the proportion of crashes occurring at "off-ramp proper" was the highest for SPUIs, and the lowest on diamond interchanges, respectively. Furthermore, the proportions of crashes occurring at off-ramp terminals on crossroads and on-ramp entries were the highest for PARCLO B interchanges, and lowest for diamond interchanges, respectively. Also, the proportion of crashes occurring at "on-ramp proper" was higher at PARCLO A and PARCLO B interchanges, compared to diamond interchanges. The proportion of crashes occurring at on-ramp terminals on crossroads was the highest at diamond interchanges, followed by PARCLO AB interchanges. Next, the proportions of crashes occurring at four-way and T-intersections on crossroads, and bridges and bridge approaches within the interchange influence areas were the highest for PARCLO B interchanges. In addition, while the proportions of crashes occurring at underpasses and merge lanes between on- and off-ramps were the highest for PARCLO AB interchanges, those at public driveways on crossroads within the interchange influence areas were higher for PARCLO A and PARCLO AB interchanges compared to diamond interchanges. Besides, the proportions of angle crashes, sideswipe same direction crashes, and crashes with pedal-cyclists were the highest for PARCLO B interchanges, while rear-end and backing up crashes, and crashes with pedestrians were the highest for PARCLO AB interchanges. PARCLO A interchanges showed the highest proportions of head-on, right-turn, and fixed-object crashes, while SPUIs had the highest proportion of run-off-road crashes. Lastly, diamond interchanges showed the highest proportion of left-turn and overturn/rollover crashes, and sideswipe opposite direction crashes and crashes with parked vehicles in this sample occurred only at diamond interchanges.

This study identified some limitations that could be addressed in future research as follows:

- In lieu of sufficient before-and-after data, this study conducted cross-sectional regression modeling. While this is a robust technique for obtaining the CMFs directly from the developed models, it fails to account for the regression-to-the-mean (RTM) phenomenon. Future research can address this gap by carrying out Empirical Bayes (EB) before-and-after analysis.
- Some less commonly occurring interchange types, including partial, trumpet, semi-directional, full cloverleaf, diverging diamond, double roundabout, and 3- and 4-leg directional interchanges, could not be included due to small sample size and data limitations. This can be addressed in future research in order to have a more holistic picture of the safety performance of alternative interchange types.
- This study excluded interchanges with 3 years of construction period, as the analysis period is considered for 5 years. A longer analysis period should be able to include these interchanges as well. This is also insightful as across the country, data exhibited very different crash trends during the COVID-19 years.
- Additional research might look into the appropriate influence area for before-and-after studies when there is a substantial change from the before to the after periods. It could be argued that the influence area should be the same for the before and after periods. However, this would lead to the inclusion of non-intersection crashes in the before period.
- This study developed models for only total, fatal and injury, and property damage only crashes. It will be worth assessing some commonly occurring crash types at interchanges, including rear-end, sideswipe, head-on, and merging crashes.
- Future research may also consider including data from other states to assess how they compare with North Carolina sites and whether there is anything unique in the NC data, including crash trends.

