GEORGIA DOT RESEARCH PROJECT 12 – 02

FINAL REPORT

SAFETY PERFORMANCE EVALUATION OF CONVERGING CHEVRON PAVEMENT MARKINGS

Georgia Department of Transportation

OFFICE OF MATERIALS & RESEARCH
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<tr><td colspan="4">16. Abstract:
The objectives of this study were (1) to perform a detailed safety analysis of converging chevron pavement markings, quantifying the potential safety benefits and developing an understanding of the incident types addressed by the treatment, and (2) to develop guidance for selecting additional implementation sites that have a high likelihood of significant improvements in safety performance. Some important conclusions from this study are the following:
• Analysis of the demographic variables showed no statistically significant observations that the effectiveness of the chevron treatment in reducing crashes was influenced by driver age, gender, proximity of driver registration, daytime/nighttime or pavement conditions.
• The chevron markings are effective at reducing crashes for the curved portions of ramps when evaluated using the before and after periods, regardless of the type of base conditions selected. Crash modification factors (CMFs) ranged from 0.453 to 0.689. The lower limit of the 95% confidence interval ranges from 0.281 to 0.428 while the upper limit ranges from 0.624 to 0.949. This indicates that even in the least effective scenario, the treatment still has the potential to reduce crashes by 5.1%.
• The chevron markings were effective for the approaches to the ramp (Ramp Section 1), the ramp segment where the treatment would generally be installed, when evaluated using the before and after periods. When evaluated using calendar year 2007 and 2009 data, no tangible benefits were observed. Fatal/injury-only crashes were not evaluated for this ramp segment due to small sample size.</td></tr>
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FINAL REPORT

SAFETY PERFORMANCE EVALUATION OF CONVERGING CHEVRON PAVEMENT MARKINGS

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Table of Contents

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List of Tables

Page

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List of Figures

Page

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Executive Summary

Measures to discourage drivers from exceeding the speed limit, especially in high-speed locations, have long been of interest to the traffic engineering community, and a variety of approaches have been adopted over the years. A somewhat nontraditional, but potentially effective, way to reduce excessive speeds is to somehow lower the drivers' perception of the traversable speed for a particular road to induce them to lower their speeds. One such approach, first proposed in Japan more than two decades ago, involves converging chevron pavement markings. These chevron markings have seen increasing interest in the United States in recent years and they have been used in a number of locations, including at two sites in Atlanta, Georgia, as a speeding control measure.

A 2010 Georgia Department of Transportation study entitled "Evaluation of the Effectiveness of Converging Chevron Pavement Markings" (GDOT RP 07-13, FHWA-GA-09-0713) evaluated the impact of chevron markings on reducing vehicle speeds on two-lane freeway-to-freeway directional ramps (I-75 SB to I-85 NB and I-285 EB to I-75 NB) as a safety treatment. Analysis of speed data collected in this project indicated that the presence of the treatment had only a modest impact on overall vehicle speeds; however, in 2011, a rudimentary crash analysis showed that the two treatment ramps had crash reductions of 76% and 87% in the 20 months after the treatment installation. Meanwhile, the control ramps had reductions of only 15% and 20% during the same period. Based on this initial analysis, this study (RP 12-02) was undertaken to

- perform a detailed safety analysis of converging chevron pavement markings, quantifying the potential safety benefits and developing an understanding of the incident types addressed by the treatment; and
- develop guidance for selecting additional implementation sites that have a high likelihood of significant improvement in safety performance.

In this study, researchers undertook a two-pronged approach. For analysis of the impact of demographic and similar data, only a single nearby control ramp was included to ensure that the fleets traversing the ramps were as similar as possible. Unfortunately, for development of *Safety Performance Functions* (SPFs) using the empirical Bayes approach, such a limited number of locations would not provide the range of vehicle activity and exposure necessary to effectively develop the necessary regression model. To balance these constraints, the evaluation region was expanded to the central counties of the metropolitan Atlanta area. In this way, the fleets were likely to remain quite similar but the analysis could incorporate a much wider range of similar freeway ramps. Using this approach, the team ultimately identified and obtained crash data for 43 freeway-to-freeway ramps in the Atlanta area for use in the SPF analysis.

Researchers analyzed the effectiveness of the treatment using three ramp scenarios and two baseline "before and after" time periods. The first period spanned the 12 months immediately preceding and following installation of the treatments in April 2008. The second time period for analysis was a comparison of calendar year 2007 (before) and 2009 (after) excluding all data from 2008. The principal results from these analyses may be summarized as follows:

- Analysis of the demographic variables showed no statistically significant observations that the effectiveness of the chevron treatment in reducing crashes was influenced by driver age, gender, proximity of driver registration, daytime/nighttime, or pavement conditions.
- The chevron markings are effective for the curved portions of ramps (Ramp Section 2) when evaluated using the before and after periods, regardless of the type of base conditions selected. *Crash Modification Factors* (CMFs) ranged from 0.453 to 0.689. The lower limit of the 95% confidence interval ranges from 0.281 to 0.428, while the upper limit ranges from 0.624 to 0.949. This range indicates that even in the least effective scenario, the treatment still has the potential to reduce crashes by 5.1%.
- When evaluated using calendar year 2007 versus 2009 data, the chevron markings' effectiveness on Ramp Section 2 is less pronounced. The estimated CMFs are still below 1.00 regardless of the type of base conditions used. The logic behind evaluating the treatment's effectiveness using calendar year 2007 and 2009 data only is that there appears to be an inherent difference between 2008 data and the data of the other years. It is also possible that the treatment had a more profound effect in 2008 immediately after installation, but its effect has decreased gradually, leading to similar crash frequencies in 2009 as there were in 2007.
- Analysis of fatal/injury crash frequency on Ramp Section 2 also showed improvements. The estimated CMFs range from 0.448 to 0.711 when evaluated using the before and after periods, and 0.659 to 0.791 when evaluated using the calendar year 2007 and 2009 data. However, the upper limit of the 95% confidence

intervals places nearly all of these CMFs over 1.00. The large range of variation in these results is due to the small sample size of such incidents.

- The chevron markings were effective for the approaches to the ramp (Ramp Section 1), the ramp segment where the treatment would generally be installed, when evaluated using the before and after periods. When evaluated using calendar year 2007 and 2009 data, no tangible benefits were observed. Fatal/injury-only crashes were not evaluated for this ramp segment due to small sample size.

The research team carefully assessed data from the Georgia crash databases to identify those data that could be considered reliable over the entire study period. Despite the uncertainties with the quality of data and the limited availability of treatment locations, the significant changes in crash frequency on both treatment locations indicate that additional research should be conducted.

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The authors of this report thank the Georgia Department of Transportation for its support and assistance throughout this project. In particular, Mr. David Adams and his staff provided important insights into the most effective methods of extracting data from the Georgia crash information databases.

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List of Abbreviations

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
ARC	Atlanta Regional Commission
CMF	Crash Modification Factor
EB	Eastbound
GDOT	Georgia Department of Transportation
GIS	Geographic Information Systems
mph	Miles Per Hour
NB	Northbound
PDO	Property Damage Only
SB	Southbound
SPF	Safety Performance Function
TRANS PI	GDOT Transportation Project Information
US	United States
WB	Westbound
WHO	World Health Organization

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1 Introduction

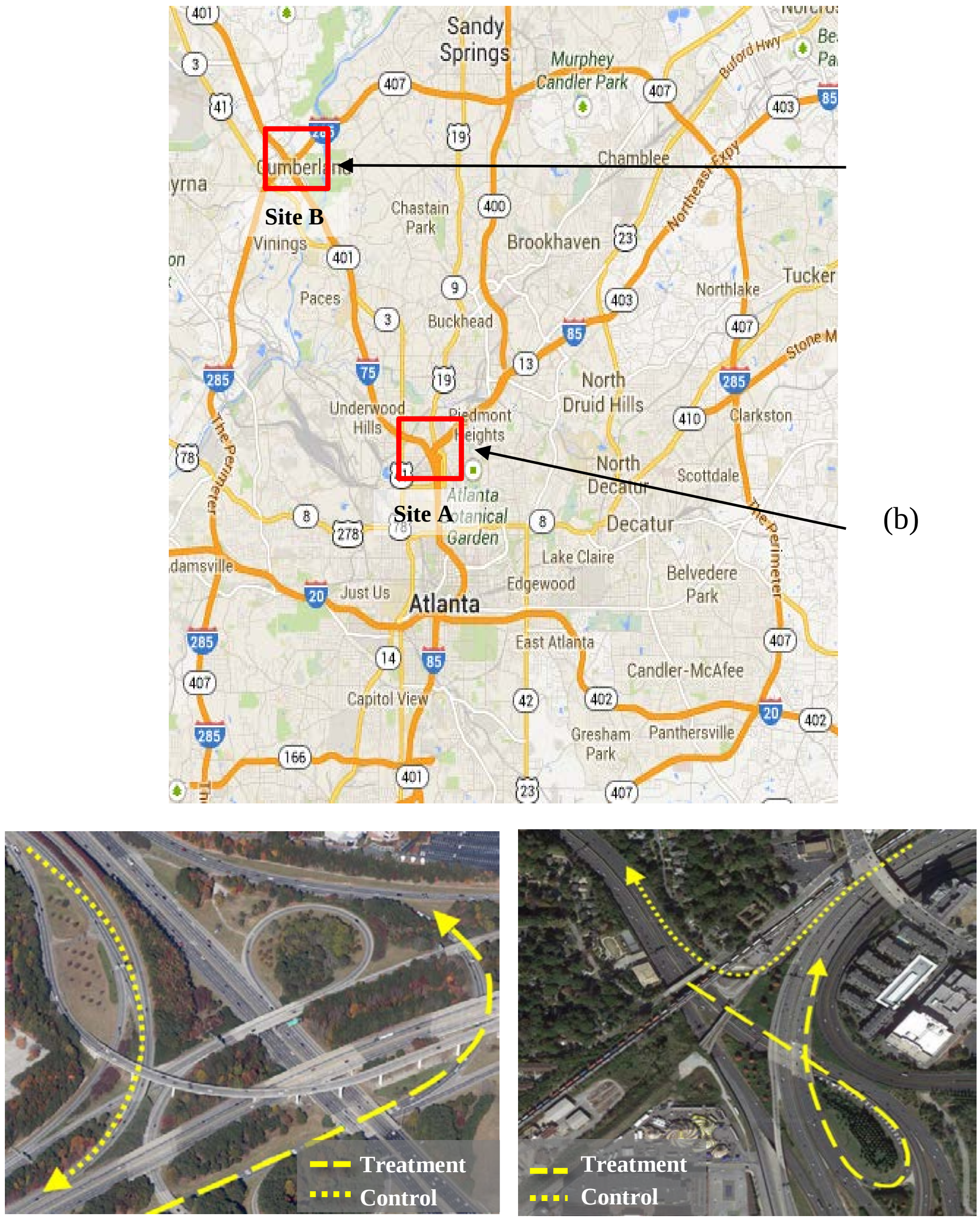
Measures to discourage drivers from exceeding the speed limit, especially in high-speed locations, have long been of interest to the traffic engineering community, and a variety of approaches have been adopted over the years. A somewhat non-traditional, but potentially effective, way to reduce excessive speeds is to somehow lower the drivers' perception of the traversable speed for a particular road to induce them to lower their speeds *(1)*. One such approach, first proposed in Japan more than two decades ago, involves converging chevron pavement markings. These chevron markings have seen increasing interest in the United States in recent years and they have been used in a number of locations, including at two sites in Atlanta, Georgia, as a speeding control measure.

A 2010 Georgia Department of Transportation (GDOT) study entitled ”Evaluation of the Effectiveness of Converging Chevron Pavement Markings” (GDOT RP 07-13, FHWA-GA-10-0713) *(2)* evaluated the impact of chevron markings on reducing vehicle speeds on two-lane freeway-to-freeway directional ramps as a safety treatment. In that study, speed data were collected at two treatment ramps before and after chevron marking installation, as well as at two control ramps without chevron markings. Figure 1 identifies the treatment and control ramp locations within the Atlanta metropolitan area. One pair of treatment and control ramps was located at the I-75/I-85 interchange in Fulton County (Site A), while the second pair was located at the I-75/I-285 interchange in Cobb County (Site B). The treatment ramp at Site A was the I-75 SB to I-85 NB ramp, while the control was the ramp between I-85 SB and I-75 NB. At Site B, the treatment ramp was located between I-285 EB and I-75 NB, while its control was the I-75 SB to I-285 WB ramp. These sites were selected by GDOT in consultation with the research team based on their ramp geometries that require a significant decrease in vehicle speeds for safe navigation.

The evaluation of vehicle speed impacts due to the presence of the converging chevron pavement markings was based on a statistical comparison of observed speeds before and after the installation of the chevron markings on the treatment ramps. Analysis of these speed data indicated that the presence of the treatment had only a modest impact on overall vehicle speeds. The effect of the treatment was most pronounced immediately following treatment implementation with the impact waning over the duration of the study. By the ninth month after installation, the average speed reduction upon entering the controlling ramp geometry was on the order of 0.5 to 2.0 mph, indicating that drivers adjusted back to their previous speeds as they acclimated to the treatment. This study noted that while the findings did not necessarily imply that the chevron markings are not an effective safety treatment, they did imply that any safety benefits would not arise from a general decrease in vehicle speeds.

In 2011, a rudimentary crash analysis was performed for these same chevron-marked ramps to determine if the markings merited reinstallation following a repaving of the ramps. The analysis showed that the two treatment ramps had crash reductions of 76% and 87% in the 20 months after the treatment installation. Meanwhile, the control ramps had reductions of only 15% and 20% during the same period. These crash reductions significantly exceeded any expected reductions or regression-to-the-mean bias, indicating that the chevron markings were likely making a contribution to enhancing the safety of these facilities. Based on this initial analysis, the chevrons were reinstalled and this study (RP 12-02) was undertaken to

- Perform a detailed safety analysis of converging chevron pavement markings, quantifying the potential safety benefits and developing an understanding of the incident types addressed by the treatment; and
- Develop guidance for selecting additional implementation sites that have a high likelihood of significant improvement in safety performance.



(b)

(a) (c)

Figure 1 Converging Chevron Treatment Locations: a) Location Sites in Atlanta, b) Site B, and c) Site A

In meeting these objectives, the research was organized around several specific tasks:

- A review of literature concerning the impacts of innovative marking and striping treatments on safety at various transportation facilities
- Detailed analyses of incidents at existing treatment and control ramps, including a representative safety analysis
- Detailed analysis of incident characteristics to understand expected safety benefits and incident contributing factors
- Development of chevron markings treatment application guidance

This final report summarizes the efforts involved in the above tasks, presents the results from the statistical analyses, and makes recommendations regarding future application of the chevron markings treatment. The report is structured to reflect the sequential findings from the major tasks above. Chapter 2 presents the comprehensive literature review. Chapter 3 discusses the methodology that was taken to complete the project. Chapter 4 discusses the findings of the incident characteristic analysis. Chapter 5 gives the findings of the safety effectiveness evaluation. Chapter 6 summarizes all of the major findings and also discusses their implications and makes recommendations for future actions.

2 Literature Review

This chapter initially presents general information regarding the relationship between human behavior and highway safety. Subsequently, these general concepts are discussed in light of existing literature regarding the application and effectiveness of various innovative pavement markings (including chevron markings) in improving safety at various transportation facilities. The chapter concludes with a short discussion of various measures of safety and their limitations.

2.1 Traffic Safety and Human Factors

In 2009, there were over 210 million licensed drivers in the US *(3)*. According to the National Highway Traffic Safety Administration *(4)*, in the same year there were over 5.5 million police-reported traffic crashes that resulted in 30,797 fatalities and 1.5 million injuries. To develop appropriate countermeasures to reduce these numbers, it is important to understand the mechanisms through which different types of crashes occur *(5)*. While previous efforts in improving vehicles and the roadway system have significantly helped to decrease these fatalities and injuries in recent years, not enough attention has been given to the study of vehicle operators and other system users. A distinct characteristic of the transportation system today is that there is a great deal of control over the design of vehicles and of the roadway system, but not enough control over the users *(6)*.

The study of human factors is concerned with the interaction of people and devices of various kinds. In the transportation systems engineering community, these devices of concern are motor vehicles and their operating environment. The aim of human factors research is to study human behaviors in the transportation system, focusing on their abilities and limitations. However, because human beings come in different shapes, sizes, attitudes, intellectual capabilities, physical health, and psychological health, addressing roadway safety issues as they relate to each individual driver has proven to be a challenge *(6)*.

2.2 Driver Perception and Information Processing

An important human factor relating to this research study is that of perception and information processing. An estimate that frequently appears in literature is that approximately 90 percent of essential driving-related information is acquired visually *(7)*. Vision is used to acquire basic information such as the geometry and alignment of the roadway, the position of the vehicle on the road, the location and movements of other roadway users, as well as the presence of potential hazards. Vision is also the targeted human sense when referring to most signals originating from vehicles (e.g., brake lights, turn signals, etc.) as well as the signs and signals placed on the roadside by traffic engineers to provide operational information.

To gain a more complete understanding of their environment, drivers not only use their vision but also their senses of hearing and touch. For example, a pothole can be processed visually if the driver is able to see it ahead. However, the driver is not able to fully understand the nature of the pothole without driving over it, feeling the impact it has on the vehicle, and hearing the sound that the vehicle makes as it goes over it. All these sensory inputs are subsequently processed in the brain in ways that help drivers understand the stimulus and gain more information about it, this is what is called driver perception. Perception is the end product of a complex process that begins with a physical stimulus *(7)*.

Since the sensory information that is available to drivers largely determines how they perceive the roadway environment, traffic engineers must change the sensory information available to drivers when danger is imminent in order to convey some type of warning to them. The following sections discuss how adjusting the sensory information available to drivers is being used to control vehicle speeds on roadways.

2.3 Passive Measures of Speed Control

A specific type of speed control measure that attempts to change the fundamental sensory information available to drivers to influence driving behavior is called a *passive* measure. By designing what sensory information is available, engineers can alter the driver perception of speed and use that to persuade the driver to slow down. This type of speed control has several advantages over traditional speeding countermeasures (e.g., speed bumps). Passive measures not only have the potential to reduce vehicle speeds without drivers being aware of their purpose, but their benefits are expected to be long term as they are less obtrusive measures that are less likely to frustrate drivers *(1)*.

Pavement markings are good examples of passive measures of speed control because they provide visual, vibratory, and auditory stimuli that can be used to control the sensory information available to drivers on the road. For example, centerlines and edge-lines can be placed on the roadway in such a way that it narrows the effective lane width visually though the physical lane width is not changed *(1)*. Similarly, transverse pavement markings can be placed on the roadway with decreasing spacing to alter driver perception. Drivers passing through these markings at a constant speed will not only see in their peripheral vision that the markings are passing by at an increasing rate, but they will also feel the vibrations caused by the markings as they run over them at an increasing rate. Both effects would suggest to the driver that he or she is driving at an increasing rate, which consequently should suggest to the driver that he or she needs to slow down *(8)*. The following sections discuss in further detail the different types of pavement markings used in the past as speed control measures.

2.4 Safety Performance of Chevron Pavement Markings

As discussed in Chapter 1, chevron pavement markings are being used in Atlanta, Georgia, in an effort to improve the safety of certain high-speed, freeway-to-freeway ramps. This treatment has also been used in other locations.

2.4.1 Osaka, Japan

A converging chevron pattern to create the illusion of both traveling faster and narrower lanes was first used on six roadway segments in Osaka, Japan, in the early 1990s *(9)*. Figure 2 presents a layout of the pavement patterns used in Osaka. Although direct results from these locations are not available, a number of authors have stated that before and after studies in Japan indicated effective reduction in crash frequencies when using chevron and comb pavement markings *(1)*. Others have noted that, although there was an overall reduction in crash frequency, there were a number of limitations regarding the evaluation of the treatment *(9)*. First, the number of crashes (i.e., the sample size) was very small in the first four locations especially in the after period. Additionally, although the last two locations had adequate sample sizes and showed consistency between the two before-and-after years, the overall reduction of crashes was not statistically significant at the time the studies were completed.

