Developing a Crash Modification Factor for Converting from an At-Grade Intersection to a Diamond Interchange

NCDOT Project 2022-14
FHWA/NC/2022-14
March 2024

Raghavan Srinivasan, Ph.D., P.E. et al.
Highway Safety Research Center
The University of North Carolina at Chapel Hill

HSRC THE UNIVERSITY OF NORTH CAROLINA HIGHWAY SAFETY RESEARCH CENTER

STATE OF NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

RESEARCH & DEVELOPMENT

Developing a Crash Modification Factor for Converting from an At-Grade Intersection to a Diamond Interchange

Prepared by:

Highway Safety Research Center
The University of North Carolina at Chapel Hill
Raghavan Srinivasan
Meghna Chakraborty
Mike Vann
Taha Saleem
Bo Lan

NCDOT Project 2022-14

FINAL REPORT
March 2024

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
NCDOT/NC/2022-14</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Developing a Crash Modification Factor for Converting from an At-Grade Intersection to a Diamond Interchange</td><td colspan="2">5. Report Date
March 2024</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Raghavan Srinivasan, Meghna Chakraborty, Mike Vann, Taha Saleem, and Bo Lan (HSRC)</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Highway Safety Research Center
University of North Carolina
Campus Box 3430, Chapel Hill, NC 27599-3430</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
North Carolina Department of Transportation
Research and Analysis Group
104 Fayetteville Street
Raleigh, NC 27601</td><td colspan="2">13. Type of Report and Time Period
Final Report (Aug. 2021 to December 2023</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
FHWA/NC/2022-14</td></tr>
<tr><td colspan="4">Supplementary Notes:</td></tr>
<tr><td colspan="4">16. Abstract
This study conducted an empirical Bayes before-after evaluation of the conversion of at-grade intersections to diamond interchanges. 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 the 10 intersections were stop controlled before conversion. The study included reference sites in both Minnesota and North Carolina. The combined results from the two States including all 20 sites indicated that injury and fatal 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.</td></tr>
<tr><td colspan="2">17. Key Words
Crash modification factor, diamond interchange, at-grade intersection, empirical Bayes,</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classif. (this report)
Unclassified</td><td>20. Security Classif. (this page)
Unclassified</td><td>21. No. of Pages</td><td>22. Price</td></tr>
</table>

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

DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the views of the North Carolina Department of Transportation. The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation or University of North Carolina at Chapel Hill, at the time of publication. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

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

Conversion of an at-grade intersection into a diamond interchange is an expensive effort that could potentially cost well over $ 10 million. However, there is very little information that is currently available on the safety impacts of this conversion. This study conducted an empirical Bayes before-after evaluation using data from Minnesota and North Carolina. The evaluation included 10 intersections that were converted in Minnesota and 10 intersections that were converted in North Carolina. In Minnesota, 6 of the intersections were stop-controlled before conversion, and 4 of them were signalized. In North Carolina, all 10 intersections were stop-controlled before conversion. In Minnesota, after conversion two of the interchanges had signalized ramp terminals. For all the other interchanges in both the States, the interchanges had stop controlled ramp terminals.

The evaluation was conducted for total crashes, injury and fatal crashes, and PDO crashes. The reference group included 32 stop-controlled and 18 signalized intersections from Minnesota, and 50 stop-controlled intersections from North Carolina. Safety performance functions were estimated and the expected number of crashes in the after period (had the treatment not been implemented) was estimated based on the empirical Bayes method.

The combined results from the two States including all sites indicated that injury and fatal crashes decreased by about 30 percent (significant at the 5% significance level) and total crashes decreased by about 8 percent. PDO crashes increased by about 11 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 experience significant reductions in all crashes, but the sample size is probably not sufficient to provide a reliable finding.

TABLE OF CONTENTS

1. INTRODUCTION

Conversion of an at-grade intersection into a diamond interchange is an expensive effort that could potentially cost well over $ 10 million. However, there is very little information that is currently available on the safety impacts of this conversion. Crash Modification Factors (CMFs) are available for conversion of diamond interchanges to other interchange designs, e.g., Diverging Diamond Interchanges (DDIs) (e.g., see Hummer et al., 2016). Hence, by developing a CMF for converting from an at-grade intersection to a diamond interchange, it would be possible to estimate the safety effect of converting from an at-grade intersection to not only a diamond interchange, but also a DDI.

Regarding CMFs for converting from an at-grade intersection to a diamond interchange, in the crash modification factor (CMF) clearinghouse, Elvik et al., (2009) report CMFs based on meta-analysis that was conducted using results from Europe. The reliability and usefulness of this specific CMF for application in the United States (US) is unknown. Having a reliable CMF based on data from the United States would allow NCDOT’s Traffic Safety and Management Unit and Traffic Systems Operations Unit to compare the potential safety impact of converting traditional intersections to a diamond interchange versus other designs such as median U-turns, continuous flow intersections (CFIs), reduced conflict intersections, and DDIs.

2. OBJECTIVES

The objective of this effort was to develop CMFs for converting from an at-grade intersection to a diamond interchange to be used by NCDOT at a planning level. The goal was to estimate CMFs for total crashes and injury and fatal crashes. The intent was to estimate CMFs using a before-after study as they are considered a more reliable method for determining CMFs compared to cross-sectional methods.

3. LITERATURE REVIEW

The first part of this section provides summaries of studies that have tried to compare the safety of at-grade intersections with diamond interchanges. The second part provides an overview of the HSM predictive methods that have been developed for freeway segments and ramps and could be applied to determine the safety of diamond interchanges. The last part of the review provides a discussion of different methodological approaches for estimating CMFs.

At-Grade Intersections versus Interchanges

As discussed in the Introduction to this report, Elvik et al., (2009) developed CMFs based on a meta-analysis of results from seven studies in Europe (two studies from Norway, three from Finland, one from Sweden, and one from Germany). These studies were conducted between 1974 and 2002. The results are provided for conversion from at-grade intersections to grade-separated intersections (the type of grade separated intersection is not mentioned). All these studies developed the results based on a comparison of crash rates between different types of intersection categories. For injury and fatal crashes, the CMF is 0.76 for 3-leg intersections and 0.43 for 4-leg intersections.

In addition to these results, Elvik et al., (2009) also developed CMFs for conversion of other grade separated interchanges to diamond interchanges. These CMFs are based on a meta-analysis of 13 studies that were conducted between 1967 and 2004: ten of these studies were conducted in the USA, two in Finland, and one in Norway. All these studies involved comparison of crash rates between different types of interchanges. The CMFs reported for this group are for total crashes or truck crashes. The lowest CMF is 0.62 for total crashes for conversion from Trumpet to Diamond, and the highest CMF is 1.43 for truck crashes on ramps for conversion from “other except loop” to diamond.

There are many issues in trying to apply the results from Elvik et al., (2009). The most important issue is that both sets of CMFs are not directly applicable to the research question being addressed in this study: conversion of at-grade intersection to diamond interchange. In addition, the CMFs are based on a meta-analysis of studies that compared crash rates of alternative intersection/interchange designs. It is now well established that comparison of crash rates is not likely to provide reliable CMFs.