5.4 Implementation and technology transfer

The CMFs developed in this research provide valuable information to NCDOT’s state of knowledge and are expected to be used as part of the safety management process and for alternative analysis. These CMFs will be of interest to NCDOT’s traffic safety and traffic management units and offer insights pertaining to the safety effects of various interchange conversions to transportation researchers, professionals, and industry experts. The research team held multiple meetings with NCDOT Steering and Implementation Committee (STIC) throughout this project to receive their feedback and ascertain that the study meets the expectations. Based on some of those feedback, the research team expanded the primary scope of this research and assumed the task of manual review of a sample of crash reports occurring at a subset of interchange types evaluated in the first phase of this study. The dissemination of this research was carried out by the research team, who presented the key details including literature review, methodology undertaken, and the final findings of this research to the NCDOT STIC during the project closeout meeting. They also developed the final project report and revised and updated it based on the feedback from the NCDOT STIC. Moreover, as part of the initial data review, the research team collected additional site characteristics data, which will be shared with the NCDOT STIC. Moreover, to encourage and facilitate implementation, the research team will value the opportunity of presenting this research as part of a webinar and invite attendees from various groups within NCDOT including the Traffic Safety Unit, Traffic Management Unit, Roadway Design Unit, the 14 Divisions within NCDOT, and the Project Management Staff. The research team also aspires that the products from this project will follow up with research articles to conference proceedings (including Pre-construction Conference, NCITE Annual Meeting, NCDOT's CLEAR (Communicate Lessons, Exchange Advice, Record) program webinar)), and/or peer-reviewed journal articles. Findings from this research may also be shared with the students of UNC's City and Regional Planning Department (DCRP) as part of an ongoing collaborative effort of teaching transportation planning course between DCRP and HSRC (Dr. Chakraborty). The knowledge transfer from this research in the form of presentations at conferences and/or seminars will begin once the project final report is approved by NCDOT STIC. The publication and dissemination of this research is likely to take place within 12-18 months from the project's completion. Moreover, having reliable interchange CMFs would allow NCDOT to compare the potential safety impacts of various common interchange designs and help ensure that the decisions on interchange design concepts get closer to the optimum in future research and implementation efforts. Lastly, the research team does not anticipate further assistance from NCDOT STIC for the knowledge transfer from this research. However, future research accounting for and implementing the findings of this research might be led by NCDOT Traffic Safety Unit.

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Appendix A. Examples of Interchange Types