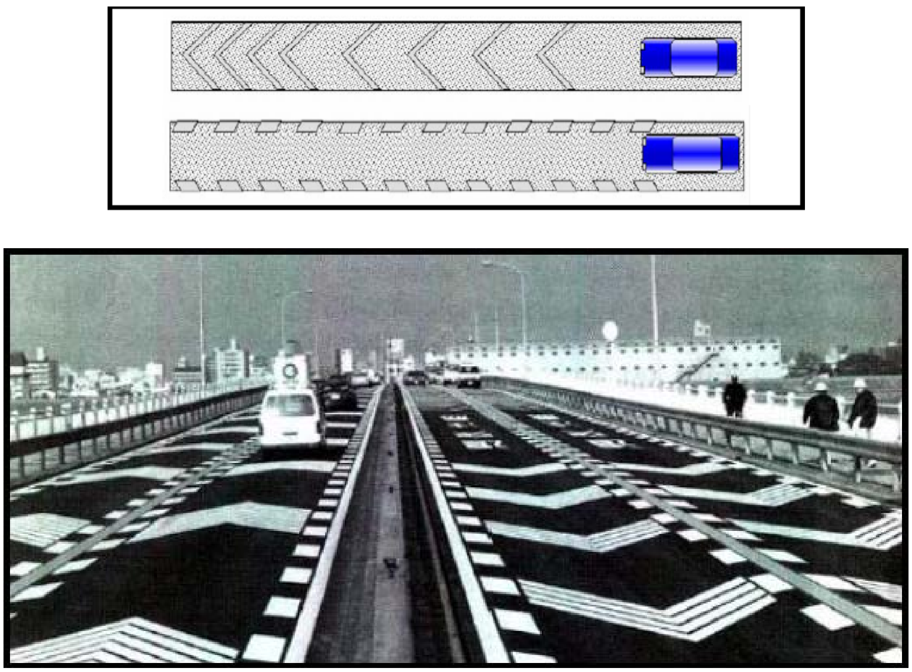


Figure 2 Chevron- and Comb-Pattern Markings – Conceptual Design (Top), Applied on the Yodogawa River Bridge, Japan (Bottom) ***(1)***

2.4.2 Milwaukee County, Wisconsin

Chevron markings were also installed at the Mitchell Interchange southbound to westbound ramp in Milwaukee County, Wisconsin. Two ramps were selected for comparison, a treatment ramp where the markings were installed and a control ramp without the treatment that had similar geometric and traffic characteristics. At the treatment ramp, detectors were placed 1960 feet upstream of the beginning of the chevron markings and also 40 feet downstream from the end of the chevron markings. At the control ramp, two detectors were placed side-by-side 200 feet downstream from the ramp point of curvature. Speed data were collected 4 months before and after the installation of the chevron markings *(9)*.

The study found that the chevron markings in the treatment ramp contributed to a statistically significant average speed reduction of approximately 12.5 mph between the before and after installation periods. The chevron markings were expected to affect speeds during the least congested parts of the day when higher levels of congestion did not influence speeds. However, speeds were found to be lower during each hour of the day, both during weekdays and weekends. In addition, both the treatment and control ramps had lower numbers of crashes in the after period despite higher traffic volumes, though this finding was not statistically significant *(9)*.

2.4.3 El Paso, Texas

Chevron markings were also installed and evaluated on the freeway-to-freeway connector of US-54 westbound to I-10 westbound in El Paso, Texas *(10)*. There were four data collection points: (1) at the midpoint of the curve, (2) at the start of the curve, (3) upstream of the curve, and (4) far upstream of the curve. Data were collected at three discrete periods: (1) before, (2) early-after (1–3 months after), and (3) late-after (4–6 months after). The duration of each data collection period was typically three to five days.

Comparison of mean speeds for all vehicle classes between the before and early-after periods indicated a slight decrease of speeds at the start and middle of the curve, with heavy trucks being the most affected by the chevron markings. The magnitude of the decrease, however, was about 0.14 to 0.45 mph. Although this magnitude is small, the effect of the chevron markings in decreasing the speeds was found to be statistically significant at a 95% confidence level.

Similarly, comparison of mean speeds for all vehicle classes between the before and late-after periods indicated a significant reduction in speeds at the upstream and start of the curve, with heavy trucks being the most affected. Moreover, the magnitude of reduction in mean speeds was much greater than the reduction in speeds between the before and early-after periods. This indicates that the effectiveness of the chevron markings did not degrade over time.

The study also found in the before and late-after comparison that mean speeds at the middle of the curve showed a significant increase for all vehicle classes. This observed increase could be due to motorists slowing more before the curve, but then judging the upcoming curve and accelerating through. In this situation, the chevron markings appear to serve as only an indication to the motorists that there was an upcoming hazard they needed to be attentive to, but not as something that they necessarily had to slow down for.

Over 60 percent of all vehicles in all study periods were also found to be driving at least 15 mph over the posted speed limit at the start of the curve: 72 percent in the before period, 69 percent in the early-after period, and 67 percent in the late-after period. An increase in the percentage of these vehicles was seen in the mid-section of the curve, indicating that vehicles may have become more familiar with the chevron markings by the late-after period. These findings once more suggest that the chevron markings are only serving as a warning to the motorists of the upcoming sharp curve *(10)*.

2.5 Safety Performance of Other Types of Pavement Markings

In addition to chevron pavement markings, considerable research has been conducted on the safety performance of various other pavement markings. In several instances, these efforts have demonstrated the potential of pavement markings as a treatment for crash reduction.

2.5.1 Transverse Bars

Godley et al. *(8)* investigated the psychological mechanisms of transverse bars responsible for speed reductions using a driving simulator. This research team recruited 24 experienced drivers for the study. The simulated driving scenario involved driving toward intersections with transverse pavement markings at both reducing and constant spacing. Three different scenarios of transverse bars were used in the simulation: (1) full-length transverse bars extending from the edge-line to the centerline, (2) peripheral transverse bars extending 0.6 meters from the edge-line toward the centerline, and (3) no transverse bars.

The study found that all types of transverse bars reduced travel speeds during the treatment areas only, or in the portion of the roadway that has the actual transverse bars. Full-length transverse bars reduced speeds more than peripheral transverse bars only in the beginning portion of the treatment area. Interestingly, however, no speed differences were found between the two transverse bar spacing schemes, suggesting that the illusion of traveling faster did not influence the vehicle speeds. These findings suggest that the transverse bars reduce speeds through alerting drivers when they initially reach the treatment area and also through the peripheral perception experienced throughout the treatment.

2.5.2 Longitudinal Markings

Retting et al. *(11)* performed a before-and-after study to evaluate the influence of longitudinal markings on traffic speeds at three urban freeway exit ramps in Virginia and one urban freeway exit ramp in New York. Traffic speeds were measured approximately 6 weeks before and 2 weeks after installation of the pavement markings. The longitudinal markings used in the experimental ramp in New York can be seen in Figure 3. The study found mixed results in terms of the treatments' effectiveness. Passenger vehicle and large truck speeds were reduced significantly at the New York ramp and at two of the three Virginia ramps. The proportion of passenger vehicles that exceeded the posted speed limit by more than 10 mph was also reduced in these three sites by at least 6 percent—the highest reduction of 17 percent was found in the New York ramp. Similarly, the proportion of large trucks that exceeded the posted speed limit by more than 5 mph was also reduced in these three sites by at least 17 percent. These findings, however, were not observed at the third ramp in Virginia.

Figure 3 Longitudinal Markings at Experimental Ramp in New York – Before (Left) and After (Right) ***(11)***

Lum *(12)* also studied the influence of longitudinal markings used to reduce the perceived lane width of roadways. In contrast to the later study by Retting et al. *(11)*, the study by Lum was performed in residential areas. Solid white edge-lines were added to the road and raised pavement markers were installed at the broken centerline to create the impression of a narrower street. The study showed that these longitudinal pavement markings combined with raised pavement markers had no discernable effect on either mean speeds or the speed distribution of vehicles. Although there have been mixed results as to the effectiveness of longitudinal markings on reducing vehicle speeds, these studies ultimately exemplify the visual-illusionary potential of pavement markings.

2.5.3 Transverse/In-Lane Rumble Strips

Harder et al. *(13, 14)* evaluated the effects of in-lane rumble strips on the stopping behavior of both attentive and sleep-deprived drivers. The results of these studies show that the presence of rumble strips has no effect on the point at which the driver begins to slow down (i.e., takes his/her foot off the gas pedal) or on the distance away from the intersection at which he or she actually stops. The presence of rumble strips only affects the point at which the drivers begin to apply their brakes. The results show that attentive drivers used their brakes earlier and more often in the slowdown process at intersections with rumble strips. Interestingly, no apparent effects of sleep deprivation were found to influence the braking patterns of the drivers.

Thompson et al. *(15)* also studied the effects of transverse rumble strips as a warning device for drivers approaching rural stop-controlled intersections. Overall, the study found that transverse rumble strips produced statistically significant reductions in approach speeds. However, these speed change reductions were only equal to or less than 1 mph, which suggests that the results should be interpreted with caution.

2.5.4 Centerline Rumble Strips

Rural two-lane roads generally lack physical measures to separate opposing traffic flows (e.g., wide medians or barriers). Consequently, a major issue on these roads involves vehicles crossing the centerline and either sideswiping or striking the front ends of opposing vehicles. A study by Persaud et al. *(16)* evaluated the potential of centerline rumble strips as a countermeasure for such crashes. The centerline rumble strips are placed to alert distracted, fatigued, or speeding motorists whose vehicles are about to the cross the centerlines and enter opposing traffic lanes. The results of the study indicated a 14 percent reduction for all types of injury crashes with a 95 percent confidence interval, specifically a 25 percent reduction for head-on and opposite-direction sideswipe injury crashes with the same confidence level.

2.6 Measures of Road Safety

The studies presented in previous sections used both speed and crash frequency as measures of safety. Of the two, the use of crash data is the more traditional approach *(17)*. However, the use of crash data has several limitations with respect to availability and accuracy as discussed in detail in Section 2.7. Consequently, the use of crash data could yield small sample sizes not only in the after period but also in the before period, leading to insignificant and inconclusive results (e.g., as in the first chevron markings study in Osaka *[9]*). Moreover, crash data generally lack the details needed by interpreters to understand the mechanisms of different accidents, especially those pertaining to the driver's accident avoidance behavior. Ultimately, the use of crash data safety analysis is a reactive approach, meaning that a significant number of crashes would need to occur before a study can be performed *(17)*. In light of this, surrogate measures of safety have been proposed and used in place of crash data because it potentially allows for a more proactive approach to safety assessment.

Speed is a widely used surrogate measure for road safety. The studies discussed in Sections 2.4 and 2.5 have all used speed as their measure of safety, and they assume that any changes in average vehicle speed equate to a change in road safety—an assumption that Tarko et al. *(17)* have argued against using. A prime example of this argument is evident in the previous GDOT study on the safety performance of chevron pavement markings *(2, 18)*. The analysis of the before-treatment and after-treatment speed data indicated that the chevron pavement markings had only a modest impact on the vehicle speeds. However, a preliminary crash analysis actually shows that the crash frequency in the two treatment ramps decreased by at least 60 percent. These results suggest that the chevron markings do have a safety benefit, but the effect was not captured by a surrogate measure (i.e., speed).

Various factors that affect safety can be divided into two categories as shown in Figure 4. One category consists of the factors whose influence can be captured with a surrogate measure of safety. For example, the influence of insufficient sight distance at an intersection can be measured using surrogate measures such as post-encroachment time and time to conflict *(19)*. The other category consists of the factors whose influence cannot be captured by a surrogate measure, such as driver expectancy, driver inattentiveness, or other human factors. For this category, crash data and police reports would be needed to perform a safety analysis, though such sources come with limitations of their own as discussed in Section 2.7.

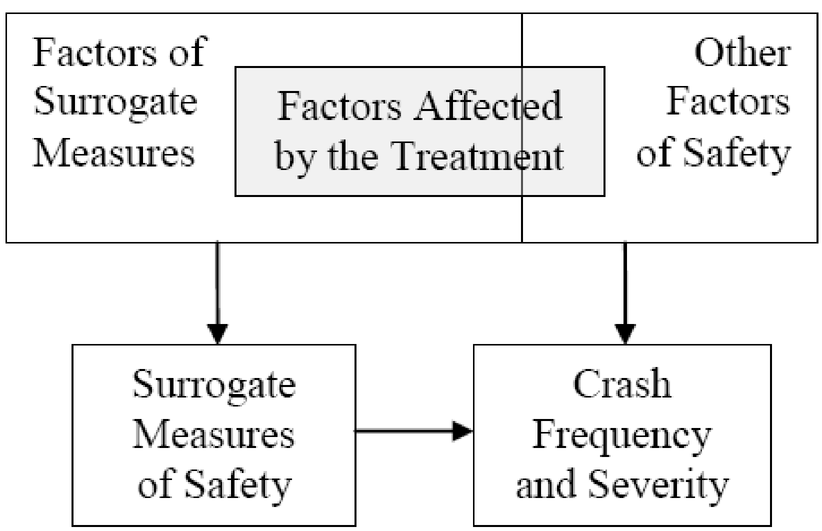


Figure 4 Relationship Between Surrogate Measures of Safety *(17)*

2.7 Limitations of Observed Crash Data Accuracy

A significant limit of much of the available crash data is the accuracy and consistency of these data due to issues associated with the recording, reporting, and measuring of crashes. These limitations can introduce bias and affect crash estimation reliability in ways that are difficult to assess. This section discusses these limitations in terms of these parameters:

- Data quality and accuracy
- Crash reporting thresholds and frequency-severity indeterminacy
- Differences in data collection methods and definitions used by jurisdictions

2.7.1 Data Quality and Accuracy

Crash data are typically collected on standardized hand-written or electronic forms by trained police personnel at the accident scene and, in some states, by integrating information provided by citizens self-reporting property damage only (PDO) crashes. This creates many opportunities for error at any stage of the data collection and interpretation process, including the following *(20)*:

- *Data entry* – typographic errors
- *Imprecise entry* – the use of general terms to describe a location
- *Incorrect entry* – entry errors related to road names, road surface, level of crash severity, vehicle types, impact description, etc.
- *Incorrect training* – lack of training in use of collision codes

- *Subjectivity* – likely inconsistency where data collection and/or interpretation rely on the subjective opinion of an individual

These potential errors create inconsistencies in the data that jeopardize the accuracy of the analysis.

2.7.2 Crash Reporting Tresholds and the Frequency-Severity Indeterminacy

In addition to concerns associated with data quality and accuracy, crashes are not always reported. A common reason for this is the use of minimum crash reporting thresholds. In most states, crashes must be reported to the police when damage is above a minimum dollar value threshold. One issue with this is that this threshold varies between states, making direct comparisons difficult or impossible. Moreover, changes in these thresholds over time may result in changes in *reported* crash frequency that is not representative of a change in long-term *actual* average crash frequency. This may create a condition where comparisons between various time periods can be seriously compromised. It is important to be aware of crash reporting thresholds and to ensure that a change to these thresholds did not occur during the period of study under consideration *(20)*.

Studies have also indicated that crashes with greater severity are reported more reliably than crashes of lower severity *(20)*. This situation creates an issue called frequency–severity indeterminacy, which represents the difficulty in determining if a change in the number of reported crashes is caused by an actual change in crashes, a shift in severity proportions, or a mixture of the two.

2.7.3 Differences in Data Collection Methods and Definitions

Another potential cause of inconsistency and inaccuracy in safety analysis is the use of different definitions and terms relating to crash data, as well as traffic volume and geometric data. For example, in terms of traffic volume, most jurisdictions use annual average daily traffic (AADT) as an indicator of yearly traffic volume while others use average daily traffic (ADT) *(20)*. Similarly, in terms of crash data, a fatal injury can be defined by some agencies as “any injury that results in death with a specified period after the road vehicle crash in which the injury occurred.” Typically, this specified period is 30 days. In contrast, World Health Organization (WHO) procedures use a 12-month limit *(21)*. These variations in the definitions and classifications of crash attributes can also lead to difficulties when comparing data between jurisdictions.

Thus, the count of reported crashes in a database is partial, may contain inaccurate or incomplete information, may not be uniform for all collision types and crash severities, may vary over time, and may differ from jurisdiction to jurisdiction.

2.8 Limitations Due to Randomness and Change

Other than limitations due to issues in the different stages of data recording, reporting, and measuring, there is another area of limitation that is associated with natural variations in the crash data and changes in site conditions. These are limitations due to inherent characteristics of data itself, not limitations due to the method by which the data are collected or reported. Because crashes are random events, crash frequencies naturally fluctuate over time at any given site. Additional factors such as traffic volume, weather, traffic control, land use, and geometric design are also subject to change and could affect crash frequency trends.

Fluctuations over time make it difficult to determine whether changes in the observed crash frequency are due to changes in site conditions or random variations. For example, when a period with a comparatively high crash frequency is observed, it is statistically probable that the following period will be followed by a comparatively low crash frequency and vice versa *(22)* even if the underlying average rate has not changed. This tendency is known as regression to the mean (RTM). Failure to account for RTM will result in a bias in the results of a safety analysis. For example, in evaluating the effectiveness of a safety treatment, it is observed that there is a large reduction in crashes, which leads to the perception that the treatment is greatly effective in improving the safety of the facility. However, due to RTM bias, a reduction in crash frequency might have been expected to occur in the absence of any safety treatment. Thus, not accounting for RTM bias could lead to the perception that the treatment has a greater effect than its actual effectiveness.

2.9 Conclusions

This chapter has discussed the great potential of passive measures of speed control in improving roadway safety. In particular, pavement markings that alter the driver's perception of the appropriate traversable speed of facility were investigated. These markings include transverse bars, longitudinal markings, in-lane and centerline rumble strips, as well as chevron markings. Based on analysis of speed data, the effectiveness of these safety treatments has been inconsistent—a similar result to this project's. However, as Tarko et al. *(17)* argued, changes in vehicle speed should not be directly translated into changes in safety. To address these issues, researchers in this study performed a detailed analysis of crash data to examine the mechanism of individual crashes to more appropriately evaluate the potential effectiveness of the converging chevron treatment. This methodology is discussed in the next chapter.

3 Methodology

This study was organized around a series of sequential tasks:

- *Task 1* – Selection of facilities with similar geometric and operational characteristics to the treatment ramps to form a control group.
- *Task 2* – Acquisition of crash, traffic volume, and road characteristic data for each facility in the Treatment and control groups for use in the before–after safety evaluation.
- *Task 3* – Performance of quality assurance on the acquired crash data through review of detailed police reports.
- *Task 4* –Analysis of crash attributes to establish patterns that reveal potential mechanisms by which the chevron markings treatment influences roadway safety.
- *Task 5* – Evaluation of the effectiveness of the chevron markings treatment as a safety treatment using an empirical Bayes before–after evaluation method, taking into account general background trends and regression-to-the-mean bias.

The details of each of these tasks are discussed in this chapter.

3.1 Task 1 – Selection of Treatment and Control Groups

3.1.1 Treatment Group

As discussed briefly in Chapter 1, the treatment group was composed of the two ramps where the chevron markings were installed: (1) the I-75 SB to I-85 NB ramp in Fulton County, and (2) the I-285 EB to I-75 NB ramp in Cobb County. The driving factor influencing GDOT's selection of these ramps for treatment was their ramp geometries that require a significant decrease in vehicle speeds in order to safely traverse.

In the previous project that examined these ramps *(2, 18)*, average vehicle speeds were recorded both upstream and immediately before the controlling curvature of the ramps. On the I-75 SB to I-85 NB ramp, the average speeds at these two locations were recorded to be 51 mph and 31 mph, respectively, for an average speed reduction of 20 mph. Similarly, on the I-285 EB to I-75 NB ramp, these average speeds were 60 mph and 45 mph for an average speed reduction of 15 mph. These speed reductions are consistent with the geometric characteristics of the ramp that requires vehicles to significantly decrease their speeds to traverse the horizontal and vertical curves of the ramp. Figure 5 shows elevated views of the two treatment ramps.