Prediction Models for Interchanges

NCHRP 17-45 developed safety prediction methods for freeways and interchanges (Bonneson et al., 2021). This effort developed separate predictive methods for freeway segments, freeway speed-change lanes, interchange ramps, and crossroad ramp terminals. To assess the safety of the interchange as whole, the predictions from these individual pieces of the interchange will have to be added along with the prediction for the crossroad (between the ramp terminals in the case of a diamond interchange). The prediction for the crossroad was not included in NCHRP 17-45 but could be estimated from prediction models that were developed earlier and included in Part C of the 1st edition of the HSM (AASHTO, 2010). The prediction methodology includes crash modification factors for specific design elements.

The prediction models from NCHRP 17-45 are most useful at the design level to determine the safety effect of changes in the design elements within a particular interchange. To use the results from NCHRP 17-45 at the planning level, e.g., to compare the safety of at-grade intersections with diamond interchanges, assumptions will need to be made regarding the specific design elements for both the at-grade intersection and the diamond interchange because these specific design elements may not be available at the planning stage.

Methods for Estimating Crash Modification Factors

As discussed in Carter et al., (2012), observational studies for estimating CMFs can be broadly classified into before-after studies and cross-sectional studies. In cross-sectional studies, the safety effect of a treatment is determined by comparing the safety of sites with and without the treatment. In before-after studies, the safety of sites after the implementation of a treatment is compared with the safety of sites before the implementation of the treatment. Hauer (2004) and Elvik (2011) indicate that before-after studies are less prone to confounding because we are dealing with the same roadway unit probably being used by the same users before and after the treatment. More recently, the use of propensity score matching methods have been proposed as one way to improve the reliability of results from cross-sectional studies (e.g., see Lan and Srinivasan, 2020).

The before-after analysis based on the empirical Bayes method is now accepted as a viable approach to deal with possible bias due to regression to the mean (RTM), trends during the study period, and the non-linear relationship between crashes and traffic volume. Over the last decade, researchers have also started using full Bayes methods as an alternative to empirical Bayes methods. Full bayes methods are more complex but are believed to require less data for the untreated reference sites, can better account for uncertainty in the data, and provide more flexibility in selecting the functional form of the model (Bhim et al., 2009). However, many studies have shown the results from empirical Bayes before-after to be generally like the results from full-Bayes studies (e.g., Bhim et al., 2009; Lan and Srinivasan, 2013; Park et al., 2016; Appiah, et al., 2018; D’Agostino et al., 2019; Tahir et al., 2023).

4. COMPILATION OF DATA

States were contacted to obtain information on when and where diamond interchanges were implemented (i.e., treatment sites). States were identified with help from the North Carolina Department of Transportation (NCDOT). In addition to identifying the locations where diamond interchanges were implemented, the project team also obtained some help in identifying reference sites, i.e., sites that were similar to the treatment sites before the treatment. After communicating with multiple States, the project team identified Minnesota and North Carolina as two States that provided useful data for the evaluation.

For both States, regarding the influence area for crashes, a 100-foot buffer area around the interchange area (including ramps) was used (see Figure 1). For at-grade intersections (the reference group as well as before period of the treatment group) a buffer of 100 feet from the Center of the intersection was used. This decision was made after consulting with NCDOT following the decision made by MNDOT as they prepared the data for the project team (the project team recognizes that an alternate approach could have been to use the same area of influence for the at-grade intersections and the diamond interchanges).

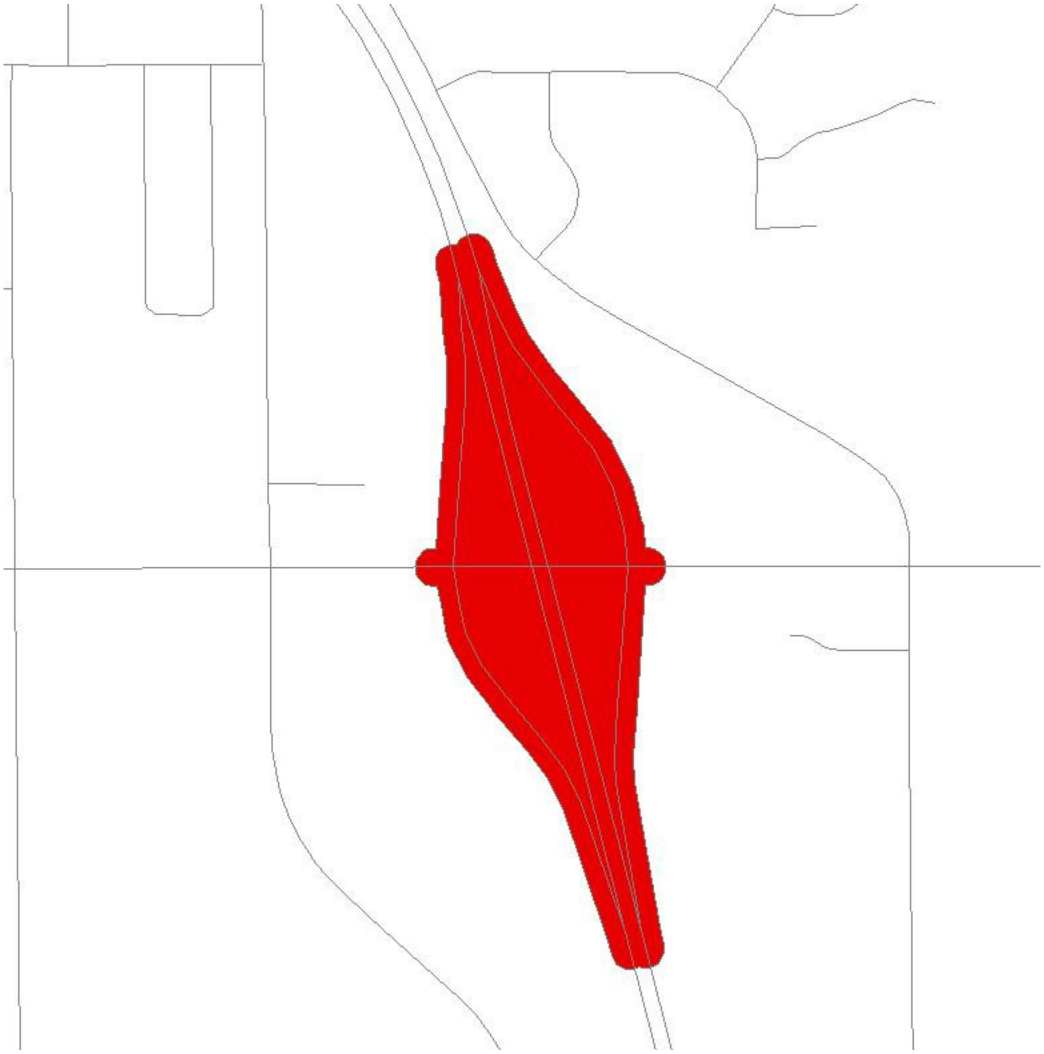

Figure 1 **Illustration of 100 foot buffer for crashes within diamond interchanges**