Figure 12 Diamond interchange: I-485 and Idlewild Rd

Figure 13 PARCLO A: I-73 and US-70

Figure 14 PARCLO B: I-77 and Sunset Rd

Figure 15 PARCLO AB: I-40 and Page Rd

Figure 16 Partial interchange: I-40 and Silas Creek Pkwy

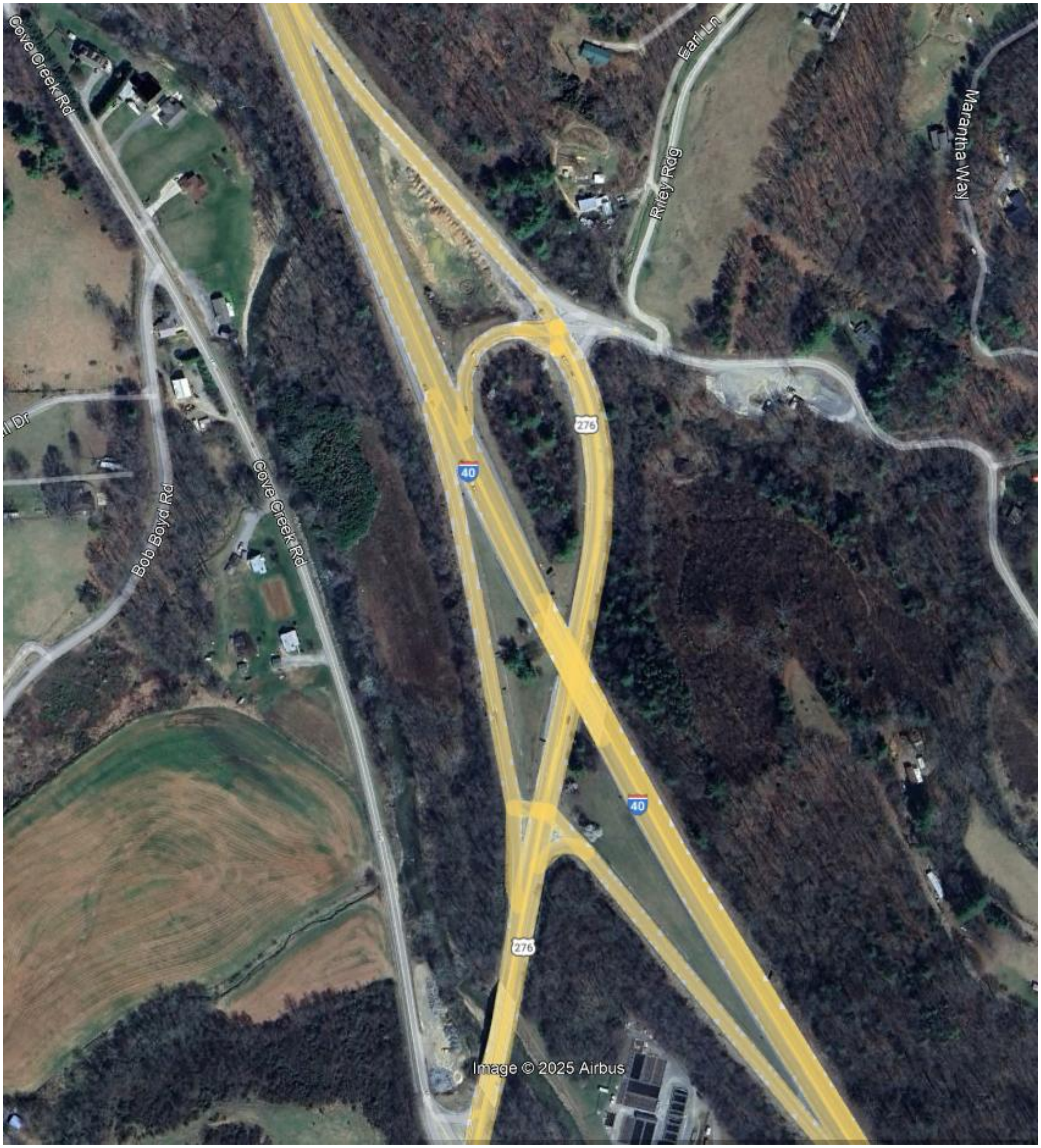

Figure 17 Trumpet: I-40 and US-276

Figure 18 Complex multi-interchange: I-540 and US-1

Figure 19 Semi-directional: I-42 and US-70 BUS

Figure 20 Other: I-26 and US-19

Figure 21 Full cloverleaf: I-95 and NC-87

Figure 22 Three-leg directional: US-52 and N Liberty St

Figure 23 Single point urban interchange: I-40 and Fayetteville Rd

Figure 24 Diverging diamond: I-85 and Poplar Tent Rd

Figure 25 Double roundabout interchange: I-485 and Moore's Chapel Rd

Appendix B. Crash Severity Distribution at Individual Interchange in Phase 2 Analysis

Table 15. Crash severity distribution at individual interchange

Interchange	Interchange Type	K	A	B	C	O	Total
TSUINTC00036	PARCLO B	0	0	4	6	7	**17**
TSUINTC00098	PARCLO AB	0	0	4	7	44	**55**
TSUINTC00201	PARCLO A	0	0	0	7	11	**18**
TSUINTC00205	SPUI	0	0	3	6	27	**36**
TSUINTC00206	PARCLO A	2	0	2	8	32	**44**
TSUINTC00254	Diamond	0	3	3	5	42	**53**
TSUINTC00295	PARCLO AB	0	1	2	4	18	**25**
TSUINTC00325	Diamond	0	0	4	13	58	**75**
TSUINTC00336	Diamond	3	0	2	10	28	**43**
TSUINTC00338	PARCLO B	0	1	4	9	30	**44**
TSUINTC00340	SPUI	0	1	3	21	54	**79**
TSUINTC00617	PARCLO B	0	1	0	12	24	**37**
Grand Total		**5**	**7**	**31**	**108**	**375**	**526**