Figure 5 Treatment Ramps – I-75 SB to I-85 NB (Left) and I-285 EB to I-75 NB (Right)

3.1.2 Control Group

To conduct the before–after evaluation, the research team selected other facilities with similar characteristics to the treatment ramps to form a control group. In this selection process the researchers used the following general criteria:

- Sites at which the chevron markings have not been installed

- High speed, freeway-to-freeway ramps with no intersection control nearby that could influence traffic flow such as traffic signals, yield/stop signs, and ramp meters
- Geometry similar to the treatment ramps (i.e., low radius)
- Traffic composition and usage patterns similar to the treatment ramps
- Sites that have not had other major changes during the evaluation study period, such as reconstruction, repaving, restriping, etc.

Based on the criteria above, control ramps were selected at the following interchanges:

- I-75/I-85 in Fulton County (excludes the treatment ramp)
- I-75/I-285 in Cobb County (excludes the treatment ramp)
- SR-400/I-285 in Fulton County (all ramps)
- I-20/I-285 in Fulton County (all ramps)
- I-85/I-285 in DeKalb County (all ramps)
- I-20/I-285 in DeKalb County (all ramps)

These ramps are sites where chevron markings have not been installed and they are also all high-speed, freeway-to-freeway ramps with no intersection control nearby that could influence traffic flow. Additionally, these ramps have a geometry that requires vehicles to slow down, although perhaps not as much as 20 mph, in order to traverse them. They are all located in Metro Atlanta and, thus, traffic compositions and usage patterns are similar. The researchers used the GDOT Transportation Project Information (TRANS PI) search to verify that no major changes had been performed on these sites during the evaluation period.

After the selection process was complete, there were 43 ramps included in this study: 2 treatment ramps and 41 control ramps. Figure 6 shows the location of the interchanges in Metro Atlanta where one or more study ramps were located. A more detailed list of the treatment and control ramps is included in Appendix A.

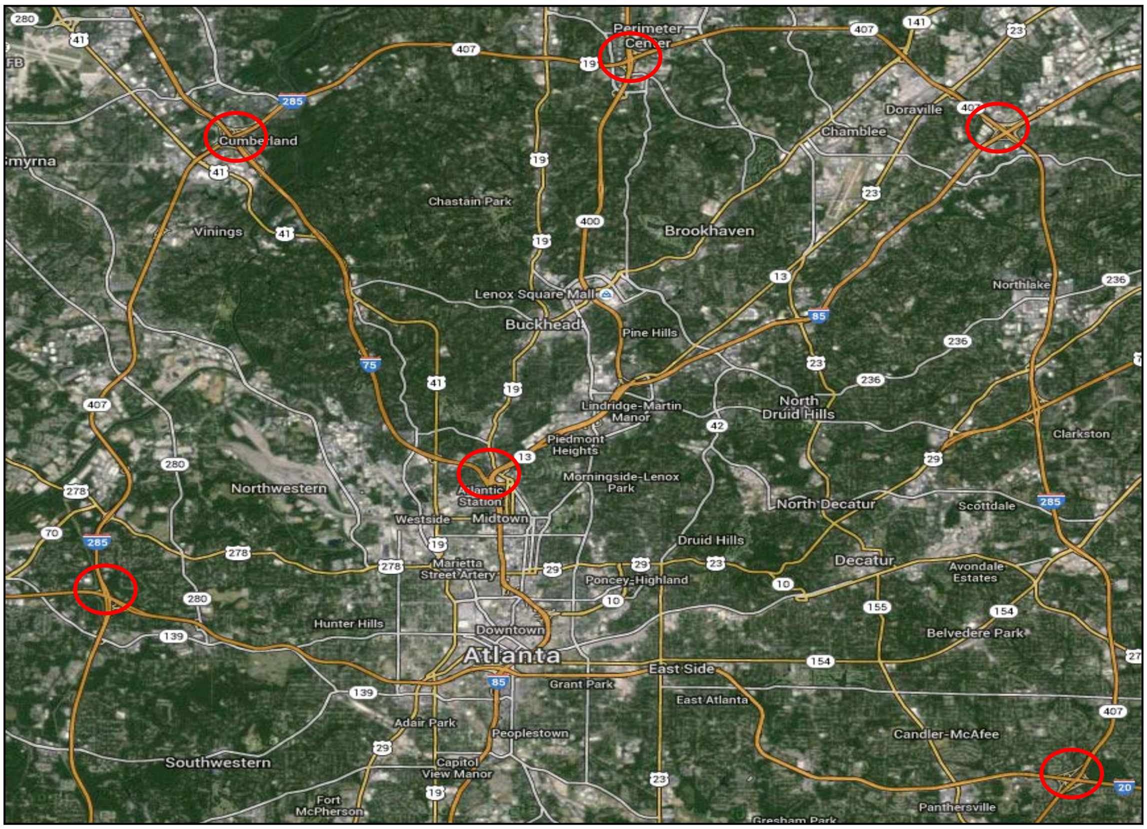


Figure 6 Locations of Treatment and Control Sites in Metro Atlanta

3.2 Task 2 – Acquisition of Data

3.2.1 Crash Data

The primary source of crash data used in this study was the Georgia crash information database maintained by the Georgia Department of Transportation. Data were available from this database dating back to the year 2000. This crash information database is constructed using information obtained from the original police incident reports collected in the field. It contains a wide range of information for each crash environment (e.g., date, time, crash type, weather, surface condition, etc.); the drivers and vehicles involved (e.g., age, gender, vehicle type, driver's county of residence, etc.); as well as the location of these crashes (e.g., street names, route numbers, milepost numbers, interchange exit numbers, etc.). To verify these data, as well as to obtain additional information (e.g., the incident description provided by the investigating officer), researchers obtained facsimile copies of the original police reports for project use.

To extract the crash data for the specific treatment and control sites, a search method was developed based on the *Road of Occurrence* and *Intersecting Road of Occurrence* of the incident. There are generally four variables in the crash database that hold these two pieces of information:

1. Road of occurrence (street name and/or route number)
2. Intersecting road of occurrence (street name and/or route number)
3. Nearest road if not at intersection (street name and/or route number)
4. Next reference point (street name and/or route number)

These four variables are the same variables recorded on the first page of the police incident report. Unfortunately, from year to year there are some inconsistencies in what these four variables represent. Instead of representing four different pieces of information, these four variables for some of the more recent years appear to represent only two different pieces of information as below:

1. Road of occurrence (street name)
2. Road of occurrence (route number)

3. Intersecting road of occurrence (street name)
4. Intersecting road of occurrence (route number)

This inconsistency was documented and the team proceeded to develop and refine a search method to take these inconsistencies into account. Each of these variables is stored in the database in plain text format and, as discussed above, could contain a street name and/or a route number. To identify crashes occurring at a specific site, users perform a search using the four variables based on the desired street names and/or route numbers for the selected site. However, a limitation of this "Route Number–Road Name Method" is that it is difficult to determine all the possible variations of street names due to misspellings and other human error. For this study, only route numbers are used in the search since the treatment and control sites are located at interchanges and thus street names do not exist for them, making this issue less relevant.

As an example, consider the process of obtaining crash data for the I-75/I-85 interchange in Fulton County from the database. First, all the possible street names and/or route numbers for I-75 and I-85 need to be compiled. In this case, the only other possible names and/or route numbers for these facilities are State Route 401 for I-75 and State Route 403 for I-85. A search based on these route numbers is conducted on the four variables discussed previously in the manner shown in Table 1. In combinations 1–3, the *Road of Occurrence* variable is kept as I-75 and the different combinations of this variable with the other three variables are explored as well. The same method is used in combinations 4–6 while keeping the *Road of Occurrence* variable as I-85.

Table 1 Route Number–Road Name Search Method Pattern 1

	Combination 1	Combination 2	Combination 3	Combination 4	Combination 5	Combination 6
Road of occurrence	I-75 / SR-401	I-75 / SR-401	I-75 / SR-401	I-85 / SR-403	I-85 / SR-403	I-85 / SR-403
Intersecting road of occurrence	I-85 / SR-403	—	—	I-75 / SR-401	—	—
Nearest road if not at intersection	—	I-85 / SR-403	—	—	I-75 / SR-401	—
Next reference point	—	—	I-85 / SR-403	—	—	I-75 / SR-401

A secondary search was also used for those records where inconsistencies in the representation of the four variables existed. This structure of this secondary search is shown in Table 2. In combinations 1–4, the *Road of Occurrence* variable is kept as I-75. However, since two variables contain information about the road of occurrence (i.e., one contains street name data while the other contains route number data), Table 2 shows that both variables are used in the search process. This is similarly done for the *Intersecting Road of Occurrence* variable. Combinations 5–8 show the same process when I-85 is kept as the *Road of Occurrence* variable.

Table 2 Route Number–Road Name Search Method Pattern 2

	Comb. 1	Comb. 2	Comb. 3	Comb. 4	Comb. 5	Comb. 6	Comb. 7	Comb. 8
Road of occurrence (street name)	I-75 / SR-401	—	I-75 / SR-401	—	I-85 / SR-403	—	I-85 / SR-403	—
Road of occurrence (route no.)	—	I-75 / SR-401	—	I-75 / SR-401	—	I-85 / SR-403	—	I-85 / SR-403
Intersecting road of occurrence (street name)	I-85 / SR-403	I-85 / SR-403	—	—	I-75 / SR-401	I-75 / SR-401	—	—
Intersecting road of occurrence (route no.)	—	—	I-85 / SR-403	I-85 / SR-403	—	—	I-75 / SR-401	I-75 / SR-401

The combined results of these searches are the raw dataset of crashes for the interchange of I-75 and I-85 in Fulton County. To determine the location of these crashes with more accuracy and to ensure that all the crashes in this raw dataset actually belong to this site, a data quality control process using the original police reports was conducted as discussed in Section 3.3.

3.2.2 Traffic Volume Data

Traffic volumes are needed for each of the study ramps to assess overall exposure for each site. There are several sources of traffic volumes used in this study: (1) GDOT traffic counts, (2) estimates from the GDOT Road Characteristics database, and (3) traffic volume estimates from Atlanta Regional Commission’s (ARC) travel demand model. Wherever possible, the actual GDOT traffic count data were used. However, if these data were unavailable or highly inconsistent across the years, the other two sources were used as guidance to reconcile the GDOT traffic count data.

3.2.3 Road Characteristic Data

Certain road characteristic data are required in both the safety analysis and for developing *Safety Performance Functions* (SPFs) for the treatment. The specific road characteristics that are needed for these ramps are: (1) number of lanes; (2) radii of curvature; and (3) existence of merges, diverges, or lane drops anywhere on the ramp. These data were obtained using images obtained from Google Maps® and/or Google Earth Pro®. From these images, the number of lanes was easily determined. The ramp radii of curvature were determined approximately through the use of Google Earth Pro using inscribed circles to estimate curve radii. Note that these data were only used to differentiate between "low-radius" and "high-radius" curves and, thus, this approximation method was sufficient for this determination. The existence of merging and diverging sections as well as lane additions and lane drops was also determined visually using the aforementioned tools.

These data were incorporated into a variable called *Ramp Condition,* which was defined as follows:

- 0 – No merges/diverges exist on current ramp segment
- 1 – Lane drop exists on current ramp segment
- 2 – Lane addition exists on current ramp segment
- 3 – Another ramp merges into current ramp segment with a lane drop
- 4 – Another ramp merges into current ramp segment without a lane drop
- 5 – A ramp diverges from current ramp segment

This *Ramp Condition* attribute was used later in conjunction with road characteristics and traffic volumes to divide each ramp into homogeneous segments for development of SPFs in the before–after safety evaluation.

In the GDOT crash database, an additional attribute called *Ramp Section* divides a ramp into the following four segments:

- 0 – Indicates that the crash is located on the mainline before or after the ramp
- 1 – Indicates that the crash is located at the intersection between the mainline and the ramp
- 2 – Indicates that the crash is located on the ramp segment
- 3 – Indicates that the crash is located at the intersection between the ramp and another facility

Figure 7 illustrates the ramp section and its corresponding identifiers.

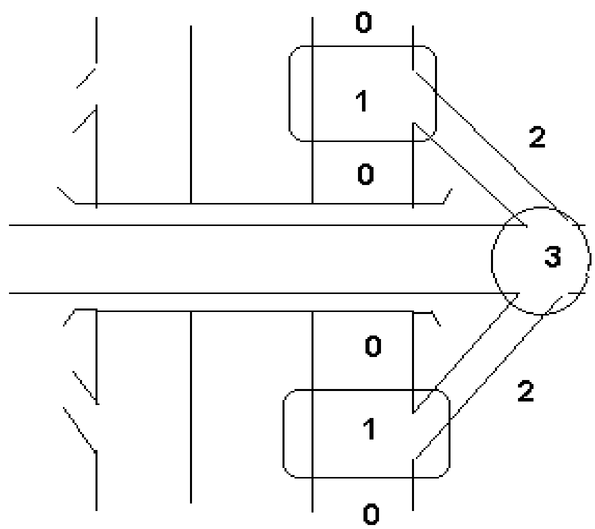


Figure 7 Ramp Section Diagram *(23)*

For this study, however, the researchers found these existing definitions of *Ramp Section* to be insufficient for the purposes of dividing a ramp into homogeneous segments along with the other characteristics. In particular, there are numerous instances where two ramps merge into one ramp before rejoining the mainline facility. These definitions of *Ramp Section* would not distinguish between the two portions of the ramp before and after the junction of the two ramps. Therefore, the research team created a new set of definitions for *Ramp Section* specifically to address this issue, as follows. Figure 8 illustrates these new definitions.

In the new definition, *Ramp Section 1* represents the segment of the ramp prior to/approaching the segment that contains the controlling curvature. This section includes the intersecting area between the mainline and the ramp, although not all crashes in this area are considered. Consideration of an incident requires clear evidence that the vehicles involved in the crash had the intention of exiting the freeway on this ramp.

Ramp Section 2 represents the segment of the ramp that contains the controlling curvature (i.e., the highest curvature point). Since this project deals with only freeway-to-freeway ramps on interchanges, there are no occurrences of straight, non-curved ramps. If there is another ramp that merges-into/diverges-out-of this ramp, this segment represents only the portion *before* that junction.

Ramp Section 2A represents the segment of the ramp *after* the junction with another ramp as it merged-into/diverged-out-of the current ramp. This segment follows *Ramp Section 2* immediately and could also still contain the controlling curvature.

Ramp Section 3 represents the segment of the ramp after *Ramp Section 2* or *2A* where the ramp merges back into the freeway. It also includes the intersecting area between the ramp and the mainline, although (similar to *Ramp Section 1*) not all crashes in this area are considered. Again, to be considered, there needs to be clear evidence that the vehicles involved in the crash were entering the freeway from this ramp.

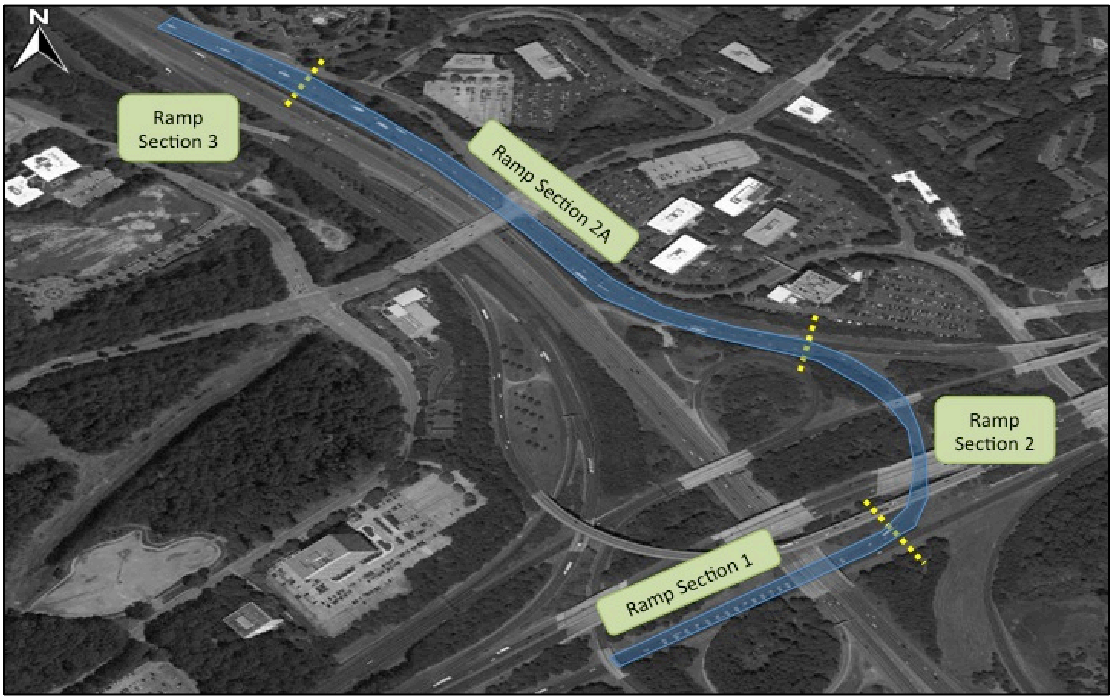


Figure 8 New Definition of Ramp Section

3.2.4 Summary of Data Acquisition

After all the crash, traffic volume, and road characteristic data were acquired, researchers produced a combined, comprehensive database. This database contained data for each of the treatment and control ramps along with their respective crash, traffic volume, and road characteristic data. After generation, a comprehensive data quality control process was conducted on all data (particularly the crash data) for one year prior to and one year after the treatment installation period:

- **Before Period –** April 9, 2007, to April 8, 2008
- **After Period –** April 15, 2008, to April 14, 2009

3.3 Task 3 – Crash Data Quality Assurance

Section 3.2.1 discussed the sources of the crash data and how the Route Number–Road Name search method was employed. The crash data retrieved for each interchange through the Route Number–Road Name search method were verified by a quality assurance process. This process involved reviewing the police report associated with each of the crashes identified by the Route Number–Road Name search method. In particular, the review of the police report involved answering the following questions and recording the answers:

1. In what county did the crash occur?
2. In what interchange did the crash occur? If the crash did not occur in an interchange, what is the interchange nearest to the location of the crash? (e.g., I-75/I-85, I-75/I-285, etc.)
3. Is the location of the crash most associated with a mainline facility or with a ramp that connects two mainline facilities?
4. If the location of the crash is most associated with a ramp, where is the exact location with respect to the ramp? Is it approaching, on, or leaving the ramp?
5. What is the direction of movement? (e.g., for mainline: eastbound, northbound, etc.; for ramp: eastbound to northbound, southbound to westbound, etc.)

To streamline the process, if researchers determined in answering the second question that the crash was not located in the interchange of interest, that was noted and the remaining questions were skipped. All crashes that were not associated with the ramps of interest were disregarded at the end of the quality assurance process.

3.4 Task 4 – Crash Attribute Analysis

After completion of the quality assurance process, crash attribute analysis was conducted for each of the treatment and control ramps. This analysis explored the trends and patterns of the crashes, vehicles, and drivers to examine if these were being affected, or unaffected, by the chevron markings treatment to aid in identifying the mechanism by which the chevron markings influence safety.

This analysis was conducted at two levels: (1) crash-level analysis and (2) vehicle-/driver-level analysis. For the crash-level analysis, attributes pertaining to the crash event as a whole were analyzed, including weather condition, accident date and time, and crash type. For the vehicle-/driver-level analysis, more specific attributes pertaining to the vehicle and/or the driver involved in the crash were analyzed, including age, gender, and vehicle type. The crash-level attributes the research team selected for this analysis are as follows:

- Ramp section
- Crash type
- Day of week
- Time of day
- Surface conditions

The researchers selected the following vehicle-/driver-level attributes for this analysis:

- Vehicle type
- Driver age
- Driver gender
- County of residence of driver

3.5 Task 5 – Empirical Bayes Before–After Safety Evaluation

The empirical Bayes before–after safety evaluation method was used to compare crash frequencies at the treatment sites before and after the converging chevron treatment was implemented. This method explicitly addresses the regression-to-the-mean issue by incorporating crash information from other but similar (i.e., control) sites into the evaluation. This is done by using a SPF and weighting the observed crash frequency with the SPF-predicted average crash frequency to obtain an expected average crash frequency. Figure 9 provides a step-by-step overview of this method.