Data collection for Minnesota Data

The HSRC research team contacted personnel from the Minnesota Department of Transportation (MNDOT) to obtain the following information:

- Treatment site information with its latitude/longitude, and roadway names. Out of 10 treatment sites, 6 were stop-controlled, and 4 were signalized before the conversion.
- Treatment years when the at-grade intersections were converted to diamond interchanges,
- Traffic volumes (AADTs) for major and minor roads at the treatment sites in both before and after periods,
- Crash counts (including animal crashes) for all severities (KABCO) for the treatment sites in both before and after periods,

- Information on reference/comparison sites (at-grade intersections) with their latitude/longitude, and roadway names. Out of the 50 reference sites, 32 were stop-controlled, and 18 were signalized.
- Traffic volumes (AADTs) for major and minor roads at the treatment sites for the whole analysis period,
- Crash counts (including animal crashes) for all severities (KABCO) for the treatment sites for the whole analysis period.

Table 1 provides the list of treatment sites analyzed for MN.

Table 1. List of MN treatment sites (10 sites)

Interchange	City/Township	Construction Year(s)	Pre-Interchange Traffic Control	Post-Interchange Ramp Traffic Control	Number of Legs before Conversion	Mainline Number of Through Lanes before Conversion	Mainline if Divided
USTH 10 / CSAH 14, CSAH 15	Big Lake Township	2002	Stop	Stop	4	4	Yes
USTH 169 / 205TH AVE	Elk River	2003	Stop	Stop	4	4	Yes
USTH 169 / CSAH 9	Baldwin Township	2002	Stop	Stop	4	4	Yes
USTH 10 / MNTH 32	Eglon Township	2005	Stop	Stop	4	4	Yes
USTH 52 / 100TH ST	Oronoco Township	2006	Stop	Stop	4	4	Yes
USTH 63 / CSAH 20	Rochester	2003-2004	Stop	Stop	4	4	Yes
MNTH 36 / ENGLISH ST	Maplewood	2013	Signal	Stop	4	4	Yes
MN100 / 36TH AVE	Robbinsdale	2000	Signal	Signal	4	4	Yes
MN100 / FRANCE AVE, LAKE BREEZE AVE	Robbinsdale	2003	Signal	Stop	4	4	Yes
USTH 169 / PIONEER TR	Eden Prairie	2004	Signal	Signal	4	4	Yes

The HSRC research team then joined the aforementioned data to create the final dataset. MNDOT indicated that the crash data for 2003 was not reliable, so they were excluded from the analysis. Also, for the years AADT data was not available, a linear interpolation and extrapolation were carried out to estimate the missing AADT. Overall, 25 years of data (from 1997 through 2019 excluding 2003) were utilized for the reference sites. For the treatment sites, initially, the complete before and after periods were utilized. However, it was postulated that some sites with very long after periods could unduly influence the results. After some discussion with NCDOT, the before and after periods were limited to 3 years closest to conversion years.

Data collection for North Carolina Data

The HSRC research team obtained the information on treatment sites from NCDOT including the following:

- Location of the treatment sites including latitude/longitude, and roadway names,
- Latest dates the treatment sites were visible as at-grade intersections,
- Earliest dates the treatment sites were visible as diamond interchanges,
- Earliest dates the treatment sites were visible as diamond interchanges that were open to traffic.

Table 2 provides the list of treatment sites analyzed for NC.

Table 2. List of NC treatment sites (10 sites)

Interchange ID	Interchange Name	County	Construction Year(s)	Pre-Interchange Traffic Control	Post-Interchange Ramp Traffic Control	Number of Legs before Conversion	Mainline Number of Through Lanes before Conversion	Mainline if Divided
TSUINTC00527	US-421, SR-1100, SR-1176, CLEO DR, Exit 267	Yadkin	1998-2005	Stop	Stop	4	2	No
TSUINTC00806	US-17, US-17 BUS, SR-1328, SR-1329, PRJ-1103, Exit 230	Chowan	1993-2005	Stop	Stop	4	2	No
TSUINTC00809	US-17, US-17 BUS, SR-1204, SR-1288, Exit 224	Chowan	1993-2005	Stop	Stop	4	2	No
TSUINTC00821	US-64, SR-1225, Exit 478	Edgecombe	1994-1998	Stop	Stop	4	4	Yes
TSUINTC00825	US-64, NC-94, SR-1113, Exit 562	Tyrrell	1998-2005	Stop	Stop	4	2	No
TSUINTC00880	US-264, US-264 ALT, Exit 51	Wilson	1998-2005	Stop	Stop	4	4	Yes
TSUINTC00881	US-264, NC-111, SR-1571, SR-1572, Crady Ct, Exit 53	Wilson	1998-2005	Stop	Stop	4	4	Yes
TSUINTC00891	US-264, NC-91, SR-1311, Exit 59	Greene	1998-2005	Stop	Stop	4	4	Yes
TSUINTC00893	US-258, US-264, SR-1221, Exit 66	Pitt	1998-2005	Stop	Stop	4	4	Yes
TSUINTC00894	US-264, SR-1210, Ashland Dr, Exit 71	Pitt	1998-2005	Stop	Stop	4	4	Yes

Next, the research team utilized the intersection inventory shapefile prepared and maintained by NCDOT to identify the reference/comparison sites. The research team chose the reference sites closest to the treatment sites where the AADT data were available for majority of the years (at least in case of major road AADTs). All the treatment sites before the conversion were stop-controlled intersections, hence only stop-controlled at-grade intersections were chosen as reference sites. This led to some of the reference sites several miles away from the treatment sites falling into a different county than its respective treatment site.

Following this, the HSRC research team obtained the traffic volume (AADT) data for both treatment and reference sites from the NCDOT maintained traffic volume shapefile ("AADT_Stations_Shapefile_Description") for the whole analysis period. As in the case of Minnesota, wherever AADT was not available for a particular year for either the treatment or comparison sites, linear interpolation and extrapolation were carried out to estimate the missing data.

Then the research team requested for the statewide crash data from NCDOT in shapefile format for the whole analysis period. As the files were very big for the whole statewide crash data, the research team eventually provided the county names where the treatment and reference sites belonged to. This data included the individual crash occurrences (including animal crashes) for all severities (KABCO) for both the treatment and reference sites for the whole analysis period. The research team then aggregated the crash data to obtain crash counts for each site (both treatment and reference) and this was done on ArcGIS geospatial platform. Finally, the research team joined all the above data to create the final dataset. As in the case of Minnesota, the before and after periods were limited to 3 years closest to conversion years.

Summary Statistics

The following Tables provide summary statistics about the treatment and reference sites in MN and NC.