Appendix C. Aerial View of Individual Sites in Phase 2 Analysis

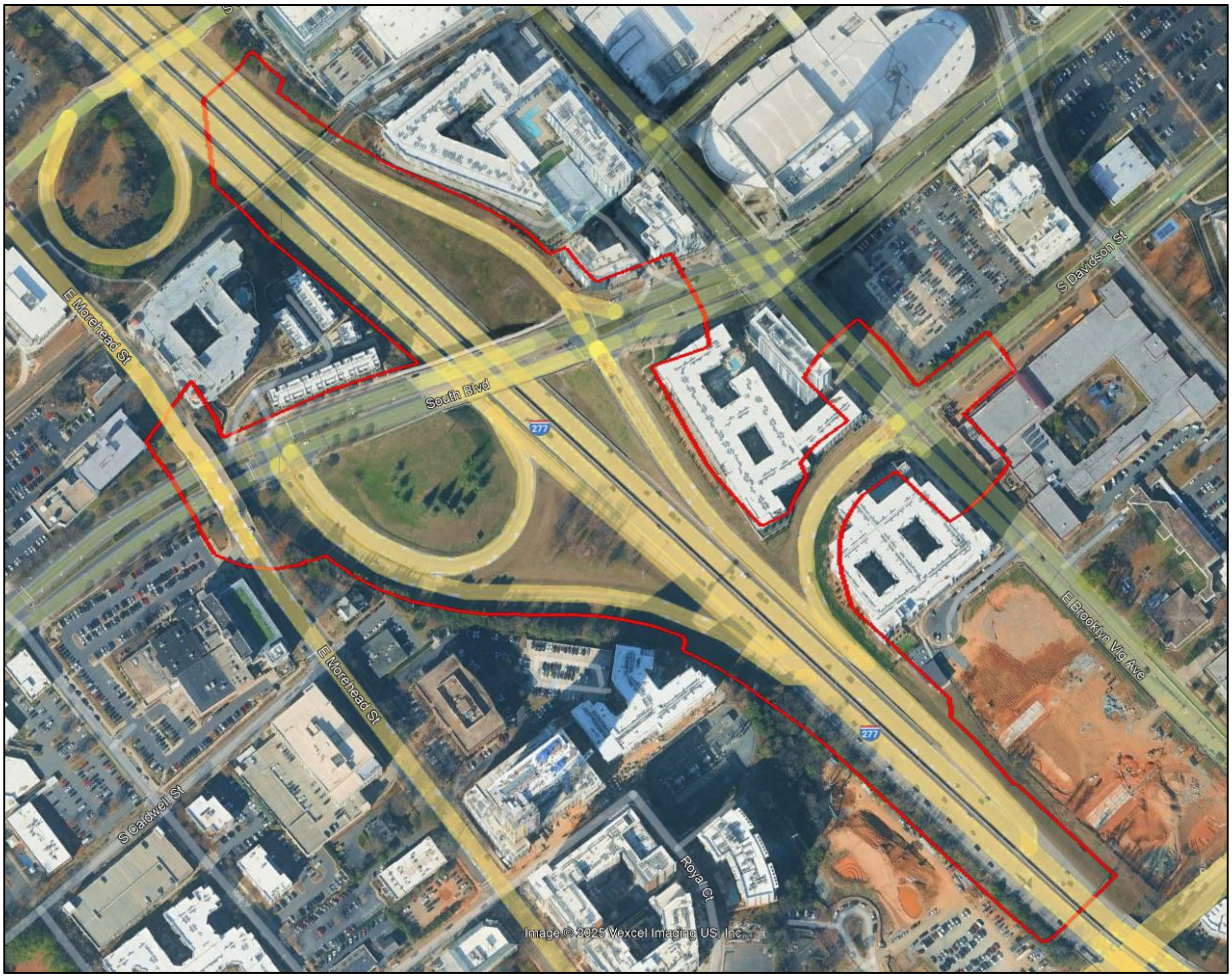

Figure 26. Interchange TSUINTC00036 - I-277, NC-27, SR-4798, S Davidson St, South Bv, E Brooklyn Village Ave (PARCLO B interchange)

Figure 27. Interchange TSUINTC00098 - I-440, US-70, Ridge Rd, Ridge Rd To I-440 Ramp EB, Varnell Ave, Arrow Dr (PARCLO AB interchange)

Figure 28. Interchange TSUINTC00201 - I-40, NC-68, SR-1607, SR-1681, SR-1695, SR-1882, SR-1883 (PARCLO A interchange)

Figure 29. Interchange TSUINTC00205 - I-77, SR-1138, W Arrowood Rd, Arrowridge Blvd (SPUI)

Figure 30. Interchange TSUINTC00206 - I-77, SR-1128, SR-1382, Westinghouse Blvd (PARCLO A interchange)

Figure 31. Interchange TSUINTC00254 - I-85, SR-2200, Remount Rd (Diamond interchange)

Figure 32. Interchange TSUINTC00295 - I-485, SR-3998, SR-4982, Rodney St, Packard St (PARCLO AB interchange)

Figure 33. Interchange TSUINTC00325 - I-77, Atando Av, Lasalle St (Diamond interchange)

Figure 34. Interchange TSUINTC00336 - I-85, SR-2480, SR-2619, SR-2620, SR-2621, SR-2622, Cannon Av, Tom Hunter Rd (Diamond interchange)