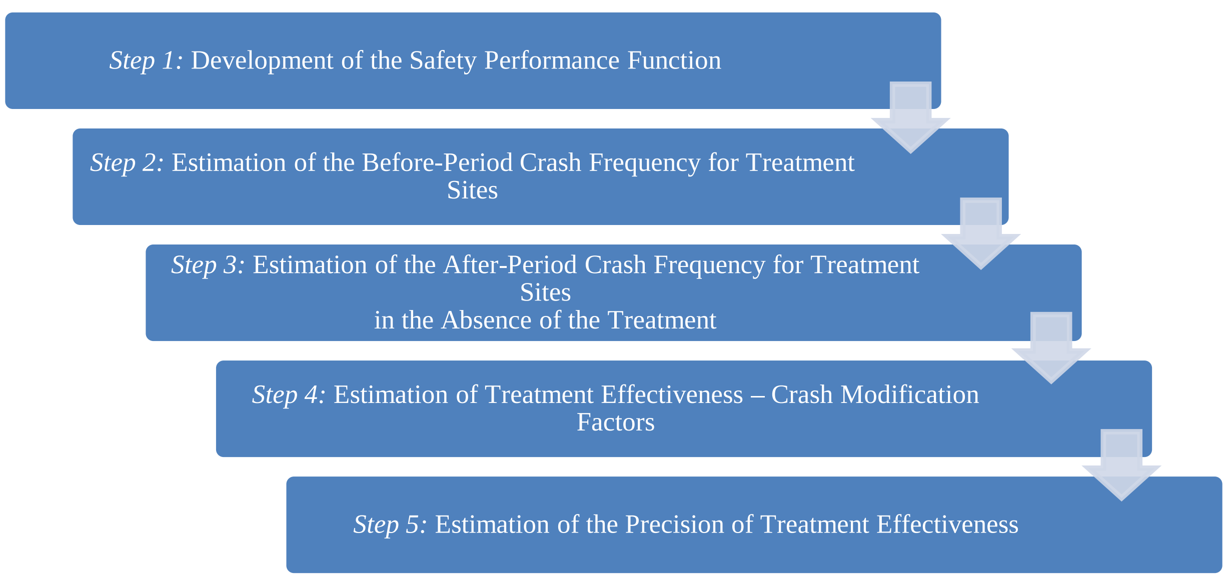


Figure 9 Overview of Empirical Bayes Before–After Safety Evaluation *(20)*

In conducting the empirical Bayes method, it is important that the relevant data (i.e., crash, roadway characteristic, and traffic volume data) are applied consistently and that the controlling variables are representative of the area being analyzed. In other words, the segments should be as homogeneous as possible and the controlling variables be well defined. Thus, to the extent possible, data were disaggregated into homogeneous segments based on *Ramp Section* as described in the previous section. The specific parameters used in the analysis include the following:

- County
- Ramp section
- Ramp condition
- Radius
- Number of lanes
- AADT for years 2007 to 2009
- AADT for before and after periods
- Crash frequency for years 2007 to 2009
- Crash frequency for before and after periods

Additionally, a second dataset was generated to include all of the same variables but specifically for fatal/injury-only crashes. The complete dataset is described in more detail in Appendix A.

4 Crash Attribute Analysis

This chapter presents the results of the incident characteristic analysis and a more detailed discussion of the trends observed on the two treatment ramps and two control ramps used in the earlier study. Table 3 presents a summary of the final quality-assured crash incident and involved-vehicle frequencies for those four ramps for the before and after periods. These findings differ somewhat from the rudimentary analysis conducted at the time of the repaving project, reflecting the impact of the data quality assurance process on the crash data, though the general conclusions that the treatment produced a significant reduction in crashes remains unchanged.

Table 3 Crash and Vehicle Frequencies at the Study Ramps

Study Ramps	Before Period		After Period		Change	
	No. Of Crashes	No. Of Vehicles	No. Of Crashes	No. Of Vehicles	Crashes (%)	Vehicles (%)
I-75 SB to I-85 NB Treatment	49	73	23	34	−53.1%	−53.4%
I-85 SB to I-75 NB Control	59	85	77	93	30.5%	9.4%
I-285 EB to I-75 NB Treatment	51	91	28	43	−45.1%	−52.7%
I-75 SB to I-285 WB Control	21	36	23	42	9.5%	16.7%

4.1 Interchange of I-75 and I-85 in Fulton County

4.1.1 Ramp Section

The first attribute analyzed the location of the crashes relative to the ramp (ramp section) to look for any changes that may have occurred as a result of the converging chevron treatment. As discussed previously, each ramp has either three and four sections: 1) the segment approaching the controlling curvature (present on all ramps); 2) the segment that contains the controlling curvature prior to any merges with/diverges to another ramp (present on all ramps); 2A) the segment after any merges/diverges to another ramp that still contains the controlling curvature (may or may not be present); and 3) the departure segment (present on all ramps). The location by ramp section and types of crashes that occurred on the I-75 SB to I-85 NB treatment ramp in the before and after periods are presented in Table 4. The crash types are those defined by the Georgia Uniform Vehicle Accident Report Instruction Guide Version 2 *(24)*: angle, head on, rear end, sideswipe (same direction), sideswipe (opposite direction), and single-vehicle. Since these are freeway ramps, there are no opposite-direction sideswipe crashes. In both the before and after periods, crashes occurred predominantly in Ramp Section 2, the controlling curvature representing 43 out of 49 (87.8%) crashes in the before period, and 21 out of 23 (91.3%) crashes in the after period. This section also experienced the largest reduction (22 crashes or −51.2%) in overall crashes between the before and after periods.

Similarly, the locations of crashes that occurred on the I-85 SB to I-75 NB control ramp in the before and after periods are presented in Table 5. The locations for the crashes on the I-75 SB to I-85 NB treatment ramp for the before and after period are illustrated in Figure 10 and Figure 11 respectively, and those for the I-85 SB to I-75 NB control ramp are similarly illustrated in Figure 12 and Figure 13. Similar to the treatment ramp, crashes occurred predominantly in Ramp Section 2 in both the before and after periods with 41 out of 59 (69.5%) crashes in the before period and 61 out of 77 (79.2%) in the after period. However, unlike the treatment ramp, Section 2 of this ramp experienced an increase of 20 crashes (48.8%). These results suggest, but do not prove, that the crash reductions seen on the treatment ramp were associated with installation of the chevron markings. The possibility of a different mechanism for the crashes cannot be excluded, however.

Table 4 Crash Frequencies by Ramp Section and Crash Type on I-75 SB to I-85 NB Treatment Ramp

Crash Type	Before Period (No. Of Crashes)				After Period (No. Of Crashes)				Change (No. Of Crashes) (%)			
	RS 1	RS 2	RS 3	Total	RS 1	RS 2	RS 3	Total	RS 1	RS 2	RS 3	Total
Angle	0	6	1	**7**	0	2	0	**2**	0 (0.0%)	−4 (−66.7%)	−1 (−100.0%)	**−5 (−71.4%)**
Head On	0	0	1	**1**	0	0	0	**0**	0 (0.0%)	0 (0.0%)	−1 (−100.0%)	**−1 (−100.0%)**
Rear End	2	4	0	**6**	1	1	0	**2**	−1 (−50.0%)	−3 (−75.0%)	0 (0.0%)	**−4 (−66.7%)**
Sideswipe	1	4	1	**6**	1	5	0	**6**	0 (0.0%)	1 (25.0%)	−1 (−100.0%)	**0 (0.0%)**
Single-Vehicle	0	29	0	**29**	0	13	0	**13**	0 (0.0%)	−16 (−55.2%)	0 (0.0%)	−16 (−55.2%)
Total	**3**	**43**	**3**	49	**2**	**21**	**0**	23	**−1 (−33.3%)**	**−22 (−51.2%)**	**−3 (−100.0%)**	**−26 (−53.1%)**

NOTE: RS = Ramp Section

Table 5 Crash Frequencies by Ramp Section and Crash Type on I-85 SB to I-75 NB Control Ramp

Crash Type	Before Period (No. Of Crashes)				After Period (No. Of Crashes)				Change (No. Of Crashes) (%)			
	RS 1	RS 2	RS 3	Total	RS 1	RS 2	RS 3	Total	RS 1	RS 2	RS 3	Total
Angle	1	2	0	**3**	1	4	0	**5**	0 (0.0%)	2 (100.0%)	0 (0.0%)	**2 (66.7%)**
Head On	1	0	0	**1**	0	0	0	**0**	−1 (−100.0%)	0 (0.0%)	0 (0.0%)	**−1 (−100.0%)**
Rear End	9	3	1	**13**	4	4	1	**9**	−5 (−55.6%)	1 (33.3%)	0 (0.0%)	**−4 (−30.8)**
Sideswipe	2	0	1	**3**	1	0	0	**1**	−1 (−50.0%)	0 (0.0%)	−1 (−100.0%)	**−2 (−66.7%)**
Single-Vehicle	1	36	2	**39**	3	53	6	**62**	2 (200.0%)	17 (47.2%)	4 (200.0%)	**23 (59.0%)**
Total	**14**	**41**	**4**	59	**9**	**61**	**7**	77	**−5 (−35.7%)**	**20 (48.8%)**	**3 (75.0%)**	**18 (30.5%)**

NOTE: RS = Ramp Section

4.1.2 Crash Type

The types of crashes that occurred on the I-75 SB to I-85 NB treatment ramp in the before and after periods were presented previously in Table 4 and illustrated in Figure 10 (before period) and Figure 11 (after period). In both the before and after periods, the dominant crash type on the treatment ramp is the single-vehicle crash: 29 out of 49 (59.2%) in the before period, and 13 out of 23 (56.5%) in the after period. This type of crash includes run-off-the-road crashes as well as crashes with non-moving objects (e.g., a pole or a median). These single-vehicle crashes all occurred in Ramp Section 2, suggesting that the controlling curvature of the ramp is a major factor in these occurrences. After the installation of the chevron markings, nearly all crash types experienced positive impacts with single-vehicle crashes experiencing a reduction of 16 crashes (−55.2%); rear ends a reduction of 4 crashes (−66.7%); and angle crashes reduced by 5 crashes (−71.4%).

The types of crashes that occurred on the I-85 SB to I-75 NB control ramp in the before and after periods are presented previously in Table 5 and in Figure 12 and Figure 13. Unlike the treatment ramp, this ramp experienced an increase of 23 single-vehicle crashes (+59.0%) during the period while other crash types were generally reduced or remained relatively constant. These findings again suggest that the chevron markings are impacting single-vehicle crashes more significantly, but also that there may be a different crash mechanism on the control ramp.

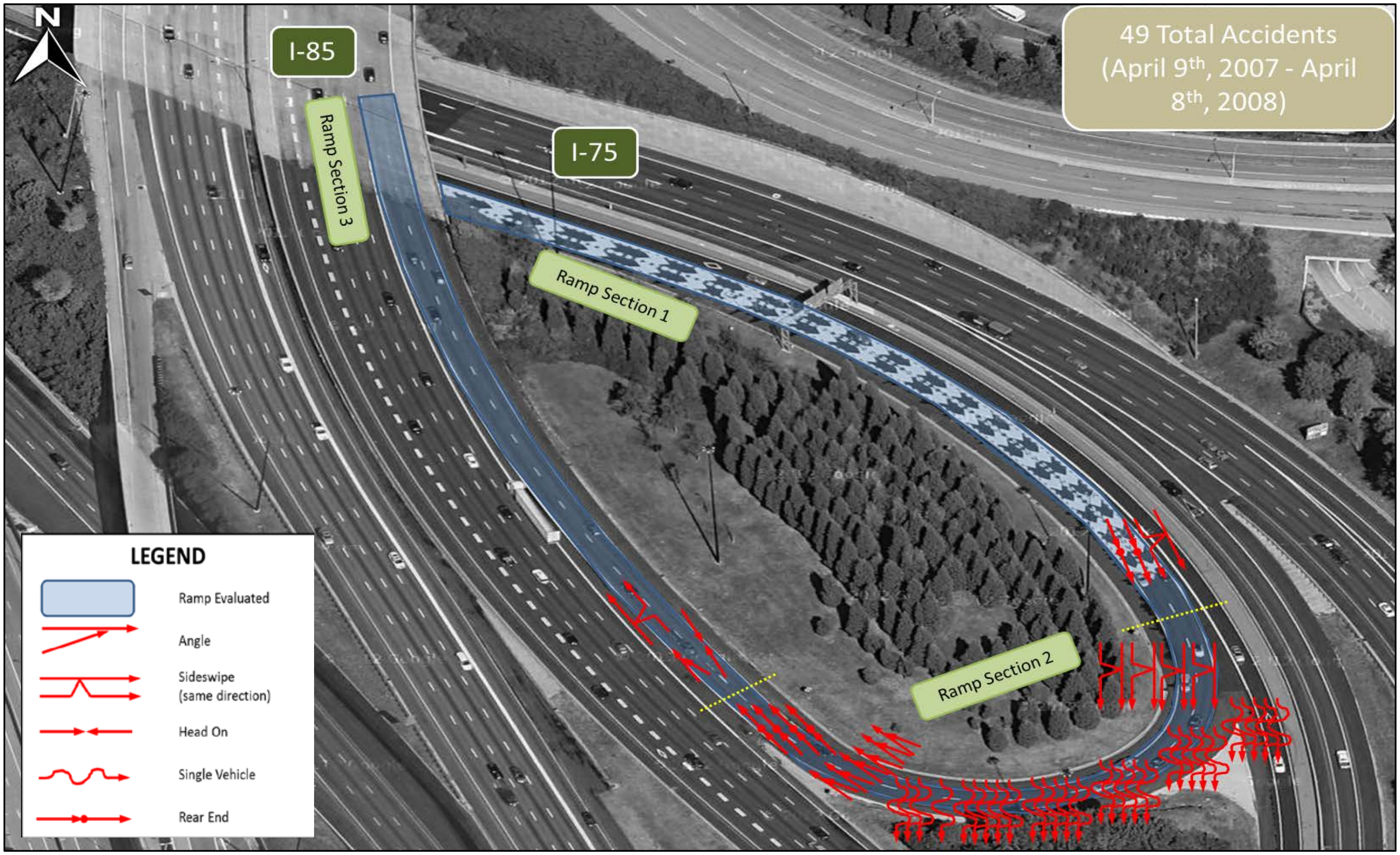


Figure 10 Collision Diagram of I-75 SB to I-85 NB Treatment Ramp in the Before Period

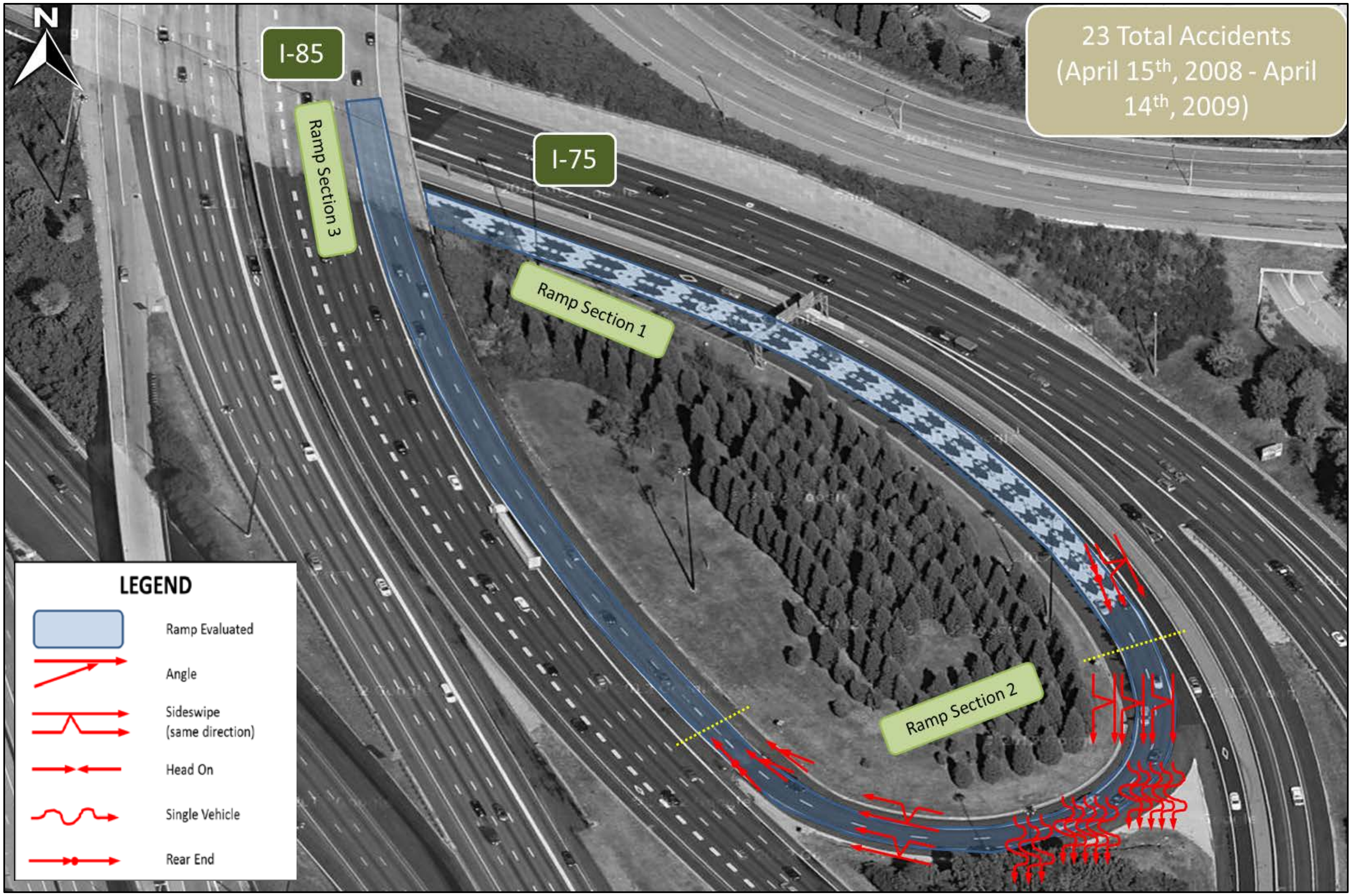


Figure 11 Collision Diagram of I-75 SB to I-85 NB Treatment Ramp in the After Period