Table 3. Summary statistics for MN treatment sites (10 sites)

Variable	Minimum	Maximum	Mean
Years before	3	3	3
Years after	3	3	3
Total Crashes/site-year before	2	41	15.30
Total Crashes/site-year after	0	31	9.97
Fatal and Injury Crashes/site-year before (KABC)	1	17	5.37
Fatal and Injury Crashes/site-year after (KABC)	0	14	3.23
Property Damage Only Crashes/site-year before (PDO)	0	26	9.93
Property Damage Only Crashes/site-year after (PDO)	0	21	6.73
Major road AADT before	11,028	59,500	34,837
Major road AADT after	11,350	68,500	37,355
Minor road AADT before	910	18,301	4,220
Minor road AADT after	977	16,600	4,577

Table 4. Summary statistics for MN reference sites (50 sites)

Variable	Minimum	Maximum	Mean
Years	25	25	25
Total Crashes/site-year	0	78	8.37
Fatal and Injury Crashes/site-year (KABC)	0	21	2.63
Property Damage Only Crashes/site-year (PDO)	0	67	5.74
Major road AADT	1,089	65,700	25,833
Minor road AADT	36	34,817	4,496

Table 5. Summary statistics for NC treatment sites (10 sites)

Variable	Minimum	Maximum	Mean
Years before	3	3	3
Years after	3	3	3
Total Crashes/site-year before	0	11	2.90
Total Crashes/site-year after	0	20	6.23
Fatal and Injury Crashes/site-year before (KABC)	0	5	1.60
Fatal and Injury Crashes/site-year after (KABC)	0	6	1.07
Property Damage Only Crashes/site-year before (PDO)	0	7	1.30
Property Damage Only Crashes/site-year after (PDO)	0	18	5.17
Major road AADT before	4,100	12,600	8,472
Major road AADT after	5,000	22,000	14,307
Minor road AADT before	170	2,900	1,161
Minor road AADT after	800	2,700	1,734

Table 6. Summary statistics for NC reference sites (50 sites)

Variable	Minimum	Maximum	Mean
Years	27	27	25
Total Crashes/site-year	0	11	1.21
Fatal and Injury Crashes/site-year (KABC)	0	8	0.66
Property Damage Only Crashes/site-year (PDO)	0	5	0.56
Major road AADT	1,800	22,800	10,338
Minor road AADT	20	17,750	1,039

Table 7. Summary statistics for MN and NC combined treatment sites (20 sites)

Variable	Minimum	Maximum	Mean
Years before	3	3	3
Years after	3	3	3
Total Crashes/site-year before	0	41	9.10
Total Crashes/site-year after	0	31	8.10
Fatal and Injury Crashes/site-year before (KABC)	0	17	3.48
Fatal and Injury Crashes/site-year after (KABC)	0	14	2.15
Property Damage Only Crashes/site-year before (PDO)	0	26	5.62
Property Damage Only Crashes/site-year after (PDO)	0	21	5.95
Major road AADT before	4,100	59,500	21,654
Major road AADT after	5,000	68,500	25,831
Minor road AADT before	170	18,301	2,690
Minor road AADT after	800	16,600	3,156

Table 8. Summary statistics for MN and NC reference sites (100 sites)

Variable	Minimum	Maximum	Mean
Years	25	27	26
Total Crashes/site-year	0	78	4.65
Fatal and Injury Crashes/site-year (KABC)	0	21	1.60
Property Damage Only Crashes/site-year (PDO)	0	67	3.05
Major road AADT	1,089	65,700	17,788
Minor road AADT	20	34,817	2,701

5. ANALYSIS METHODOLOGY

As discussed earlier, the empirical Bayes before-after evaluation was used for this evaluation:

1. Identified a group of reference sites that were otherwise similar to the treatment sites, but without the treatment. As mentioned earlier, for Minnesota, staff from MNDOT identified the reference sites, but for North Carolina, the research identified the reference sites.
2. Using the crash data and the characteristics of the reference sites and before period of the treatment sites, estimated safety performance functions (SPFs) relating crash frequency with the site characteristics. The research team has used this approach in many recent studies partly to account for the differences in traffic volumes between reference and treatment sites. SPFs were estimated for MN and NC separately for total crashes, fatal and injury crashes, and PDO crashes. For Minnesota, major and minor AADT were used along traffic control (signalized or unsignalized) before treatment. For North Carolina, major and minor road AADT were used along with variables to represent the number of lanes in the major road (two-lane versus multilane) and if the major road was undivided or divided. The SPFs (documented in Appendix A) were estimated using negative binomial regression. In general, the intersections in Minnesota were higher volume compared to the intersections in North Carolina. As expected, the coefficients for the AADT terms in the SPFs were positive in both States. The coefficient for major road AADT was higher than the coefficient for minor road AADT in the Minnesota SPFs. However, it was the opposite for the North Carolina SPFs, and the coefficient for major road AADT was not statistically significant in the SPFs estimated for total crashes and injury and fatal crashes (Table 9 shows the AADT terms from the SPFs). The relatively weak relationship between major road AADT and crashes in North Carolina is surprising.
3. The SPFs were also used to estimate annual calibration factors (ACFs) for each year. The ACFs are defined as the ratio of the total observed crash frequency to the total predicted crash frequency from the SPF for each year. The ACFs are estimated to account for trends due to changes in crash reporting, weather, driver population, vehicle population, etc.
4. Used the SPFs, ACFs, and the characteristics of the each treatment site (including traffic volume) to estimate the predicted number of crashes in the before period for each treatment site. As discussed earlier, we limited the before and after periods to 3 years. The predicted number of crashes in the before period is denoted as P_b.
5. Used a weighted average of the observed crashes in the before period (A_b) and the predicted crashes from previous step, we estimated the EB expected crashes in the before period (EB_b). The weights are based on P_b and the overdispersion parameter that was estimated as part of the SPF development.

6. Used the SPFs, ACFs, and the characteristics of each treatment site to estimate the predicted number of crashes in the after period at each treatment site (P_a). The EB expected crashes in the after period (π) was estimates as follows:

$$\pi = EB_b\left(\frac{P_a}{P_b}\right)$$

The sum of π (π_{sum}) and the variance of this sum was used along with the sum of the actual reported number of crashes in the after period (λ_{sum}) to estimate the crash modification factors (and the standard error of the CMFs) associated with the treatment. The formula for the CMF and the standard error of the CMF is as follows (based on Hauer (1997)):

$$CMF = \frac{\frac{\lambda_{sum}}{\pi_{sum}}}{1+\frac{Var(\pi_{sum})}{\pi_{sum}^2}}$$

Standard error of CMF= $\sqrt{\frac{CMF^2\left(\frac{Var(\lambda_{sum})}{\lambda_{sum}^2}+\frac{Var(\pi_{sum})}{\pi_{sum}^2}\right)}{\left(1+\frac{Var(\pi_{sum})}{\pi_{sum}^2}\right)^2}}$

The estimated SPFs are documented in Appendix A.