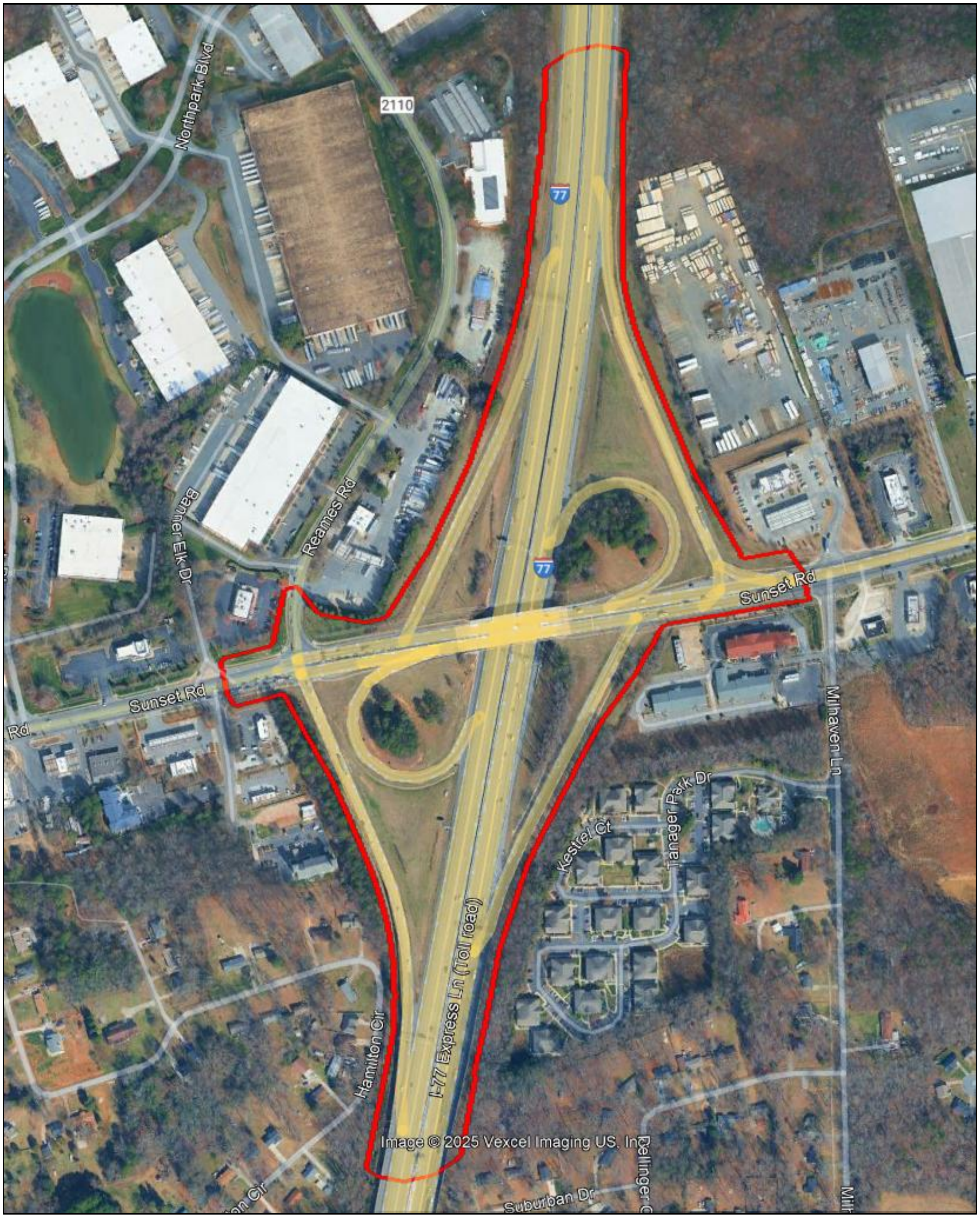

Figure 35. Interchange TSUINTC00338 - I-77, US-21, SR-2108, SR-2110, Hamilton Cr (PARCLO B interchange)