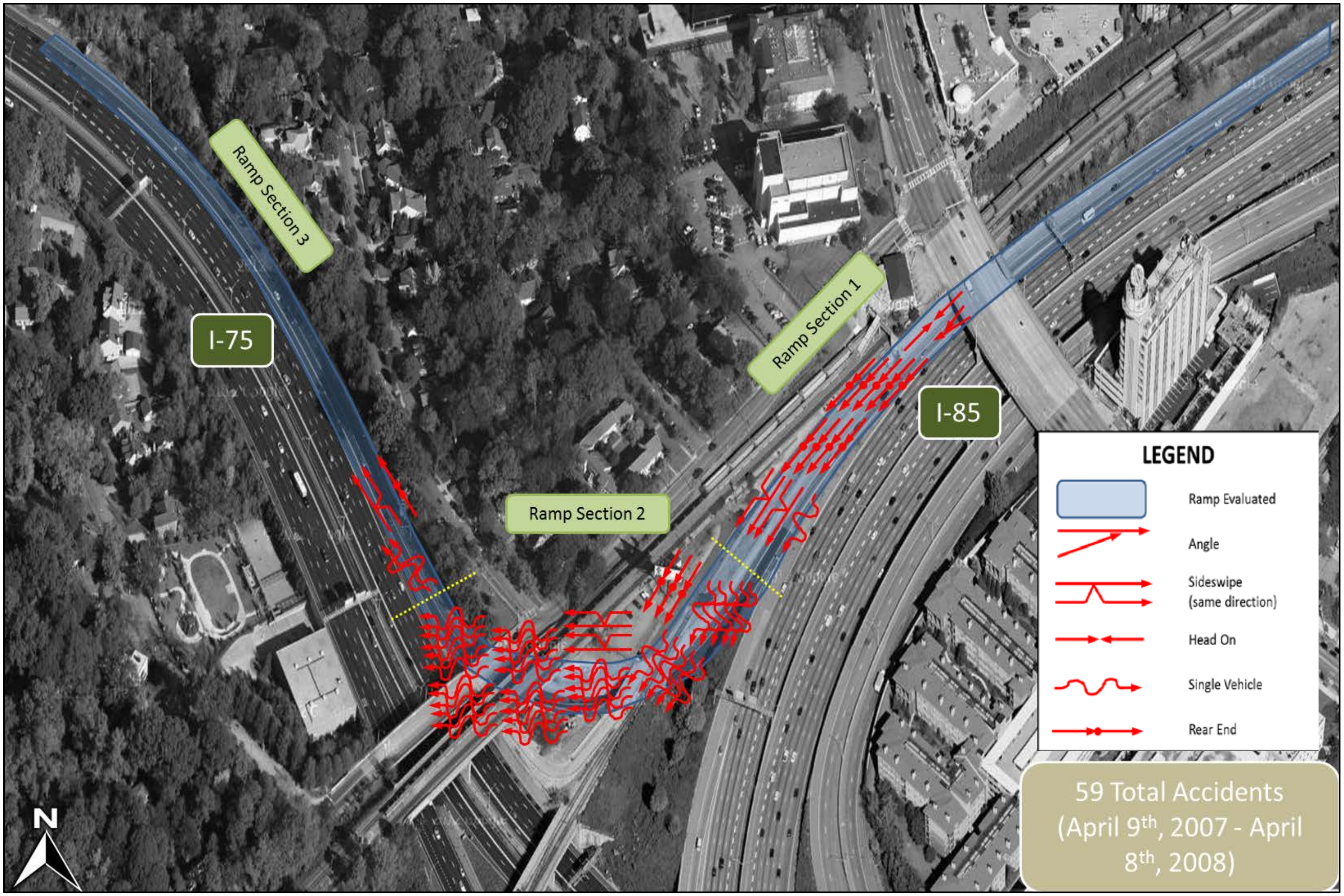


Figure 12 Collision Diagram of I-85 SB to I-75 NB Control Ramp in the Before Period

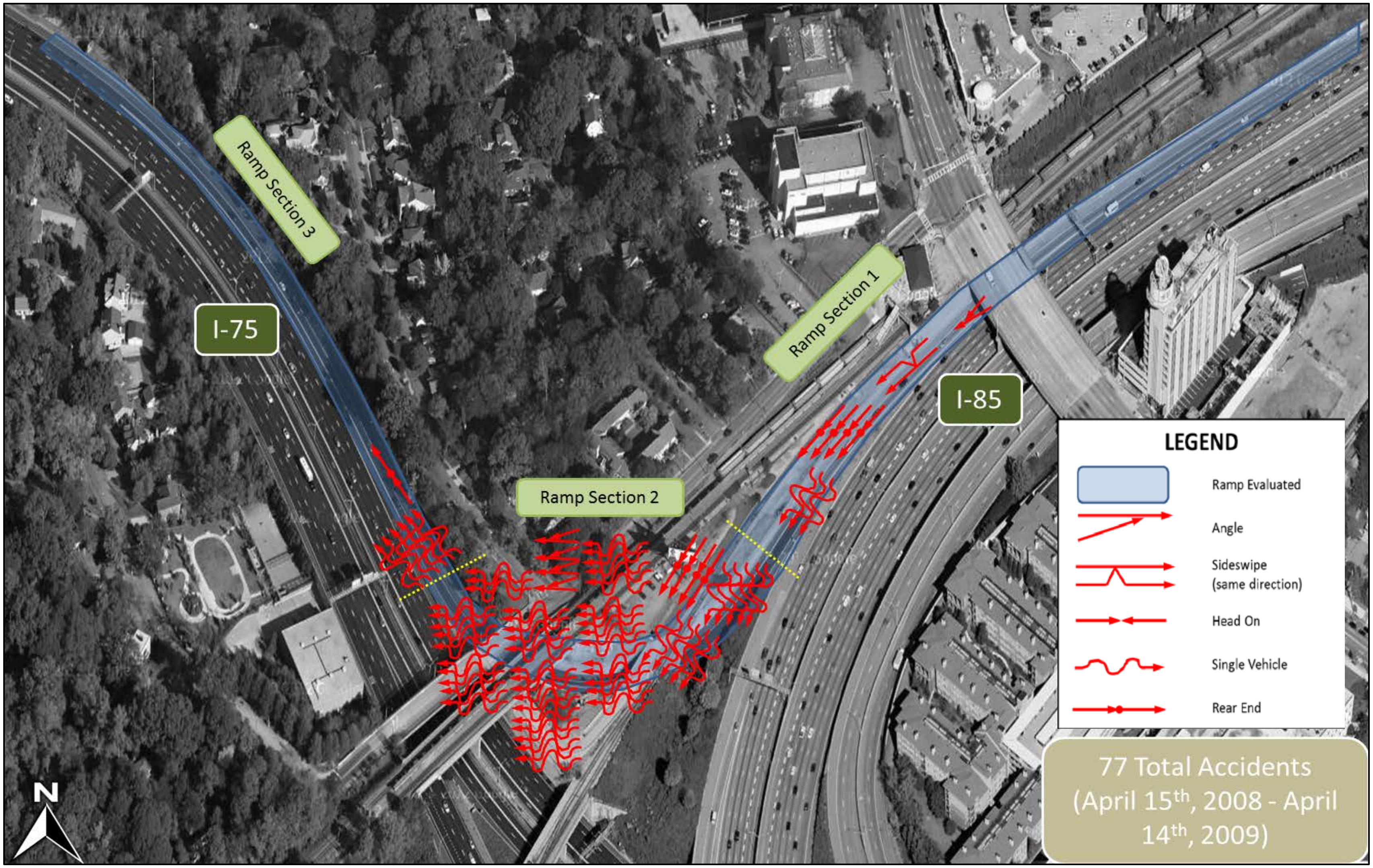


Figure 13 Collision Diagram of I-85 SB to I-75 NB Control Ramp in the After Period

4.1.3 Day of Week

Figure 14 presents the crash frequency distributions of both the I-75 SB to I-75 NB treatment ramp and the I-85 SB to I-75 NB control ramp categorized by day of week for both the before and after periods. The treatment ramp distribution shows that peak crash frequencies in the before period occur on Sundays, Thursdays, and Fridays. Moreover, it appears that incidents generally increase between Wednesdays and Fridays, drop on Saturdays, and increase again on Sundays. If the data were categorized into weekend and weekday incidents, the division is actually relatively even with 26 crashes occurring between Friday and Sunday and 23 crashes occurring between Monday and Thursday. After the installation of the chevron markings, crash reductions are seen for all days except Wednesdays and Saturdays.

On the control ramp, increases in crash frequency are seen on Sundays, Fridays, and Saturdays. This suggests that during the after period there may actually have been an increase in weekend travel on this interchange. If this were true, the overall reductions in crashes at the treatment ramp on the weekends also supports the potential effectiveness of the treatment.

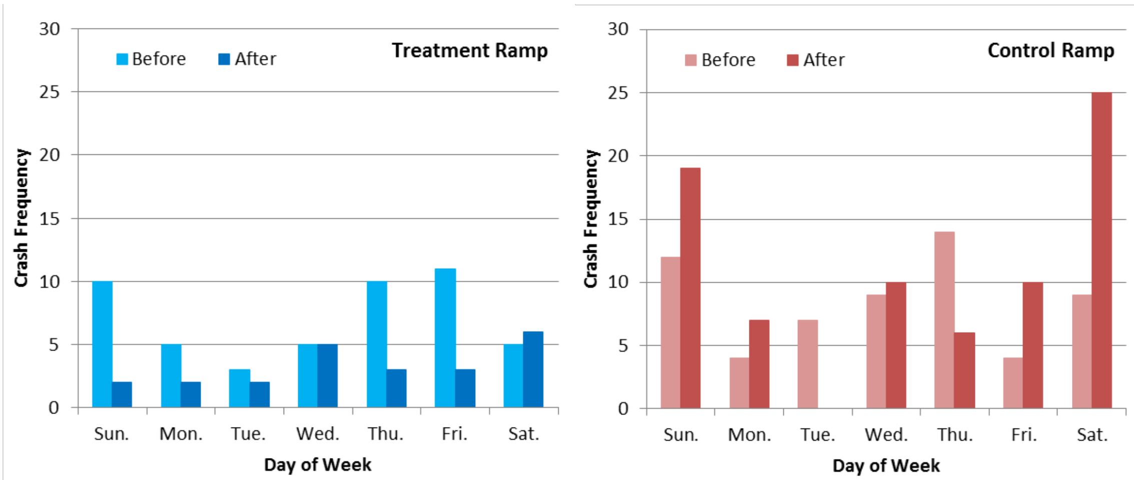
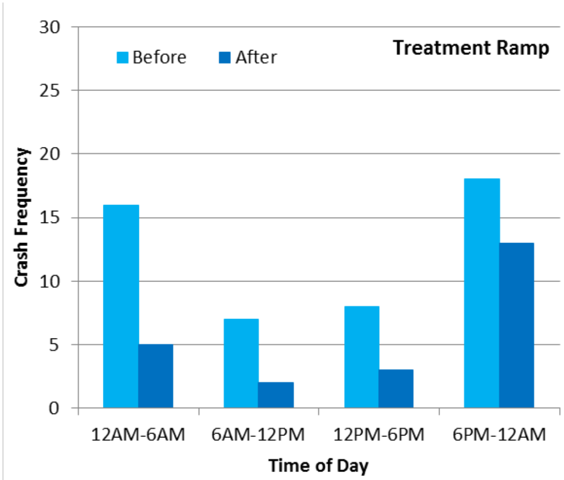


Figure 14 Crash Frequencies by Day of Week – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.4 Time of Day

Figure 15 presents the crash frequency distributions of the I-75/I-85 ramps by time of day for both the before and after periods. As expected, the treatment ramp distribution shows that peak crash frequencies are between 6 p.m. and 6 a.m. (i.e., the evening and night periods of the day). For the control ramp, however, this pattern is less clear.

The highest crash reduction in magnitude on the treatment ramp is found between 12 a.m. and 6 a.m., although other time periods also experienced great crash reductions. Meanwhile, the control ramp experienced crash increases in three of the four time periods. Taken together, these results indicate that the potential impacts of the chevron markings are not limited to a particular time of day.



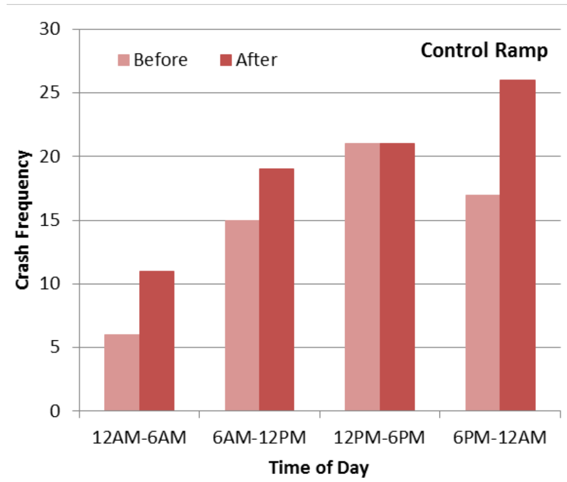


Figure 15 Crash Frequencies by Time of Day – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.5 Surface Condition

The effects of different surface conditions on crash frequency also were considered. These results are illustrated in Figure 16 for wet and dry pavement conditions. In the before period, the total numbers of crashes during dry conditions (55.1%, 27 crashes) and wet conditions (44.8%, 22 crashes) were similar on the treatment ramp. On the control ramp, a much higher percentage of crashes occurred during wet pavement with total number of crashes at 95.9% (47 crashes) in the before period and 89.6% (69 crashes) in the after period. These findings suggest that pavement conditions are a far more significant factor in crashes for the control ramp than for the treatment ramp at this interchange. Even so, a close to evenly distributed number of crashes on dry and wet conditions on the treatment ramp still suggest that this type of crash was overrepresented even at the treatment ramp.

Data from the National Oceanic and Atmospheric Administration *(25)*, indicate the presence of precipitation during only 8.6% of the total hours in the before period and 10.1% of the total hours in the after period. While wet pavements can occur during periods without precipitation and not all precipitation events result in wet pavements (a more frequent event), the presence of precipitation and wet pavements are strongly correlated. Taking these precipitation frequencies as a likely upper limit on the frequency of wet pavements, the much larger percentage of crashes occurring in wet surface conditions indicates that wet surface conditions are an important causation factor in crashes at these locations.

Nonetheless, all crashes on the treatment ramps, in wet or dry conditions, were significantly reduced in the after period. Crashes in dry conditions at the treatment ramp were reduced to a total of 13 crashes (−51.9%), and crashes during wet conditions were reduced to 10 crashes (−54.5%). This reduction again suggests that the chevron markings are having a significant impact on crash frequencies under a variety of conditions.

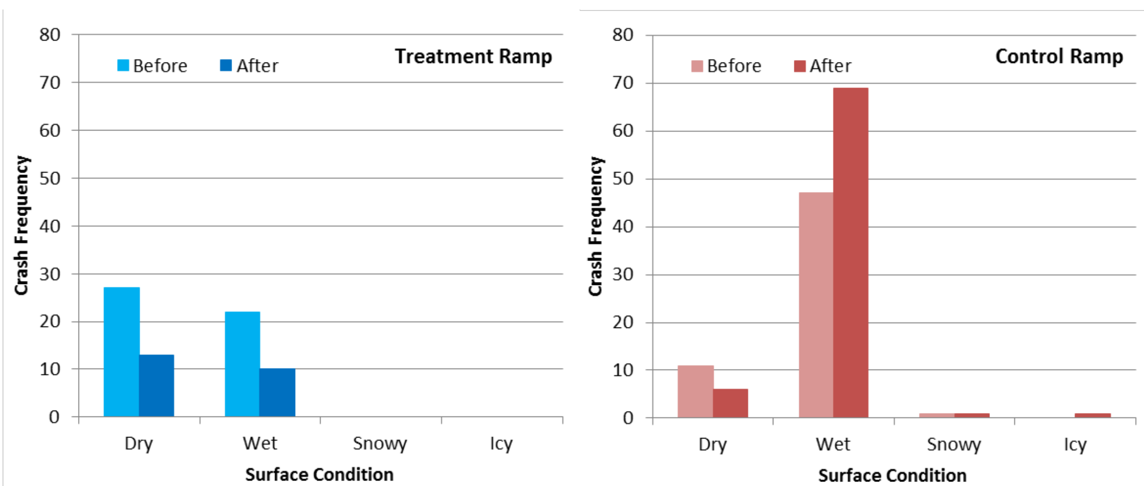


Figure 16 Crash Frequencies by Surface Condition – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.6 Vehicle Type

The impacts of the chevron treatment were also examined by vehicle type. These results are presented in Figure 17. On the treatment ramp, over 97% of vehicles involved in crashes in the before period were passenger vehicles, which include passenger cars, vans, SUVs, and pickup trucks. This dominance also is seen in the after period on the treatment ramp, as well as in the control ramp in both time periods. This finding is consistent with the restriction of heavy vehicles in the region inside of I-285 *(26)*. On the treatment ramp, passenger vehicles experienced a reduction in crashes of 53.5%, while on the control ramp they experienced an increase of 12.2%. This finding is consistent with all other findings in that it is likely that a significant portion of the reduction is related to the chevron markings.

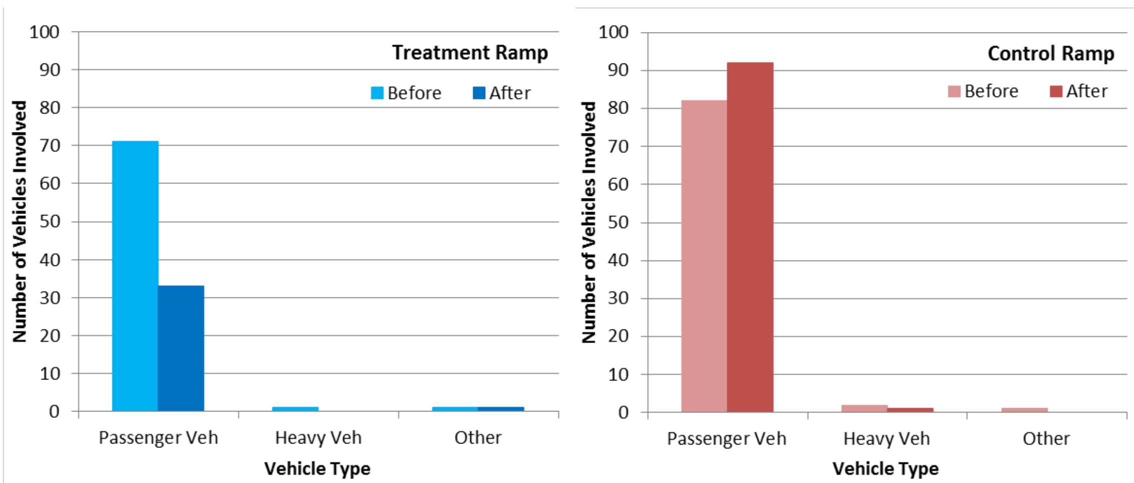


Figure 17 Frequencies of Vehicle Types Involved – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.7 Driver Age

To explore whether the chevron markings had a disproportionate influence on specific age groups, the research team also considered the age of drivers involved in crashes. As shown in Figure 18, nearly all age groups experienced a reduction in crashes, with the exception of drivers between the ages of 16 and 20 and the ages of 51 and 60. For these age groups, the crash frequencies were more or less consistent between the before and after periods.

On the control ramp, increases in crashes were seen for drivers between the ages of 21 and 25 and 31 and 35, while other age groups appeared to have either experienced a decrease or remained relatively constant. Taken together, these results do not suggest an age-related bias in the effectiveness of the chevron treatment.