Table 9. AADT Terms from the SPFs

Crash Severity	North Carolina	Minnesota
Total	$MajorAADT^{0.1530}$ $MinorAADT^{0.3550}$	$MajorAADT^{0.8474}$ $MinorAADT^{0.2889}$
Injury and Fatal	$MajorAADT^{0.0516}$ $MinorAADT^{0.4177}$	$MajorAADT^{0.7778}$ $MinorAADT^{0.2216}$
PDO	$MajorAADT^{0.2679}$ $MinorAADT^{0.2905}$	$MajorAADT^{0.8701}$ $MinorAADT^{0.3170}$

6. RESULTS AND CONCLUSIONS

Table 10 shows the crash modification factors (CMFs) for all sites that were included this evaluation (CMFs are provided based on the naïve before-after comparison as well). For the CMFs derived using the EB before-after method, the Table also shows the standard error of the CMF and if the CMFs are statistically different from 1.0 from the 5 percent or 10 percent significance level. Results are provided for total crashes, injury and fatal crashes, and PDO crashes, separately for North Carolina and Minnesota, as well as for North Carolina and Minnesota combined.

The results for North Caolina show that fatal and injury crashes reduce by 15 percent, although it is not statistically significant. Conversely, the PDO and total crashes increased dramatically after the conversion. On the other hand, for Minnesota, there is a 33 percent reduction in total crashes, and it is statistically significant at the 5% significance level. Additionally, fatal and injury, and PDO crashes also decreased by 33.5 percent and 29.3 percent, respectively, and these reductions are also statistically significant at the 5% significant level. When both states are combined, there is a reduction in total crashes by 8 percent that is not statistically significant. The expected reduction in injury and fatal crashes is about 29.5 percent that is significant at the 5 percent significance level. However, there is an increase in PDO crashes of about 11 percent that is not statistically significant.

Table 11 through Table 13 show the CMFs based on the traffic control before the conversion and the traffic control at the ramp terminals after conversion. As mentioned earlier, all the 10 sites in North Carolina were stop-controlled before conversion and had stop-controlled ramp terminals after conversion; 6 sites from Minnesota belonged to this category. The results from these 16 sites are shown in Table 11. In both States, PDO crashes increased significantly, and injury and fatal crashes decreased. Looking at the combined results from both States, injury and fatal crashes decreased by about 12 percent, PDO crashes increased by about 156 percent, and total crashes increased by about 60 percent.

Table 12 shows the CMFs when the sites were signalized before conversion and ramp terminals were stop-controlled after conversion. These CMFs are based on two locations in Minnesota. Table 13 shows the CMFs when the sites were signalized before conversion and the ramp terminals were signalized after conversion. These CMFs are again based on two locations in Minnesota. Both these groups show larger reductions (compared to sites that went from stop-controlled at-grade intersections to stop-controlled ramp terminals), especially for PDO and total crashes. However, both these groups have only two sites, and the sample size is probably not sufficient to provide a reliable CMF.

Table 10. Crash Modification Factors (all sites)

State	Crash Type	Actual Crashes in the Before Period	Actual Crashes in the After Period	Naïve CMF	Expected Crashes in the After Period Without the Conversion (based on EB procedure)	CMF (SE) (based on EB procedure)
NC (10 sites)	Total	87	187	2.149	77.24	2.397 (0.294)**
	Injury and Fatal	48	32	0.667	37.00	0.851 (0.183)
	PDO	39	155	3.974	30.16	5.055 (0.758)**
MN (10 sites)	Total	459	309	0.670	460.21	0.670 (0.049)**
	Injury and Fatal	157	98	0.624	146.70	0.665 (0.082)**
	PDO	302	211	0.699	297.73	0.707 (0.062)**
NC-MN Combined (20 sites)	Total	546	496	0.908	537.45	0.921 (0.056)
	Injury and Fatal	205	130	0.634	183.68	0.705 (0.076)**
	PDO	341	366	1.07	327.89	1.113 (0.082)

**Statistical different from 1.0 at the 0.05 level
*Statistically different from 1.0 at the 0.10 level

Table 11. Crash Modification Factors (stop control before conversion and stop-controlled ramp terminals after conversion)

State	Crash Type	Actual Crashes in the Before Period	Actual Crashes in the After Period	Naïve CMF	Expected Crashes in the After Period Without the Conversion (based on EB procedure)	CMF (SE) (based on EB procedure)
NC (10 sites)	Total	87	187	2.149	77.24	2.397 (0.294)**
	Injury and Fatal	48	32	0.667	37.00	0.851 (0.183)
	PDO	39	155	3.974	30.16	5.055 (0.758)**
MN (6 sites)	Total	143	130	0.909	119.47	1.082 (0.125)
	Injury and Fatal	51	29	0.569	40.31	0.711 (0.152)*
	PDO	92	101	1.098	69.29	1.445 (0.195)**
NC-MN Combined (16 sites)	Total	230	317	1.378	196.71	1.606 (0.133)**
	Injury and Fatal	99	61	0.616	77.31	0.783 (0.119)*
	PDO	131	256	1.954	99.45	2.559 (0.250)**

**Statistical different from 1.0 at the 0.05 level
*Statistically different from 1.0 at the 0.10 level

Table 12. Crash Modification Factors (signalized before conversion and stop-controlled ramp terminals after conversion) (2 sites from Minnesota)

Crash Type	Actual Crashes in the Before Period	Actual Crashes in the After Period	Naïve CMF	Expected Crashes in the After Period Without the Conversion (based on EB procedure)	CMF (SE) (based on EB procedure)
Total	138	59	0.428	162.62	0.360 (0.055)**
Injury and Fatal	47	25	0.532	50.57	0.486 (0.115)**
PDO	91	34	0.374	107.43	0.313 (0.062)**

**Statistical different from 1.0 at the 0.05 level
*Statistically different from 1.0 at the 0.10 level

Table 13. Crash Modification Factors (signalized before conversion and signalized ramp terminals after conversion) (2 sites from Minnesota)

Crash Type	Actual Crashes in the Before Period	Actual Crashes in the After Period	Naïve CMF	Expected Crashes in the After Period Without the Conversion (based on EB procedure)	CMF (SE) (based on EB procedure)
Total	178	120	0.674	178.13	0.670 (0.078)**
Injury and Fatal	59	44	0.746	55.80	0.777 (0.148)
PDO	119	76	0.639	121.01	0.623 (0.090)**

**Statistical different from 1.0 at the 0.05 level
*Statistically different from 1.0 at the 0.10 level

By taking the difference between the actual number of crashes in the after period and the expected crashes in the after period without the conversion, it is possible to determine the change in crashes due to the conversion. Based on Table 11 and using the combined values from Minnesota and North Carolina, the *reduction* in injury and fatal crashes is 77.31 – 61= 16.31. Similarly, the *increase* in PDO crashes is 256 – 99.45 = 156.55. These results along with information on crash costs by severity can be used to determine the net benefit (or cost) associated with conversion of at-grade stop-controlled intersections to diamond interchanges with stop-controlled ramp terminals.

Results for Individual Sites

With respect to results at the individual site level, for injury and fatal crashes, 14 sites (out of 20 sites) experienced a reduction following the conversion, and one site did not experience any change in the crash count. Out of the 5 sites that experienced an increase, 4 of them were from North Carolina. For PDO crashes, only 6 sites (out of 20 sites) experienced a reduction following the conversion. For total crashes, 10 sites experienced a reduction following the conversion. Information about individual sites is available in Table 20 in Appendix B.