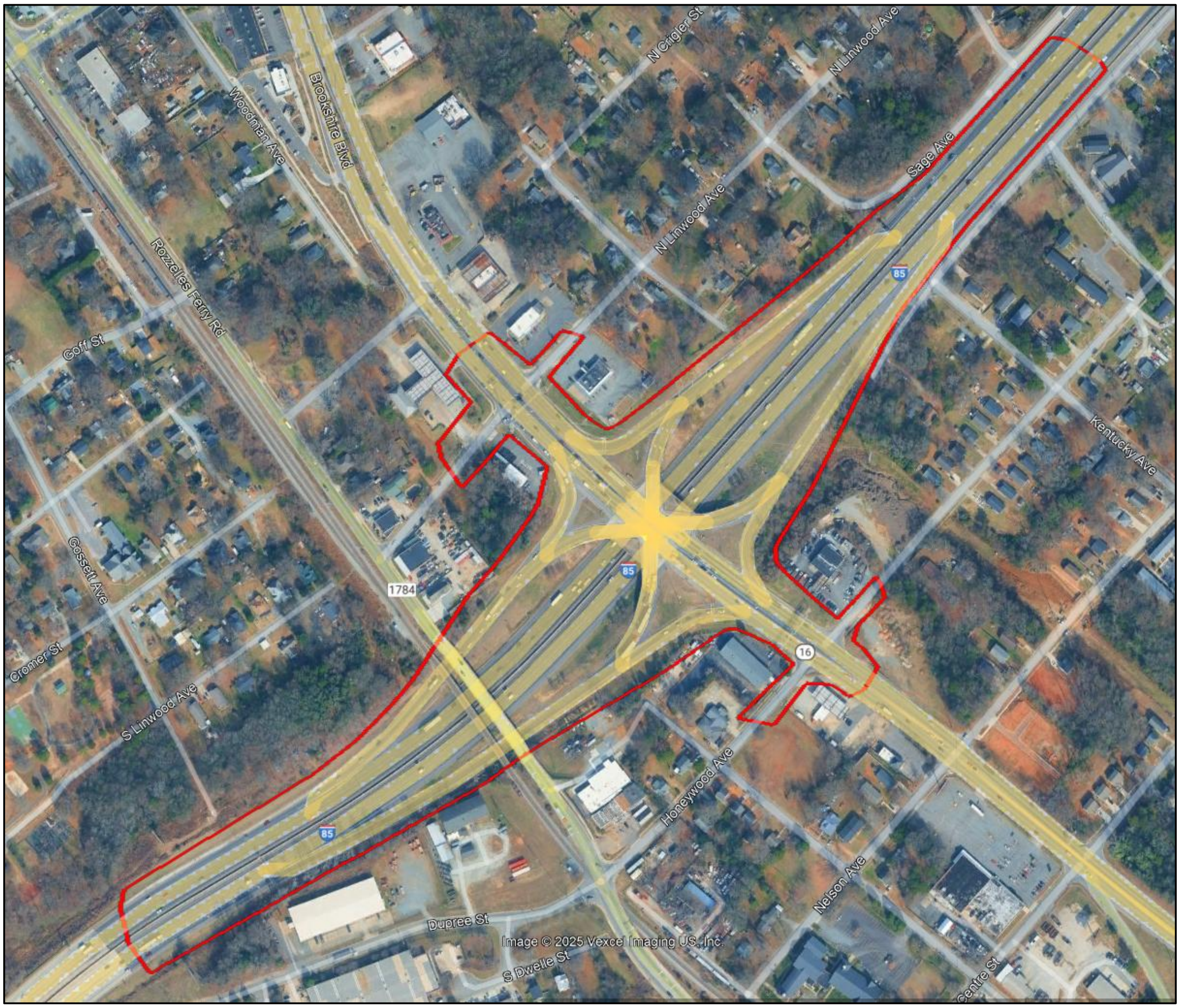

Figure 36. Interchange TSUINTC00340 - I-85, NC-16, SR-1811, SR-1812, SR-2179, SR-2180, Tennessee Av, N Linwood Av, Honeywood Av, Darby Av, Kentucky Av, Rozzelles Ferry Rd, Alabama Av (SPUI)

Figure 37. Interchange TSUINTC00617 - I-40, SR-1541, On Ramp I-40e, Lanada Rd, River Oaks Dr (PARCLO B interchange)