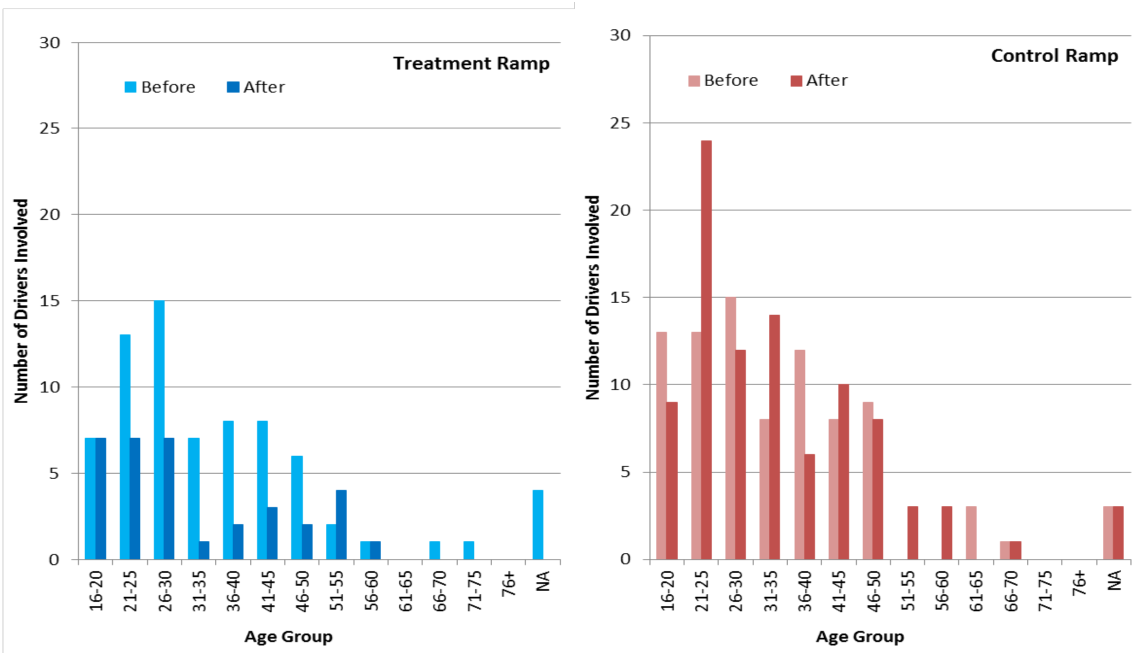


Figure 18 Frequencies of Drivers Involved by Age Group – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.8 Driver Gender

To examine whether the chevron markings had an influence on a specific group, the gender of drivers in the I-75 and I-85 ramps was also considered. The findings of this analysis are shown in Figure 19. On the treatment ramp, 63.0% of drivers involved in crashes for the before period were male, while 37.0% were female. Similar trends are seen in the after period where 61.8% of drivers involved were male while 38.2% were female. On the control ramp, these percentages are more evenly distributed. In the before period, 54.1% of drivers involved were male, while 45.9% were female. In the after period, 49.5% of drivers involved were male, while 50.5% were female.

These findings suggest that male drivers are more likely to be in a crash on the treatment ramp, while on the control ramp, the likelihood is relatively equal. However, the findings do not suggest that the chevron markings work better on a particular gender group. Large reductions were seen in both male and female drivers on the treatment ramp: a 54.3% reduction in crash frequency for male drivers and a 51.9% reduction for female drivers.

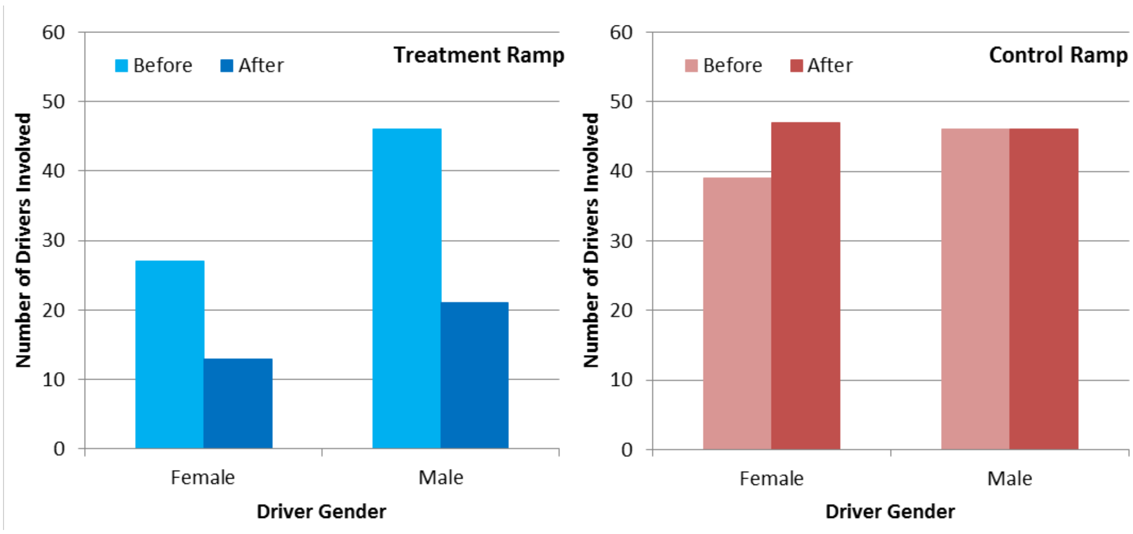


Figure 19 Frequencies of Drivers Involved by Gender – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.9 County of Vehicle Registration

County of vehicle registration was used as a surrogate variable to measure the familiarity of drivers with the I-75 and I-85 interchange. For this purpose, familiarity with the area was defined as having a county of vehicle registration inside of the 13-county Atlanta metropolitan region that includes the following counties: Cherokee, Clayton, Cobb, Coweta, DeKalb, Douglas, Fayette, Forsyth, Fulton, Gwinnett, Henry, Paulding, and Rockdale. The researchers assumed that drivers residing within these counties would be more likely to have been exposed to this interchange and its surrounding areas more frequently on average and, thus, would be less vulnerable to a crash resulting from a driver expectancy violation *(6)* than those living outside the 13-county area. Conversely, these "familiar" drivers may also have an increased likelihood of "driving with inattention" *(27–29)* with such a state having an increased likelihood of crash given the sharp (low radius) curvature of the ramps.

As shown in Figure 20, 63.5% of drivers involved in crashes on the treatment ramp in the before period (47 out of 74 drivers) were from counties inside the 13-county area. In the after period, an even higher percentage of drivers involved were from counties inside the 13-county area—73.5% (25 out of 34 drivers). Drivers that live outside the 13-county area are likely overrepresented in both periods: 32.4% of drivers in the before period and 26.5% of drivers in the after period. This is supported by a license plate study done by Nelson et al. that examined the geographic and demographic profiles of commuters in Atlanta where a reported percentage of 10.5% of commuters were of counties outside the 13-county area *(30)*. In contrast, drivers from outside the 13-county area on the control ramp represented approximately 14.1% and 20.4% of the drivers involved in the before and after periods, respectively.

This finding suggests that both drivers familiar and unfamiliar with the area are vulnerable to the sharp curve. However, significant assumptions are required to draw this conclusion, including the correlation of the county of vehicle registration with familiarity and whether or not the treatment ramp has a population distribution similar to stated demographic profiles. Currently, the data are insufficient to statistically differentiate the effect on familiar and unfamiliar drivers.

Nevertheless, large reductions were observed on the treatment ramp in the after period for both groups: drivers from within the 13-county area experienced a reduction of 46.8%, while drivers from outside the area experienced a reduction of 62.5%. These findings suggest that the chevron markings appear to be addressing both groups of drivers, although the impacts are more evident on drivers from outside the 13-county area.

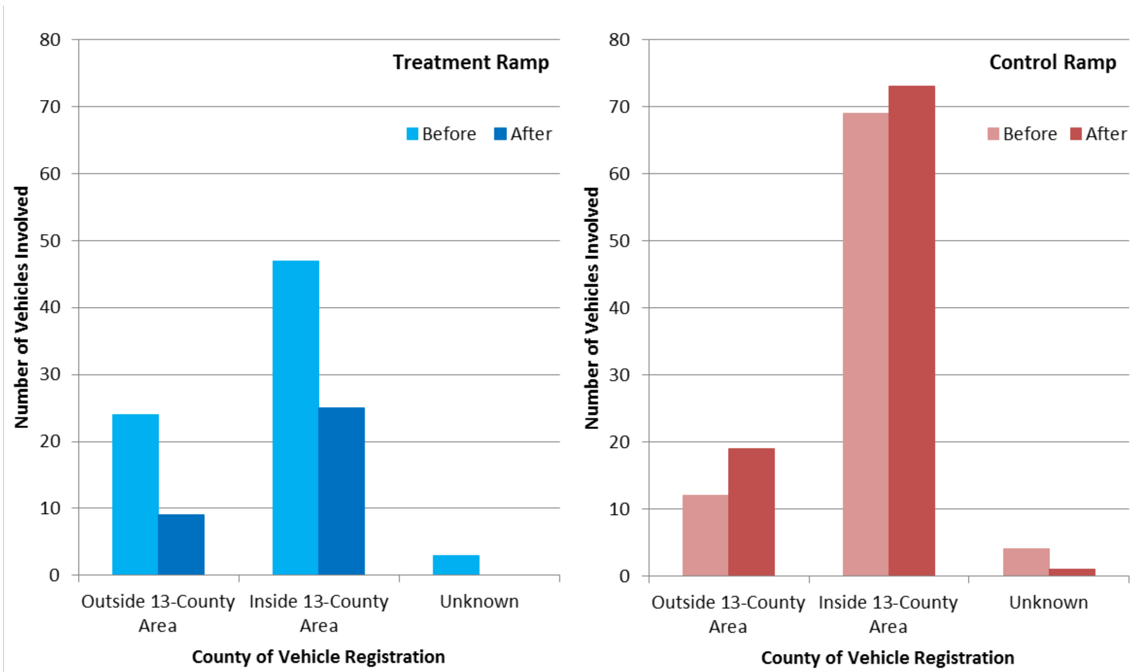


Figure 20 Frequencies of Vehicles Involved by County of Vehicle Registration – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.1.10 Crash Severity

Crash severity was also examined to establish whether the chevron markings impacted the seriousness of the crashes. As shown in Figure 21, most of the crashes that occurred on both the treatment and control ramps at this interchange are property-damage–only (PDO) crashes. Crashes on the treatment ramp experienced significant reductions regardless of severity. Meanwhile, PDO crashes on the control ramp actually increased by 65.8%. This finding suggests that the chevron markings are impacting all crashes, regardless of severity.

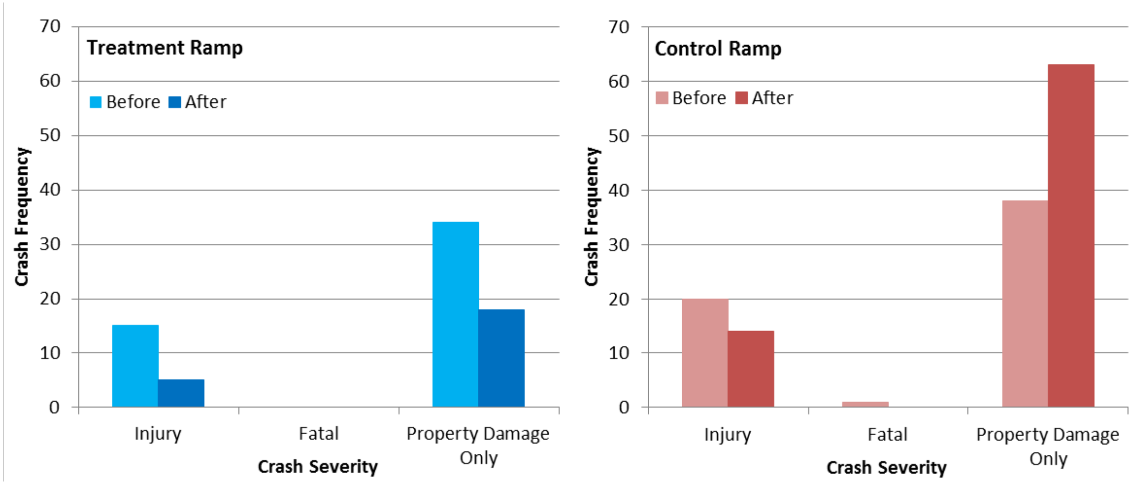


Figure 21 Crash Frequencies by Severity – I-75 SB to I-85 NB Ramp (Left) and I-85 SB to I-75 NB Ramp (Right)

4.2 Interchange of I-75 and I-285 in Cobb County

4.2.1 Ramp Section

Analysis of the I-75 and I-285 interchange essentially mirrored that described in Section 4.1 for the I-75 and I-85 interchange. The first attribute analyzed was ramp section, or the location of the crashes relative to the ramp. The locations of crashes that occurred on the I-285 EB to I-75 NB treatment ramp in the before and after periods are presented in Table 6 and illustrated in Figure 22 and Figure 23 for the before and after periods, respectively. In the before period, crashes predominantly occurred in Ramp Sections 2 and 2A, representing 21 out of 51 crashes (41.2%) and 18 out of 51 crashes (35.3%), respectively. In the after period, however, Section 2A experienced a large reduction in crashes, 13 crashes (−72.2%), while Section 2 exhibited only one fewer crash than in the before period. This is a finding that was not present on the I-75 SB to I-85 NB treatment ramp. Moreover, unlike its counterpart, the I-75 SB to I-285 WB control ramp did not experience any significant changes in its crash frequency between the before and after periods. The locations of the I-75 SB to I-285 WB control ramp crashes are presented in Table 7 and illustrated in Figure 24 and Figure 25.

Table 6 Crash Frequencies by Ramp Section and Crash Type on I-285 EB to I-75 NB Treatment Ramp

Crash Type	Before Period (No. Of Crashes)					After Period (No. Of Crashes)					Change (No. Of Crashes) (%)				
	RS 1	RS 2	RS 2A	RS 3	Total	RS 1	RS 2	RS 2A	RS 3	Total	RS 1	RS 2	RS 2A	RS 3	Total
Angle	0	3	1	0	**4**	0	2	1	0	**3**	0 (0.0%)	−1 (−33.3%)	0 (0.0%)	0 (0.0%)	**−1 (−25.0%)**
Head On	0	0	0	0	**0**	0	1	0	0	**1**	0 (0.0%)	1 (100.0%)	0 (0.0%)	0 (0.0%)	**1 (100.0%)**
Rear End	6	4	4	0	**14**	1	0	2	0	**3**	−5 (−83.3%)	−4 (−100.0%)	−2 (−50.0%)	0 (0.0%)	**−11 (−78.6%)**
Sideswipe	3	1	12	3	**19**	1	3	2	0	**6**	−2 (−66.7%)	2 (200.0%)	−10 (−83.3%)	−3 (−100.0%)	**−13 (−68.4%)**
Single-Vehicle	0	13	1	0	**14**	1	14	0	0	**15**	1 (100.0%)	1 (7.7%)	−1 (−100.0%)	0 (0.0%)	**1 (7.1%)**
Total	**9**	**21**	**18**	**3**	**51**	**3**	**20**	**5**	**0**	**28**	**−6 (−66.7%)**	**−1 (−4.8%)**	**−13 (−72.2%)**	**−3 (−100.0%)**	**−23 (−45.1%)**

NOTE: RS = Ramp Section

Table 7 Crash Frequencies by Ramp Section and Crash Type on I-75 SB to I-285 WB Control Ramp

Crash Type	Before Period (No. Of Crashes)				After Period (No. Of Crashes)				Change (No. Of Crashes) (%)			
	RS 1	RS 2	RS 3	Total	RS 1	RS 2	RS 3	Total	RS 1	RS 2	RS 3	Total
Angle	0	2	1	**3**	0	0	0	**0**	0 (0.0%)	−2 (−100.0%)	−1 (−100.0%)	**−3 (−100.0%)**
Head On	0	0	0	**0**	0	1	0	**1**	0 (0.0%)	1 (100.0%)	0 (0.0%)	**1 (100.0%)**
Rear End	0	2	1	**3**	1	2	7	**10**	1 (100.0%)	0 (0.0%)	6 (600.0%)	**7 (233.3%)**
Sideswipe	4	3	1	**8**	3	2	2	**7**	−1 (−25.0%)	−1 (−33.3%)	1 (100.0%)	**−1 (−12.5%)**
Single-Vehicle	2	4	1	**7**	1	4	0	**5**	−1 (−50.0%)	0 (0.0%)	−1 (−100.0%)	**−2 (−28.6%)**
Total	**6**	**11**	**4**	**21**	**5**	**9**	**9**	**23**	**−1 (−16.7%)**	**−2 (−18.2%)**	**5 (125.0%)**	**2 (9.5%)**

NOTE: RS = Ramp Section

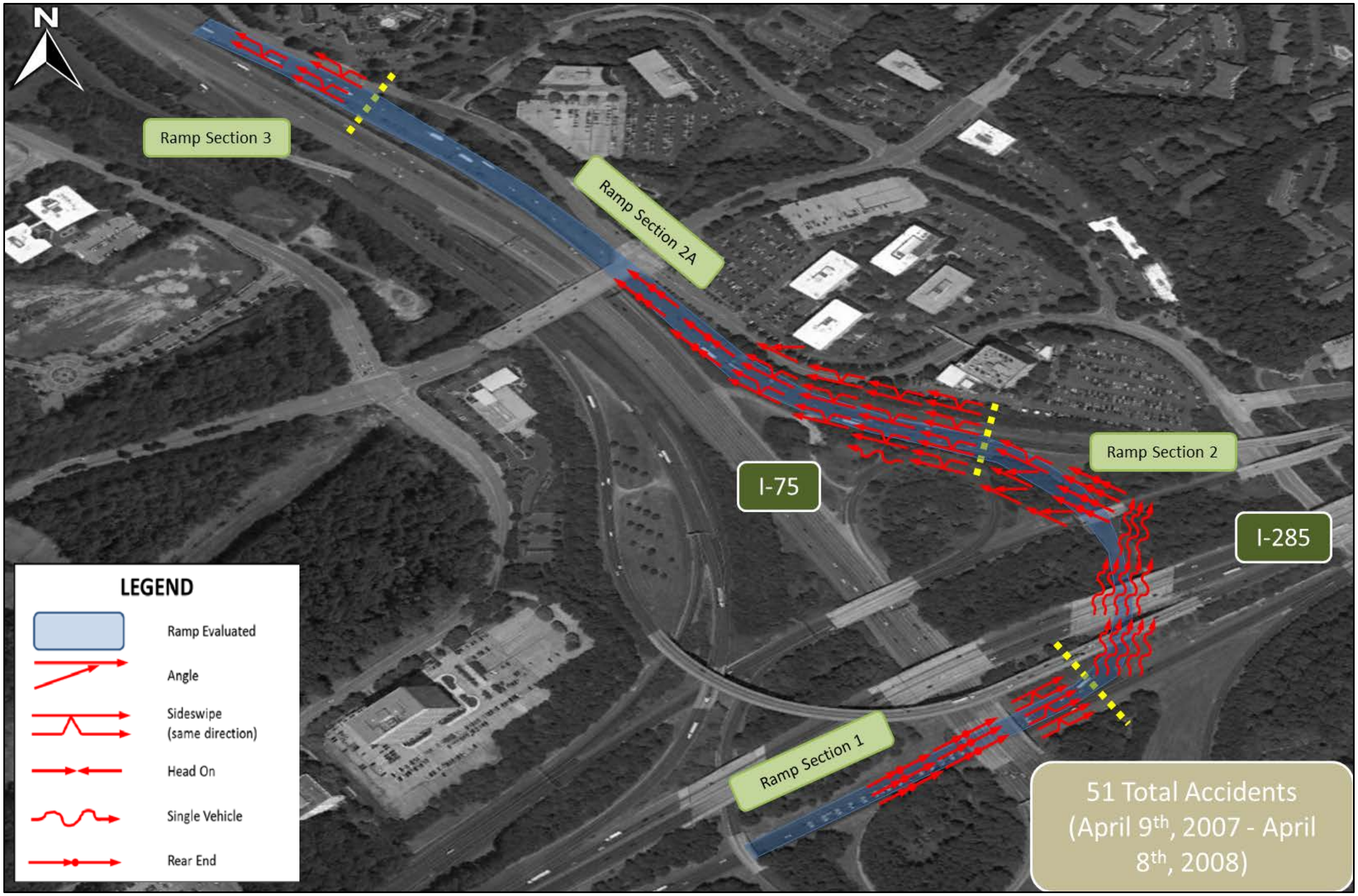


Figure 22 Collision Diagram of I-285 EB to I-75 NB Treatment Ramp in the Before Period