It is encouraging that there is a significant reduction in injury and fatal crashes associated with the conversion from at-grade to a diamond interchange. It is possible that the increase in PDO crashes could be due to the difference in the influence area for at-grade intersections and diamond interchanges. The influence area was the same in both the States, but the CMFs for PDO crashes were much higher in North Carolina compared to Minnesota.

Future Research Needs

This study has raised many issues that could be addressed in future research. Here are some examples:

- What is the appropriate influence area for before-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.
- A larger sample of conversions could provide more insight into specific safety effects of traffic control at the ramp terminal as well as traffic control before the conversion. A larger sample (from other States) may also indicate if the increase in PDO crashes is unique to the sites in North Carolina that were part of this evaluation.
- It may be worthwhile to compare the CMFs from this type of a before-after study with the results from NCHRP Project 17-45 (Bonneson et al., 2021). This would require the different models (including the models for ramps) from NCHRP 17-45 to be calibrated using local data.

7. REFERENCES

Appiah, J., King, A.F., Fontaine, M., and Cottrell, B.H. (2018), *Transportation Research Record: Journal of the Transportation Research Board,* Vol 2672(21), pp. 20-29.

Bhim, R., Lyon, C., Lan, B., and Persaud, B. (2009), Comparison of Empirical Bayes and Full Bayes Approaches for Before-After Road Safety Evaluations, *Accident Analysis and Prevention*, Vol. 42(1), pp. 38-43.

Bonneson, J., Geediapally, S., Pratt, M.P., and Lord, D. (2021), *Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges*, NCHRP Web-Only Document 306, National Cooperative Highway Research Program, Washington, DC.

Carter, D., Srinivasan, R., Gross, F., and Council, F. (2012), *Recommended Protocols for Developing Crash Modification Factors*, NCHRP Project 20-07, Task 314, NCHRP.

D'Agostino, C., Cafiso, S., and Kiec, M. (2019), Comparison of Bayesian Techniques for the Before-After Evaluation of the Safety Effectiveness of Short 2+1 Road Sections, *Accident Analysis and Prevention*, Vol. 127, pp. 163-171.

Elvik, R., Hoye, A., Vaa, T., and Sorenson, M. (2009), *The Handbook of Road Safety Measures*, Emerald Publishing Limited.

Elvik, R. (2011), Assessing Causality in Multivariate Accident Models, *Accident Analysis and Prevention*, Vol. 43, pp. 253-264.

Hauer, E. (1997), *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*, Emerald Publishing Limited.

Hauer, E. (2004), Statistical Road Safety Modeling, *Transportation Research Record: Journal of the Transportation Research Board* 1897, National Academies, Washington, DC.

Lan, B. and Srinivasan, R. (2013), Safety Evaluation of Discontinuing Late Nighttime Flash Operations at Signalized Intersections, *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2398, pp. 1-8.

Lan, B. and Srinivasan, R. (2020), Comparison of Crash Modification Factors for Engineering Treatments Estimated by Before-After Empirical Bayes and Propensity Score Matching Methods, *Transportation Research Record: Journal of the Transportation Research Board*, Vol 2675(1).

Park, J., Abdel-Aty, M., and Lee, J. (2016), Evaluation of the Safety Effectiveness of Installing Roadside Barriers with Different Driver, Vehicle, Weather, and Time of Day Conditions, *Presented at the 95th Annual Meeting of the Transportation Research Board*, Washington, DC.

Tahir, H.B., Yasmin, S., Lord, D., and Haque, M. (2023), Examining the Performance of Engineering Treatment Evaluation Methodologies Using the Hypothetical Treatment and Actual Treatment Settings, *Accident Analysis and Prevention*, Vol. 188.

APPENDIX A. SAFETY PERFORMANCE FUNCTIONS

The safety performance functions were estimated with the following form:

$$Y = \exp\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots \ldots \ldots + \beta_n X_n\right)$$

Where X's are the independent variables shown in the first of the column of the Tables in this Appendix, and the βs are the coefficients. The estimate of the βs are shown in the second column of the Tables. The rest of the columns provide the standard error of the βs along with the z value and the p value that provide insight into the statistical significance of the coefficients.

Table 14. Safety Performance Functions for Total Crashes (North Carolina)

Variable	Estimate	Std. Error	z value	Pr(>|z|)
intercept	-4.1117	0.8323	-4.9400	<0.001
Ln_AADT_Maj	0.1530	0.1027	1.4900	0.1362
Ln_AADT_Min	0.3550	0.0404	8.7970	<0.001<
Two-lane	Baseline			
Multilane	0.4586	0.1629	2.8150	0.0049
Undivided	Baseline			
Divided	0.1819	0.1051	1.7310	0.0835
Year_1990	Baseline			
Year_1991	0.1020	0.2413	0.4230	0.6724
Year_1992	-0.0605	0.2469	-0.2450	0.8064
Year_1993	0.2943	0.2370	1.2420	0.2144
Year_1994	-0.0634	0.2493	-0.2540	0.7994
Year_1995	0.1469	0.2342	0.6270	0.5304
Year_1996	0.1881	0.2336	0.8050	0.4206
Year_1997	0.1551	0.2346	0.6610	0.5085
Year_1998	0.1212	0.2428	0.4990	0.6178
Year_1999	-0.0866	0.2488	-0.3480	0.7277
Year_2000	-0.0370	0.2470	-0.1500	0.8809
Year_2001	0.1498	0.2403	0.6240	0.5329
Year_2002	-0.1327	0.2482	-0.5350	0.5928
Year_2003	0.1366	0.2401	0.5690	0.5694
Year_2004	0.1039	0.2407	0.4320	0.6660
Year_2005	-0.1285	0.2484	-0.5170	0.6049
Year_2006	-0.2630	0.2536	-1.0370	0.2996
Year_2007	-0.0640	0.2465	-0.2590	0.7953
Year_2008	-0.3196	0.2558	-1.2490	0.2115
Year_2009	-0.0307	0.2456	-0.1250	0.9007
Year_2010	-0.2006	0.2518	-0.7970	0.4255
Year_2011	-0.2516	0.2532	-0.9940	0.3204
Year_2012	-0.1543	0.2503	-0.6160	0.5376
Year_2013	-0.0830	0.2472	-0.3360	0.7370
Year_2014	-0.1137	0.2490	-0.4570	0.6479
Year_2015	-0.2942	0.2561	-1.1490	0.2508
Year_2016	-0.0999	0.2494	-0.4000	0.6889
Inverse Overdispersion	1.706	0.1800		

Table 15. Safety Performance Functions for Injury and Fatal Crashes (North Carolina)