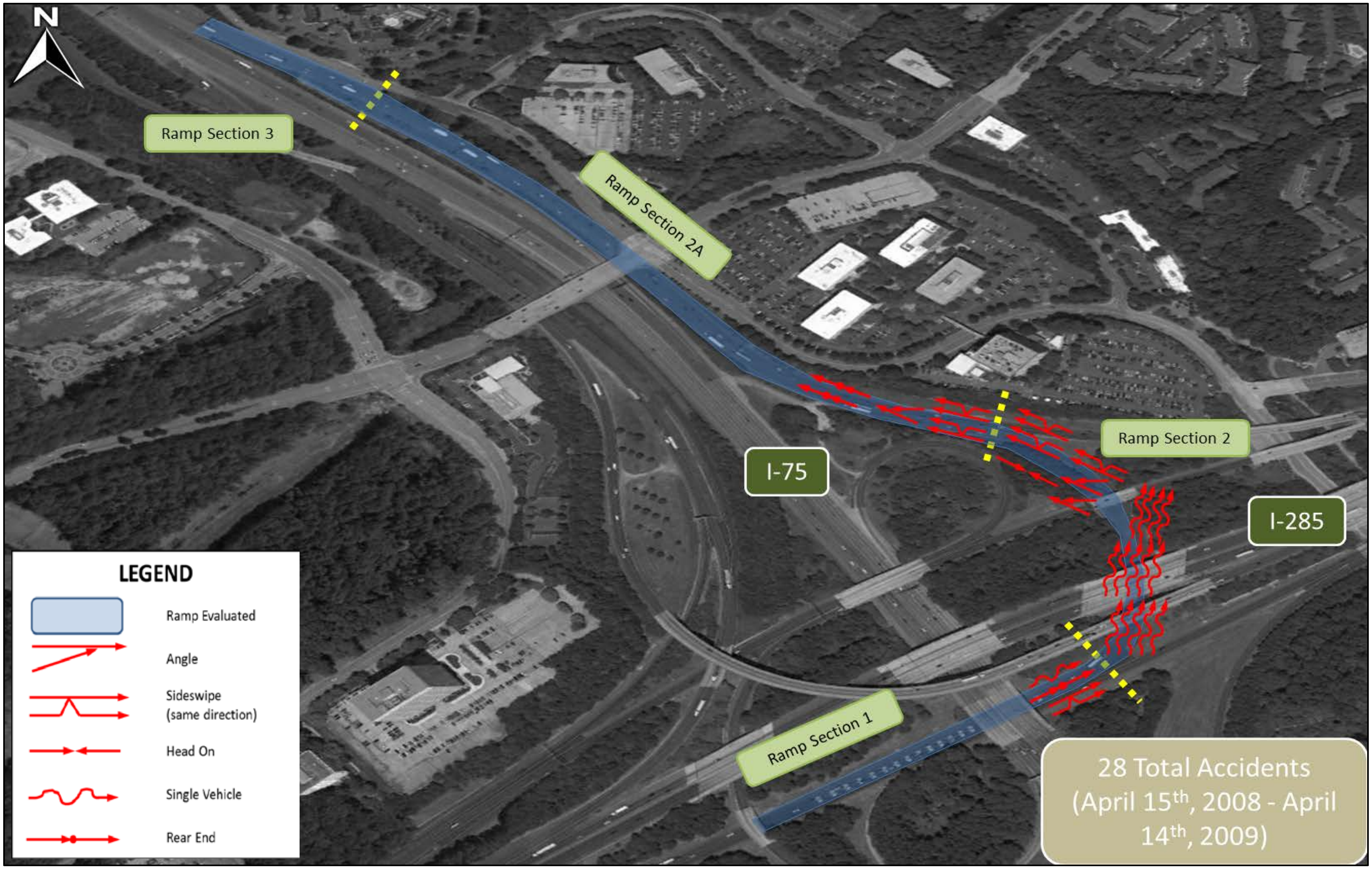


Figure 23 Collision Diagram of I-285 EB to I-75 NB Treatment Ramp in the After Period

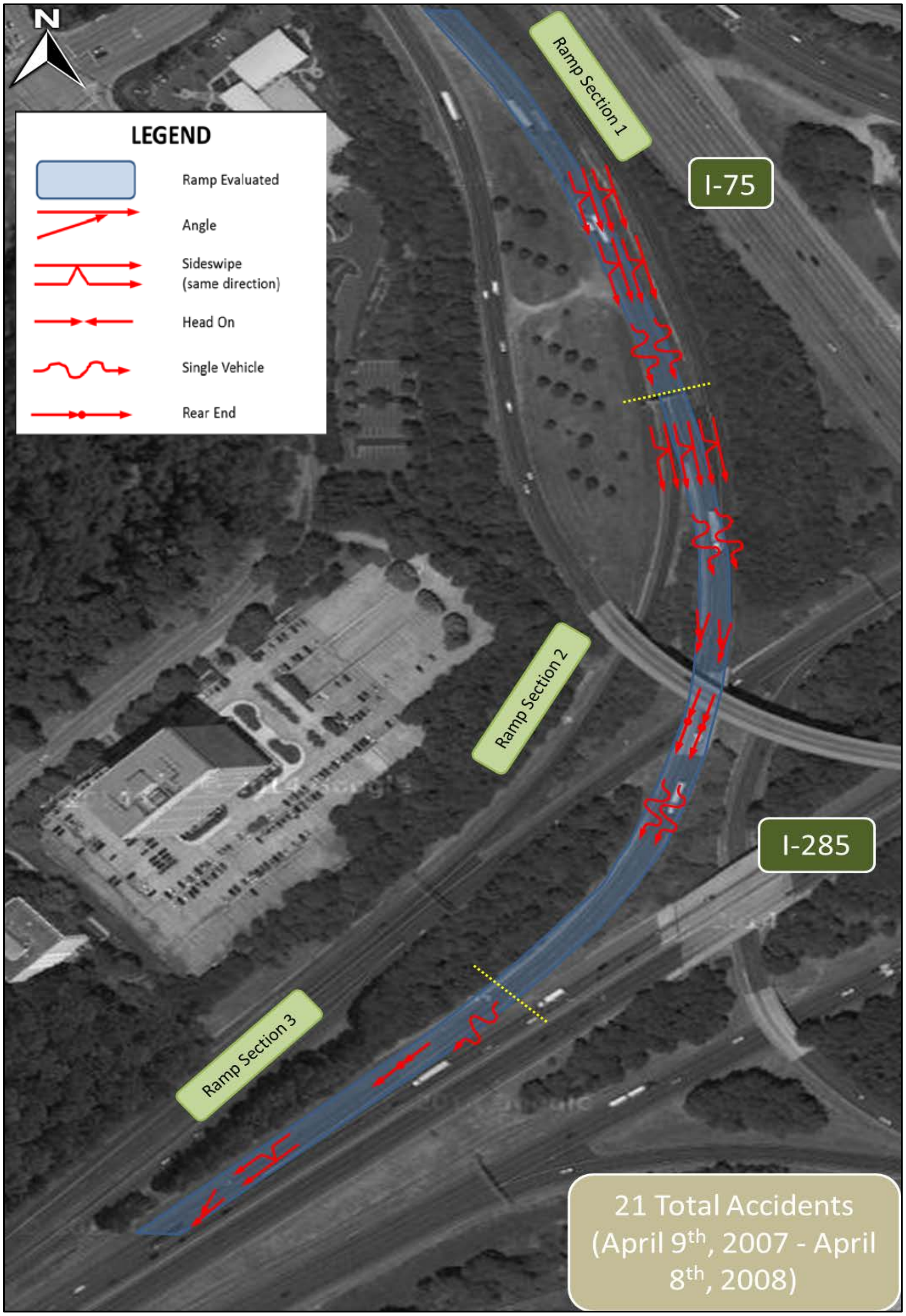


Figure 24 Collision Diagram of I-75 SB to I-285 WB Control Ramp in the Before Period

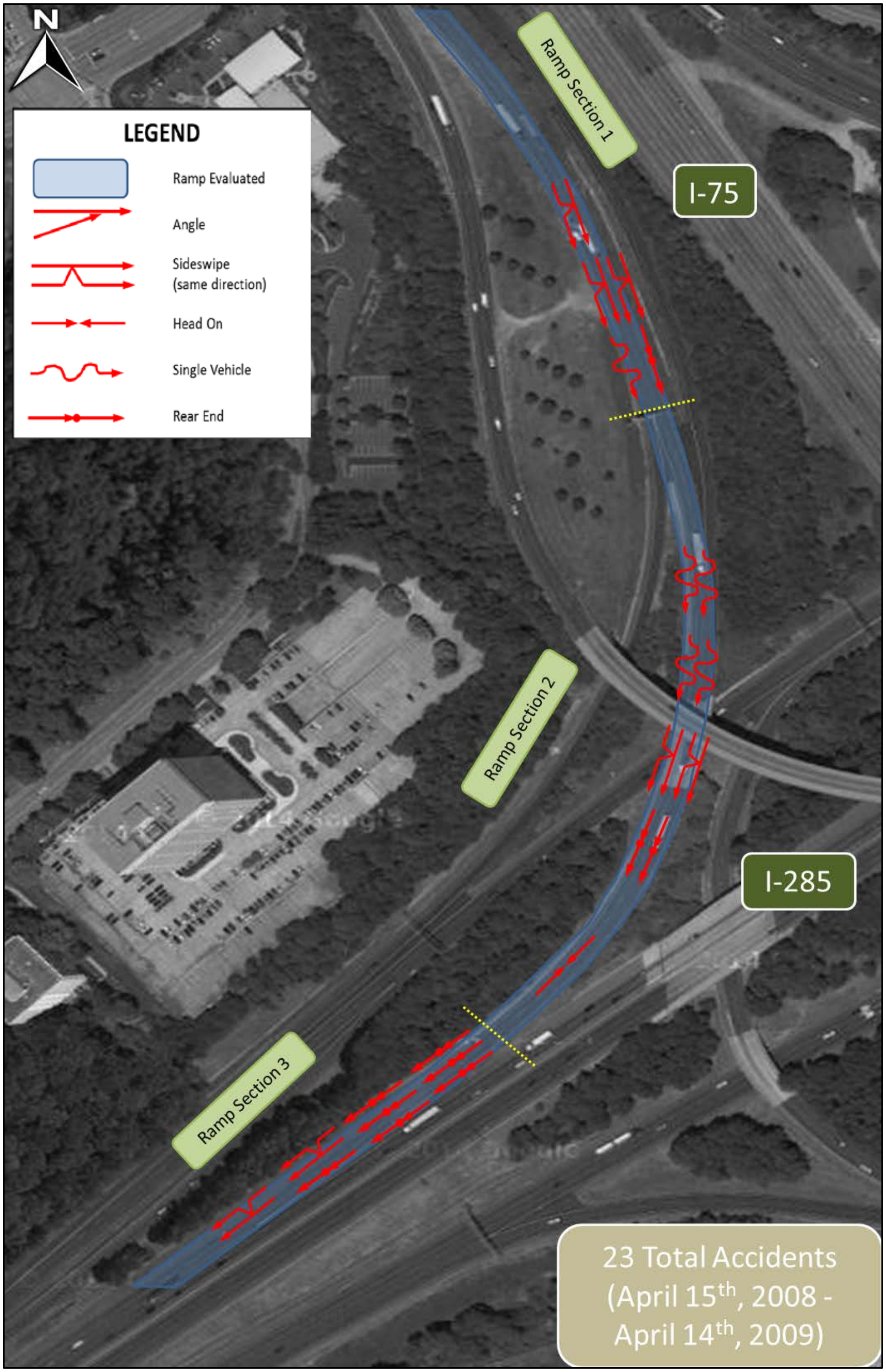


Figure 25 Collision Diagram of I-75 SB to I-285 WB Control Ramp in the After Period

4.2.2 Crash Type

The types of crashes that occurred on the I-285 EB to I-75 NB treatment ramp were presented previously in Table 6 and in Figure 22 and Figure 23. During the before period, the dominant crash types on the treatment ramp were rear-end collisions (14 out of 51, 27.5%); sideswipes (19 out of 51, 37.3%), and single-vehicle crashes (14 out of 51, 27.5%). Of the single-vehicle crashes, 13 out of the 14 occurred on Ramp Section 2, suggesting again that this crash type was highly influenced by the controlling curvature of the ramp.

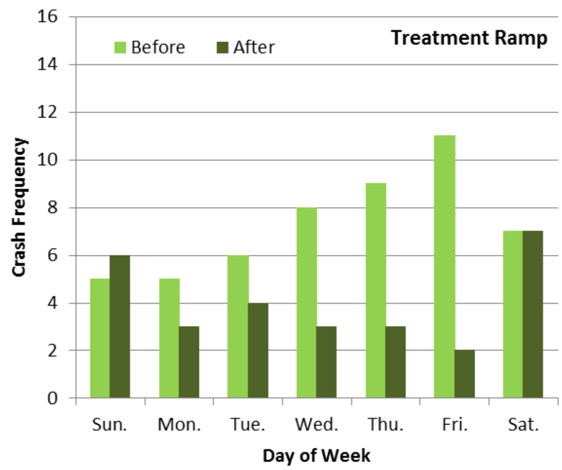
In contrast, 12 of the 19 sideswipe crashes at this location occurred on Ramp Section 2A, suggesting that this crash type was highly influenced by the weaving zone created by the merging of the I-285 WB to I-75 NB ramp instead of the sharp curve. In the after period, single-vehicle crashes in Ramp Section 2 were not reduced—a finding that is inconsistent with the findings from the I-75 SB to I-85 NB treatment ramp. In fact, the highest reductions are seen for rear ends (11 crashes or −78.6%) and sideswipes (13 crashes or −68.4%). Due to the locations of these crashes, however, this does not intuitively suggest that the chevron markings are responsible for these reductions. As discussed previously, Ramp Section 2A experienced the largest reduction in crashes (−13) of which 10 were sideswipes that are more likely to be influenced by the weaving behavior of Section 2A rather than the sharp curve of Section 2 containing the chevron markings. Therefore, it is unclear in this situation as to whether the chevron markings were responsible for these observed crash reductions.

While the I-75 SB to I-285 WB control ramp again did not experience any change in crashes, it did have an increase in rear-end crashes from 3 crashes in the before period to 10 crashes in the after period. However, this result is not statistically significant.

4.2.3 Day of Week

Figure 26 presents the crash frequency distributions of both the I-285 EB to I-75 NB ramp and the I-75 SB to I-285 WB ramp categorized by day of week for the before and after periods. The treatment ramp distribution shows that in the before period, crash frequencies increase throughout the week and drop on Saturdays and Sundays. In the after period, crash reductions are seen in all days except for Saturdays and Sundays.

On the control ramp, crash frequencies are generally consistent throughout the week. No significant changes to crash frequencies in relation to the day of week were seen on this ramp.



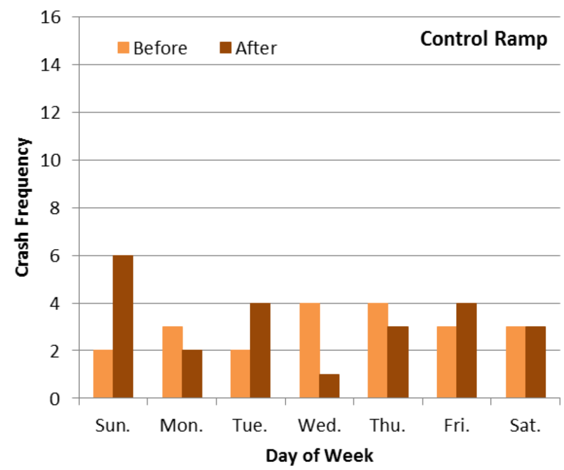


Figure 26 Crash Frequencies by Day of Week – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

4.2.4 Time of Day

Figure 27 presents the crash frequency distributions of the I-75/I-285 ramps by time of day for the before and after periods. Unlike on the I-75 SB to I-85 NB ramp, this treatment ramp distribution shows that peak crash frequencies are found between 6 a.m. and 6 p.m. (i.e., daytime conditions). This suggests that perhaps the usage of this interchange is inherently different than that of the I-75/I-85 interchange. Although all time periods experienced crash reductions, the largest crash reduction is found for the 12 p.m. to 6 p.m. time period (14 crashes or −63.6%). Meanwhile, the control ramp did not experience any significant changes over the before and after period.

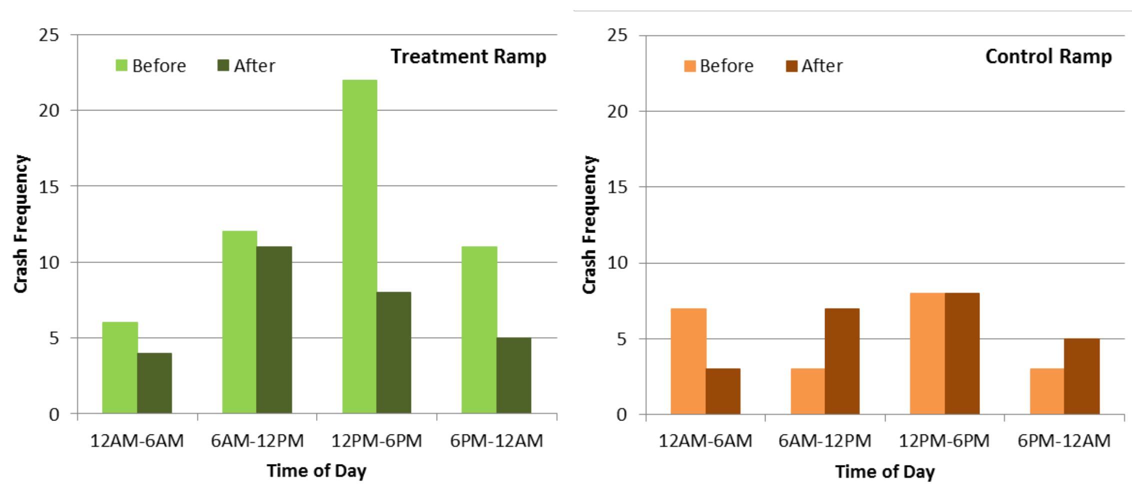


Figure 27 Crash Frequencies by Time of Day – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

4.2.5 Surface Condition

The research team also considered the impacts of surface conditions. These results are shown in Figure 28. In the before period, the total number of crashes in dry conditions (54.9%, 28 crashes) and wet conditions (45.1%, 23 crashes) were similar for the treatment ramp. On the control ramp, higher percentages of crashes in dry conditions were observed in the before period (76.2%, 16 crashes) than in the after period (56.5%, 13 crashes), although these differences are not statistically significant.

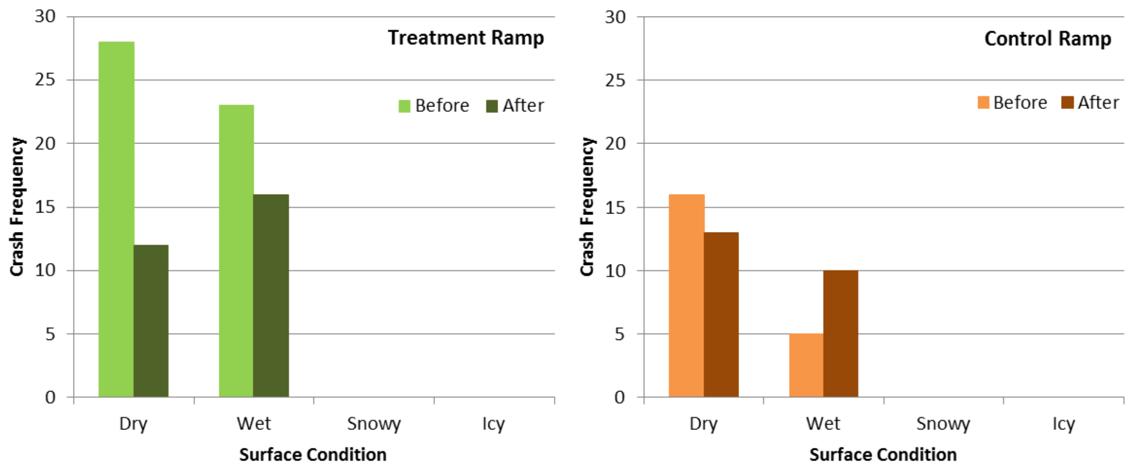


Figure 28 Crash Frequencies by Surface Conditions – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

Crashes were reduced for both wet and dry conditions on the treatment ramp after the installation of the chevron markings. Crashes in dry conditions were reduced to 12 (−57.1%) and crashes under wet conditions were reduced to 16 (−30.4%). This suggests that any crash reductions associated with the chevron markings are associated with both types of surface conditions.