Variable	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	-4.3667	1.0157	-4.2990	<0.0001
Ln_AADT_Maj	0.0516	0.1244	0.4150	0.6784
Ln_AADT_Min	0.4177	0.0499	8.3770	<0.0001
Two-lane	Baseline			
Multilane	0.6626	0.2116	3.1310	0.0017
Undivided	Baseline			
Divided	0.2279	0.1311	1.7390	0.0821
Year_1990	Baseline			
Year_1991	-0.0020	0.2922	-0.0070	0.9946
Year_1992	-0.1860	0.3022	-0.6150	0.5383
Year_1993	0.2412	0.2829	0.8530	0.3939
Year_1994	-0.0920	0.2990	-0.3080	0.7585
Year_1995	0.1350	0.2784	0.4850	0.6278
Year_1996	0.3020	0.2731	1.1050	0.2690
Year_1997	0.1409	0.2792	0.5050	0.6139
Year_1998	0.1545	0.2873	0.5380	0.5907
Year_1999	0.0580	0.2900	0.2000	0.8414
Year_2000	-0.1510	0.3004	-0.5030	0.6151
Year_2001	-0.0709	0.2949	-0.2410	0.8099
Year_2002	-0.1046	0.2946	-0.3550	0.7226
Year_2003	0.1418	0.2845	0.4990	0.6181
Year_2004	0.1287	0.2846	0.4520	0.6512
Year_2005	-0.1302	0.2966	-0.4390	0.6607
Year_2006	-0.2681	0.3042	-0.8810	0.3782
Year_2007	-0.3269	0.3076	-1.0630	0.2878
Year_2008	-0.2926	0.3055	-0.9580	0.3382
Year_2009	-0.1038	0.2961	-0.3510	0.7259
Year_2010	-0.5824	0.3246	-1.7940	0.0727
Year_2011	-0.7213	0.3329	-2.1670	0.0302
Year_2012	-0.5158	0.3204	-1.6100	0.1074
Year_2013	-0.1989	0.3006	-0.6620	0.5081
Year_2014	-0.2515	0.3046	-0.8260	0.4090
Year_2015	-0.4866	0.3192	-1.5250	0.1273
Year_2016	-0.5780	0.3253	-1.7770	0.0756
Inverse Overdispersion	1.6927	0.2660		

Table 16. Safety Performance Functions for PDO Crashes (North Carolina)

Variable	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	-5.4305	1.0636	-5.1060	<0.0001
Ln_AADT_Maj	0.2679	0.1310	2.0460	0.0408
Ln_AADT_Min	0.2905	0.0505	5.7520	<0.0001
Two-lane	Baseline			
Multilane	0.3061	0.2059	1.4870	0.1371
Undivided	Baseline			
Divided	0.1020	0.1296	0.7870	0.4314
Year_1990	Baseline			
Year_1991	0.2633	0.3114	0.8450	0.3979
Year_1992	0.1147	0.3191	0.3590	0.7194
Year_1993	0.3999	0.3056	1.3080	0.1908
Year_1994	0.0271	0.3269	0.0830	0.9338
Year_1995	0.1912	0.3064	0.6240	0.5326
Year_1996	0.0436	0.3143	0.1390	0.8896
Year_1997	0.2004	0.3060	0.6550	0.5125
Year_1998	0.0377	0.3238	0.1160	0.9073
Year_1999	-0.2552	0.3418	-0.7470	0.4553
Year_2000	0.1469	0.3159	0.4650	0.6420
Year_2001	0.4203	0.3016	1.3940	0.1634
Year_2002	-0.1321	0.3292	-0.4010	0.6882
Year_2003	0.1538	0.3128	0.4920	0.6229
Year_2004	0.1072	0.3148	0.3400	0.7336
Year_2005	-0.1099	0.3271	-0.3360	0.7368
Year_2006	-0.2430	0.3361	-0.7230	0.4696
Year_2007	0.2292	0.3094	0.7410	0.4589
Year_2008	-0.3500	0.3448	-1.0150	0.3100
Year_2009	0.0580	0.3183	0.1820	0.8554
Year_2010	0.1964	0.3115	0.6300	0.5284
Year_2011	0.1717	0.3120	0.5500	0.5822
Year_2012	0.2300	0.3101	0.7420	0.4581
Year_2013	0.0733	0.3177	0.2310	0.8174
Year_2014	0.0747	0.3179	0.2350	0.8141
Year_2015	-0.0536	0.3251	-0.1650	0.8692
Year_2016	0.3342	0.3064	1.0910	0.2753
Inverse Overdispersion	2.2928	0.4910		

Table 17. Safety Performance Functions for Total Crashes (Minnesota)

Variable	Estimate	Std. Error	Z value	Pr(>|z|)
Intercept	-9.3163	0.5274	-17.6630	<0.0001
Ln_AADT_Maj	0.8474	0.0502	16.8830	<0.0001
Ln_AADT_Min	0.2889	0.0233	12.4100	<0.0001
Stop-controlled	Baseline			
Signalized	0.6622	0.0888	7.4570	<0.0001
Year_1997	Baseline			
Year_1998	-0.0184	0.1362	-0.1350	0.8928
Year_1999	0.0486	0.1338	0.3630	0.7164
Year_2000	-0.0489	0.1321	-0.3700	0.7113
Year_2001	0.0775	0.1298	0.5970	0.5507
Year_2002	0.0064	0.1310	0.0490	0.9609
Year_2004	-0.0809	0.1348	-0.6000	0.5483
Year_2005	-0.0497	0.1346	-0.3690	0.7119
Year_2006	-0.0703	0.1353	-0.5200	0.6033
Year_2007	-0.1035	0.1358	-0.7620	0.4459
Year_2008	-0.0742	0.1356	-0.5480	0.5840
Year_2009	-0.1767	0.1369	-1.2910	0.1968
Year_2010	-0.0175	0.1336	-0.1310	0.8956
Year_2011	-0.1990	0.1359	-1.4640	0.1433
Year_2012	-0.2411	0.1365	-1.7660	0.0774
Year_2013	-0.0648	0.1353	-0.4780	0.6323
Year_2014	0.1079	0.1329	0.8120	0.4169
Year_2015	-0.0280	0.1342	-0.2080	0.8349
Year_2016	-0.0604	0.1345	-0.4490	0.6534
Year_2017	0.0382	0.1331	0.2870	0.7743
Year_2018	-0.0595	0.1342	-0.4440	0.6573
Year_2019	0.0030	0.1333	0.0230	0.9818
Year_2020	0.0105	0.1347	0.0780	0.9377
Year_2021	0.1644	0.1329	1.2370	0.2162
Year_2022	0.2403	0.1329	1.8080	0.0706
Inverse Overdispersion	4.8507	0.3650		

Table 18. Safety Performance Functions for Injury Crashes (Minnesota)

Variable	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-8.9979	0.7201	-12.4950	<0.0001
Ln_AADT_Maj	0.7778	0.0682	11.4070	<0.0001
Ln_AADT_Min	0.2216	0.0301	7.3650	<0.0001
Stop-controlled	Baseline			
Signalized	0.6080	0.1207	5.0390	<0.0001
Year_1997	Baseline			
Year_1998	0.0271	0.1657	0.1640	0.8699
Year_1999	0.0449	0.1637	0.2740	0.7838
Year_2000	-0.1439	0.1643	-0.8760	0.3811
Year_2001	-0.0294	0.1607	-0.1830	0.8547
Year_2002	-0.0678	0.1618	-0.4190	0.6751
Year_2004	-0.1495	0.1671	-0.8950	0.3708
Year_2005	-0.1089	0.1664	-0.6550	0.5127
Year_2006	0.0104	0.1642	0.0630	0.9497
Year_2007	-0.2511	0.1704	-1.4740	0.1405
Year_2008	-0.0974	0.1669	-0.5840	0.5593
Year_2009	-0.0197	0.1651	-0.1190	0.9050
Year_2010	-0.0278	0.1636	-0.1700	0.8650
Year_2011	-0.2604	0.1690	-1.5410	0.1234
Year_2012	-0.2914	0.1699	-1.7150	0.0863
Year_2013	-0.0874	0.1666	-0.5250	0.5998
Year_2014	-0.1241	0.1670	-0.7430	0.4575
Year_2015	-0.2321	0.1690	-1.3740	0.1696
Year_2016	-0.2617	0.1697	-1.5420	0.1230
Year_2017	-0.0939	0.1654	-0.5680	0.5702
Year_2018	-0.2549	0.1690	-1.5080	0.1316
Year_2019	-0.4289	0.1734	-2.4730	0.0134
Year_2020	-0.4072	0.1766	-2.3060	0.0211
Year_2021	-0.1217	0.1690	-0.7200	0.4714
Year_2022	-0.1912	0.1729	-1.1060	0.2687
Inverse Overdispersion	5.0331	0.6050		

Table 19 Safety Performance Functions for PDO Crashes (Minnesota)

Variable	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-10.3025	0.6289	-16.3810	<0.0001
Ln_AADT_Maj	0.8701	0.0594	14.6450	<0.0001
Ln_AADT_Min	0.3170	0.0268	11.8200	<0.0001
Stop-controlled	Baseline			
Signalized	0.7117	0.1039	6.8530	<0.0001
Year_1997	Baseline			
Year_1998	-0.0171	0.1567	-0.1090	0.9130
Year_1999	0.0617	0.1538	0.4010	0.6882
Year_2000	0.0248	0.1510	0.1640	0.8695
Year_2001	0.1243	0.1487	0.8360	0.4030
Year_2002	0.0658	0.1498	0.4390	0.6607
Year_2004	-0.0641	0.1549	-0.4140	0.6790
Year_2005	0.0118	0.1540	0.0770	0.9389
Year_2006	-0.0876	0.1560	-0.5620	0.5744
Year_2007	-0.0285	0.1550	-0.1840	0.8542
Year_2008	-0.0583	0.1557	-0.3750	0.7080
Year_2009	-0.2633	0.1592	-1.6540	0.0982
Year_2010	-0.0385	0.1539	-0.2500	0.8026
Year_2011	-0.1615	0.1558	-1.0360	0.3000
Year_2012	-0.1604	0.1558	-1.0300	0.3032
Year_2013	-0.0564	0.1556	-0.3630	0.7170
Year_2014	0.1853	0.1516	1.2220	0.2216
Year_2015	0.0959	0.1525	0.6290	0.5292
Year_2016	0.0875	0.1524	0.5740	0.5661
Year_2017	0.1365	0.1516	0.9010	0.3677
Year_2018	0.0783	0.1522	0.5140	0.6073
Year_2019	0.2052	0.1504	1.3640	0.1725
Year_2020	0.2165	0.1520	1.4240	0.1544
Year_2021	0.3172	0.1508	2.1030	0.0355
Year_2022	0.4683	0.1500	3.1220	0.0018
Inverse Overdispersion	4.3517	0.3550		

APPENDIX B. RESULTS FOR INDIVIDUAL SITES

λ – Observed crashes in the after period; π – Expected crashes in the after period without the treatment
Var(π) – Variance of the expected crashes in the after period without the treatment

Table 20. Results for Individual Sites

Site_Name	Treatment Year	State	Total			PDO			Injury and Fatal		
			λ	π	Var(π)	λ	π	Var(π)	λ	π	Var(π)
USTH 10 / CSAH 14, CSAH 15	2002	MN	24	25.7	21.3	18	15.8	11.1	6	7.3	4.1
USTH 169 / 205TH AVE	2003	MN	25	26.4	18.9	18	13.8	8.6	7	10.6	5.9
USTH 169 / CSAH 9	2002	MN	15	18.7	12.6	14	11.0	6.2	1	6.2	2.9
USTH 10 / MNTH 32	2005	MN	6	6.6	3.2	6	3.1	1.2	0	3.1	1.0
USTH 52 / 100TH ST	2006	MN	31	25.4	16.2	21	16.5	8.7	10	6.0	2.8
USTH 63 / CSAH 20	2003-2004	MN	29	16.7	12.2	24	9.1	5.7	5	7.1	3.9
MNTH 36 / ENGLISH ST	2013	MN	9	65.7	74.7	8	46.0	55.2	1	18.9	14.9
MN100 / 36TH AVE	2000	MN	76	107.9	106.1	43	71.2	73.1	33	35.5	27.9
MN100 / FRANCE AVE, LAKE BREEZE AVE	2003	MN	50	96.9	104.5	26	61.4	61.5	24	31.6	30.3
USTH 169 / PIONEER TR	2004	MN	44	70.2	63.3	33	49.8	42.5	11	20.3	17.2
US-421, SR-1100, SR-1176, CLEO DR, Exit 267	1998-2005	NC	5	3.1	1.5	3	1.4	0.5	2	1.4	0.4
US-17, US-17 BUS, SR-1328, SR-1329, PRJ-1103, Exit 230	1993-2005	NC	7	1.9	1.0	5	1.2	0.4	2	0.9	0.3
US-17, US-17 BUS, SR-1204, SR-1288, Exit 224	1993-2005	NC	4	2.3	1.2	4	1.7	0.6	0	0.6	0.2
US-64, SR-1225, Exit 478	1994-1998	NC	9	15.9	15.1	8	2.6	1.6	1	10.9	8.1
US-64, NC-94, SR-1113, Exit 562	1998-2005	NC	4	2.5	1.7	4	1.2	0.4	0	1.3	0.7
US-264, US-264 ALT, Exit 51	1998-2005	NC	24	3.4	2.0	18	3.0	1.5	6	0.8	0.4
US-264, NC-111, SR-1571, SR-1572, Crady Ct, Exit 53	1998-2005	NC	33	14.5	9.7	30	6.0	2.9	3	6.0	3.1
US-264, NC-91, SR-1311, Exit 59	1998-2005	NC	21	10.4	7.4	17	2.6	1.2	4	6.0	3.1
US-258, US-264, SR-1221, Exit 66	1998-2005	NC	50	17.8	15.2	38	7.0	4.0	12	7.2	4.9
US-264, SR-1210, Ashland Dr, Exit 71	1998-2005	NC	30	5.3	5.0	28	3.4	2.2	2	1.9	1.4