Similar to the I-75/I-85 ramps, the high number of crashes in wet conditions on the treatment ramp suggests that this crash type was overrepresented in the sample. The percentage of crashes in wet conditions actually rose to 57.1% in the after period from 45.1%. As discussed previously, NOAA had recorded that only 8.6% of the total hours in the before period and 10.1% of the total hours in the after period had some trace of precipitation *(25)*. Since the percentage of crashes in wet surface conditions is higher than these rates, wet surface crash types are likely overrepresented in the sample of this interchange, as well.

4.2.6 Vehicle Type

Vehicle type was also considered in the study, as shown in Figure 29. On the treatment ramp, over 74% of vehicles involved in crashes in the before and after periods were passenger vehicles; between 14% and 19% were heavy vehicles, and the remaining are other vehicle types (e.g., motorcycles, etc.).

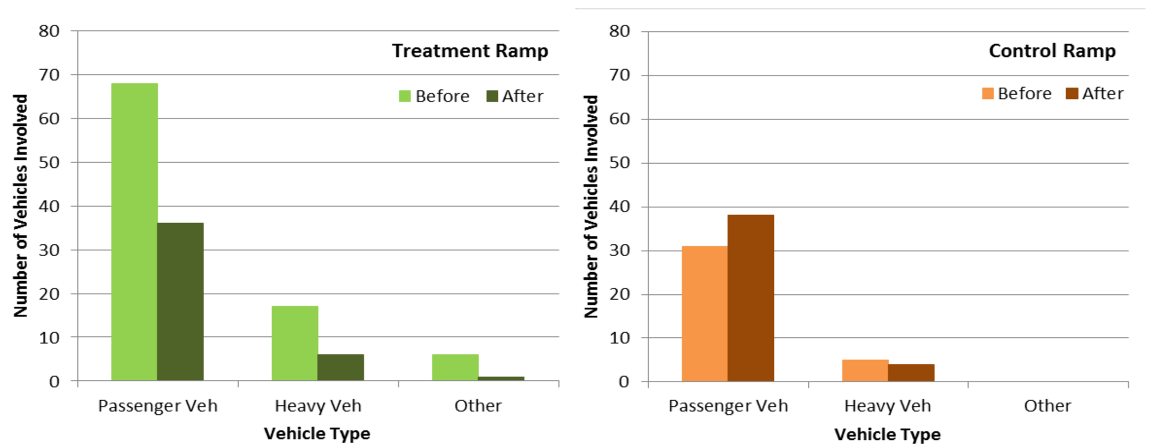


Figure 29 Frequencies of Vehicle Types Involved – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

This larger percentage of heavy vehicles indicates the presence of more heavy vehicles on I-285 than on I-75 or I-85 near the downtown connector. This is consistent with the restriction of heavy vehicles in the region inside of I-285 *(26)*. On the treatment ramp, passenger vehicles experienced a reduction of 47.1%, while heavy vehicles experienced a reduction of 64.7%. Meanwhile, the vehicle composition on the control ramp did not experience significant changes between the before and after periods. This suggests that the chevron markings are impacting both passenger vehicles and heavy vehicles in roughly equal proportion.

4.2.7 Driver Age

As shown in Figure 30, nearly all age groups on the treatment ramp appear to have experienced an average crash reduction of 61.0%. Similarly, on the control ramp, no clear trends are observed. While there are some exceptions due to small sample sizes, these findings suggest that any impacts associated with the chevron markings were not significantly impacted by driver age.

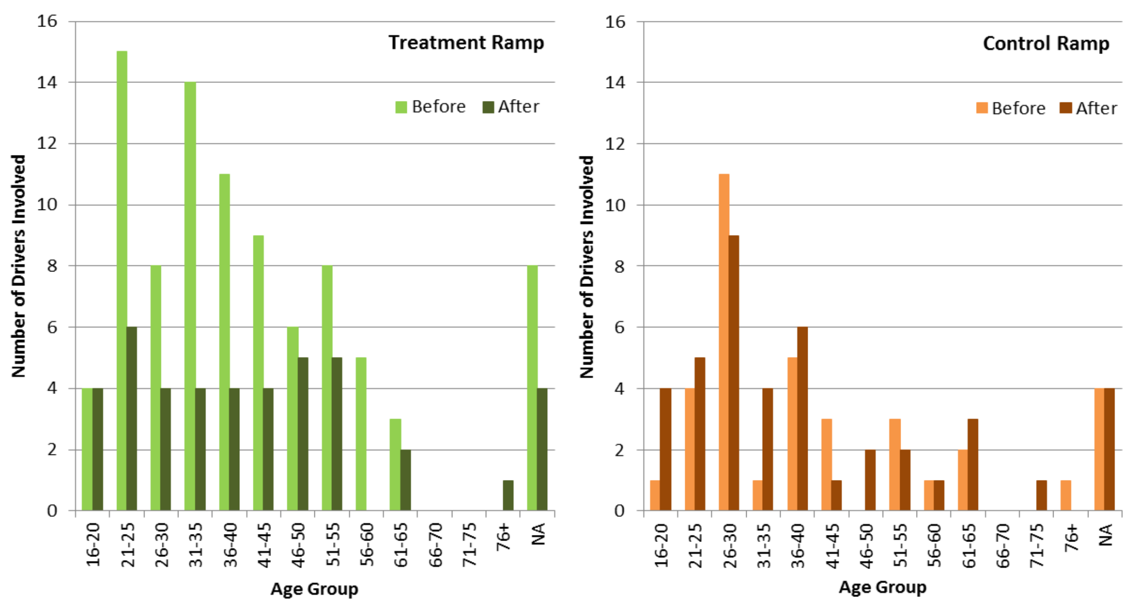


Figure 30 Frequencies of Drivers Involved by Age Group – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

4.2.8 Driver Gender

The frequency distributions of crash-involved drivers categorized by gender are shown in Figure 31. In terms of gender, in both the before and after periods, higher percentages of male drivers are seen on the treatment ramp crashes (64.8% and 74.4%, respectively). A similar trend is seen on the control ramp (69.4% male in the before period and 78.6% in the after period). After the installation of the chevron markings, both male and female drivers experienced large crash reductions. Male drivers experienced a reduction of −45.8% (27 crashes), while female drivers experienced a reduction of −65.6% (21 crashes). These reductions were not seen on the control ramp, as both female and male drivers experienced increases. This finding suggests the chevron markings were effective at reducing crashes for both male and female drivers.

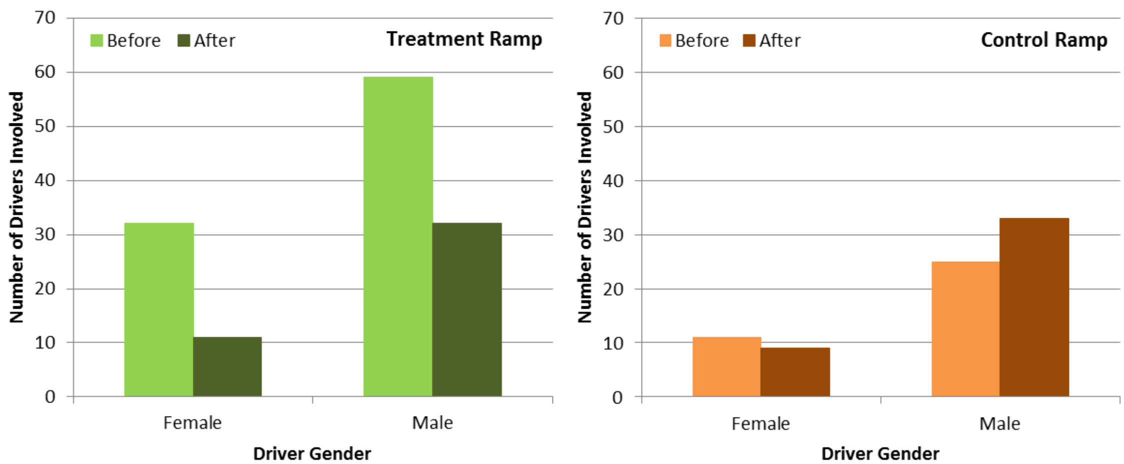


Figure 31 Frequencies of Drivers Involved by Gender – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

4.2.9 County of Vehicle Registration

As with the I-75/I-85 ramps, county of vehicle registration was used as a surrogate variable to measure the familiarity of drivers with the area. Familiarity with the area was defined as having a county of vehicle registration inside of the 13-county Atlanta metropolitan region, which includes the following counties: Cherokee, Clayton, Cobb, Coweta, DeKalb, Douglas, Fayette, Forsyth, Fulton, Gwinnett, Henry, Paulding, and Rockdale. It may be hypothesized that drivers residing within these counties would be exposed to this interchange and its surrounding areas more frequently and, thus, are less vulnerable to a crash resulting from an expectancy violation *(6)*. However, familiar drivers may have an increased likelihood of "driving with inattention" *(27–29)* with such a state having an increased likelihood of crash given the sudden sharp geometry.

As shown on Figure 32, the majority of drivers involved in crashes on the treatment ramp were from counties inside the 13-county area: 67.1% (61 out of 91 drivers) in the before period and 58.1% (25 out of 43 drivers) in the after period. Drivers who have their vehicles registered outside of the 13-county area are likely overrepresented in both periods: 24.2% in the before period and 34.9% in the after period. This is supported by a license plate study performed by Nelson et al. that examined the geographic and demographic profiles of commuters in Atlanta where a reported percentage of 10.5% of commuters were of counties outside of the 13-county area *(30)*. Similar percentages are seen on the control ramp for drivers from outside of the 13-county area (25.0% in the before and 33.3% in the after).

This finding suggests that both drivers familiar and unfamiliar with the area are vulnerable to crashes on the treatment ramp. However, significant assumptions are required to draw this conclusion, including the correlation of the county of vehicle registration with familiarity and whether or not the treatment ramp has a population distribution similar to stated demographic profiles. Currently, the data are insufficient to statistically differentiate the effect on familiar and unfamiliar drivers.

Nevertheless, large reductions were observed on the treatment ramp in the after period for both groups: drivers from within the 13-county area experienced a reduction of 59.0%, while drivers from outside the area experienced a reduction of 31.8%. These findings suggest that the chevron markings appear to be addressing both groups of drivers, although the impacts are more evident on drivers from inside the 13-county area in this situation.

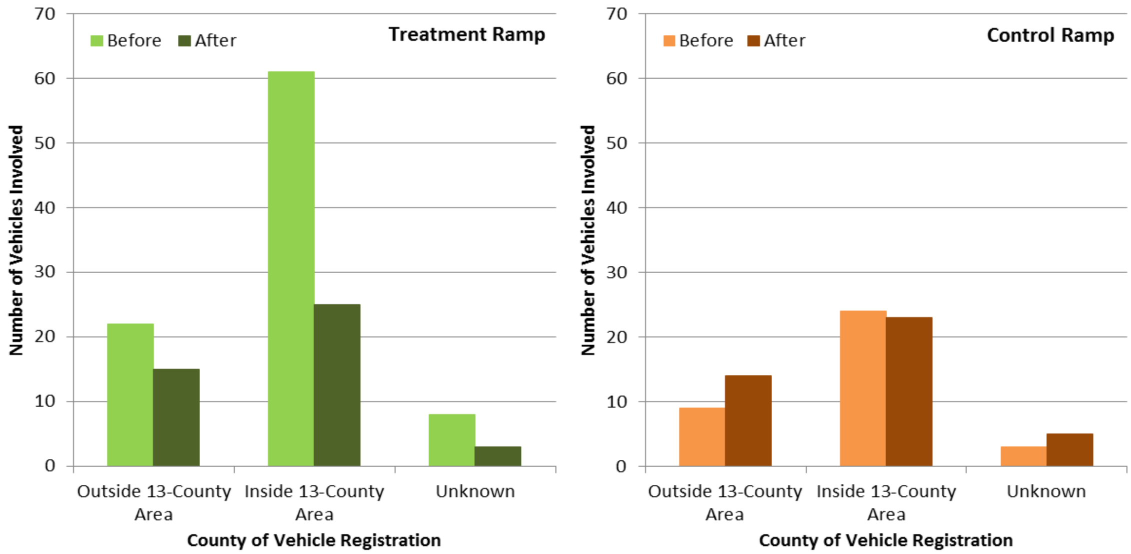


Figure 32 Frequencies of Vehicles Involved by County of Vehicle Registration – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

4.2.10 Crash Severity

To determine whether the chevron markings are impacting severity groups differently, the researchers also examined crash severity. As shown in Figure 33, most of the crashes that occurred on both the treatment and control ramps at this interchange were PDO crashes. On the treatment ramp, these crashes experienced a 46.7% reduction in observed crashes, while on the control ramp they remained relatively constant. Other severity types had very small sample sizes for both treatment and control ramps and no conclusive results can be drawn.

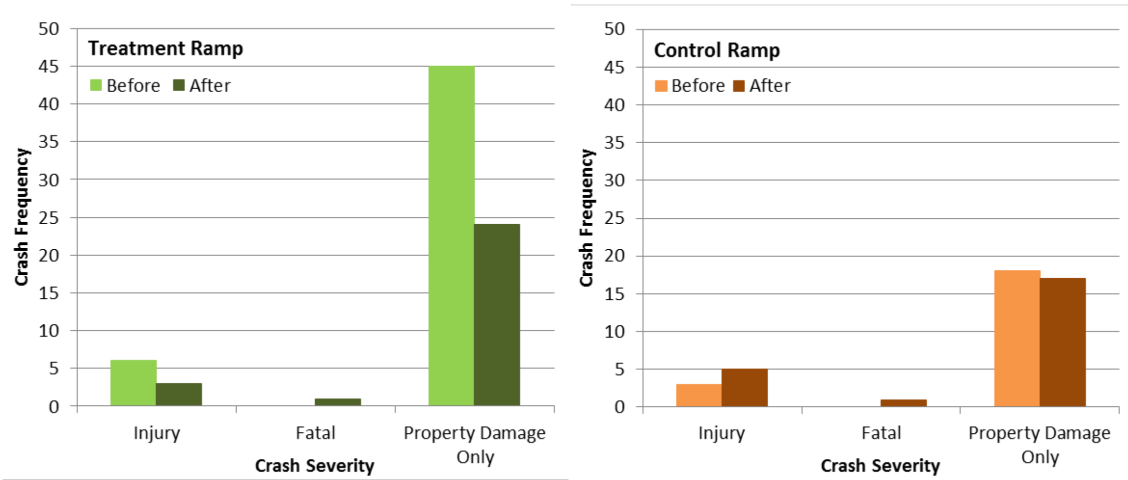


Figure 33 Crash Frequencies by Severity – I-285 EB to I-75 NB Ramp (Left) and I-75 SB to I-285 WB Ramp (Right)

5 Empirical Bayes Before–After Safety Evaluation

This chapter presents the findings of the empirical Bayes before–after safety evaluation. As discussed in the previous chapters, data for total crash frequencies are available for the two treatment sites and the remaining 41 control sites for the years 2007, 2008, and 2009. The chevron markings were installed between April 9, 2008, and April 15, 2008. Other available data include the before- and after-period traffic volumes, as well as roadway characteristic data. The comprehensive base dataset used in this evaluation procedure can be found in Appendix A.

As briefly discussed in Section 3.5, the empirical Bayes methodology involves the following steps:

1. Development of the safety performance function
2. Estimation of the before-period crash frequency for treatment sites
3. Estimation of the after-period crash frequency for treatment sites in the absence of the treatment
4. Estimation of the treatment effectiveness
5. Estimation of the precision of treatment effectiveness

Section 5.1 discusses the first step in the empirical Bayes methodology—the development of a *Safety Performance Function* (SPF). Section 5.2 discusses the remaining steps in the empirical Bayes methodology, arriving at the safety effectiveness of the treatment in terms of a *Crash Modification Factor* (CMF).

5.1 Development of a Base Safety Performance Function Model

The primary objective of the empirical Bayes methodology is to estimate the number of crashes that would have occurred at an individual treated ramp, or a group of treated ramps, in the after period had a treatment (i.e., the chevron markings) not been implemented. Based on this estimation, the effectiveness of the chevron markings can be estimated. Although there are several other methods that can be used to conduct a before–after safety evaluation, the advantage of the empirical Bayes approach is that it accounts for observed changes in crash frequencies before and after a treatment that may be due to regression to the mean as well as traffic volumes and time trends *(20, 31, 32)*.

In accounting for regression to the mean, the number of crashes expected in the before period without the treatment is estimated based on two pieces of information: (1) the number of observed crashes in the before period at the treatment sites, and (2) the number of predicted crashes at the treatment sites based on reference sites with similar traffic and physical characteristics. The first piece of information can be directly taken from the compiled crash data. The second piece of information involves developing a safety performance function that relates crash experience of the reference sites (i.e., the control group of ramps) to their traffic and physical characteristics *(20, 31, 32)*.

SPFs are regression equations that estimate the average crash frequency for a specific site type (with specified base conditions) as a function of traffic volume and roadway characteristics. They are generally based on the negative binomial distribution, which is better suited for modeling the high natural variability of crash data compared to the normal distribution *(20, 31, 32)*. The following is the general form of the SPF:

$$N_{SPF} = e^{(\alpha+\beta \ln(AADT))}$$

Where,

N_{SPF} – predicted average crash frequency
α, β – estimated by the negative binomial regression
$AADT$ – annual average daily traffic

The site type or base conditions for which the SPFs are developed must be homogeneous in nature. For this study, there are a number of homogeneous segments that can be modeled using an SPF, and they are categorized based on four roadway characteristics: ramp section, ramp condition, number of lanes, and radius. For definitions of these variables, refer to Section 3.2.3. These homogeneous segments are shown in Table 8.

Table 8 Specific Base Conditions Used in Generating SPFs

Model	Ramp Section	Ramp Condition	Number of Lanes	Radius
1	1 – approaching curve	0 – no merges/diverges	1	n/a
2	1 – approaching curve	0 – no merges/diverges	2	n/a
3	2 – on controlling curvature	0 – no merges/diverges	1	all
4	2 – on controlling curvature	0 – no merges/diverges	2	all
5	2 – on controlling curvature	0 – no merges/diverges	2	Low – less than 850 ft.
6	2 – on controlling curvature	0 – no merges/diverges	2	High – more than 850 ft.
7	2A – on controlling curvature after merge	Post merge/diverge	varies	all
8	3 – departing curve	0 – no merges/diverges	1	n/a
9	3 – departing curve	0 – no merges/diverges	2	n/a

From Table 8, the SPFs that are most applicable in evaluating the effectiveness of the chevron markings are model 2 and models 4 through 6. These models, and the results of the safety evaluation based on them, are discussed in this section. The remaining SPFs can be found in Appendix B.

5.1.1 Ramp Section 2 – Ramp Condition 0–2 Lanes

Models 4 through 6 are the most applicable SPFs in this safety evaluation of the chevron markings because they represent the ramp segment type where the treatment's impacts are most anticipated. This ramp segment type is of Ramp Section 2, which means these SPFs contain the controlling curvature of the ramp and the chevron markings are generally located prior to this section. In addition, much like the two treatment ramps, they are two-lane ramps and they do not experience any merges or diverges.

Six different SPFs were produced for the ramps. Researchers developed each SPF using a different data source or, more specifically, a different time interval and/or exclusion criterion from the Georgia Crash Information Database. These individual data sets were comprised of data from: (1) calendar year 2007 for all selected ramps, (2) calendar year 2008 including all ramps, (3) calendar year 2008 excluding treatment ramps, (4) calendar year 2009 excluding ramps, (5) the 12-month "before" period including treatment ramps, and (6) the 12-month "after" period excluding treatment ramps. Note that for the SPFs that cover the time period "before" the installation of the chevron markings (i.e., before April 9, 2008), treatment ramp data were included. Conversely, for the SPFs that cover the time period "after" the installation of the chevron markings (after April 15, 2008), treatment ramp data were excluded. These SPFs are shown in Figure 34.

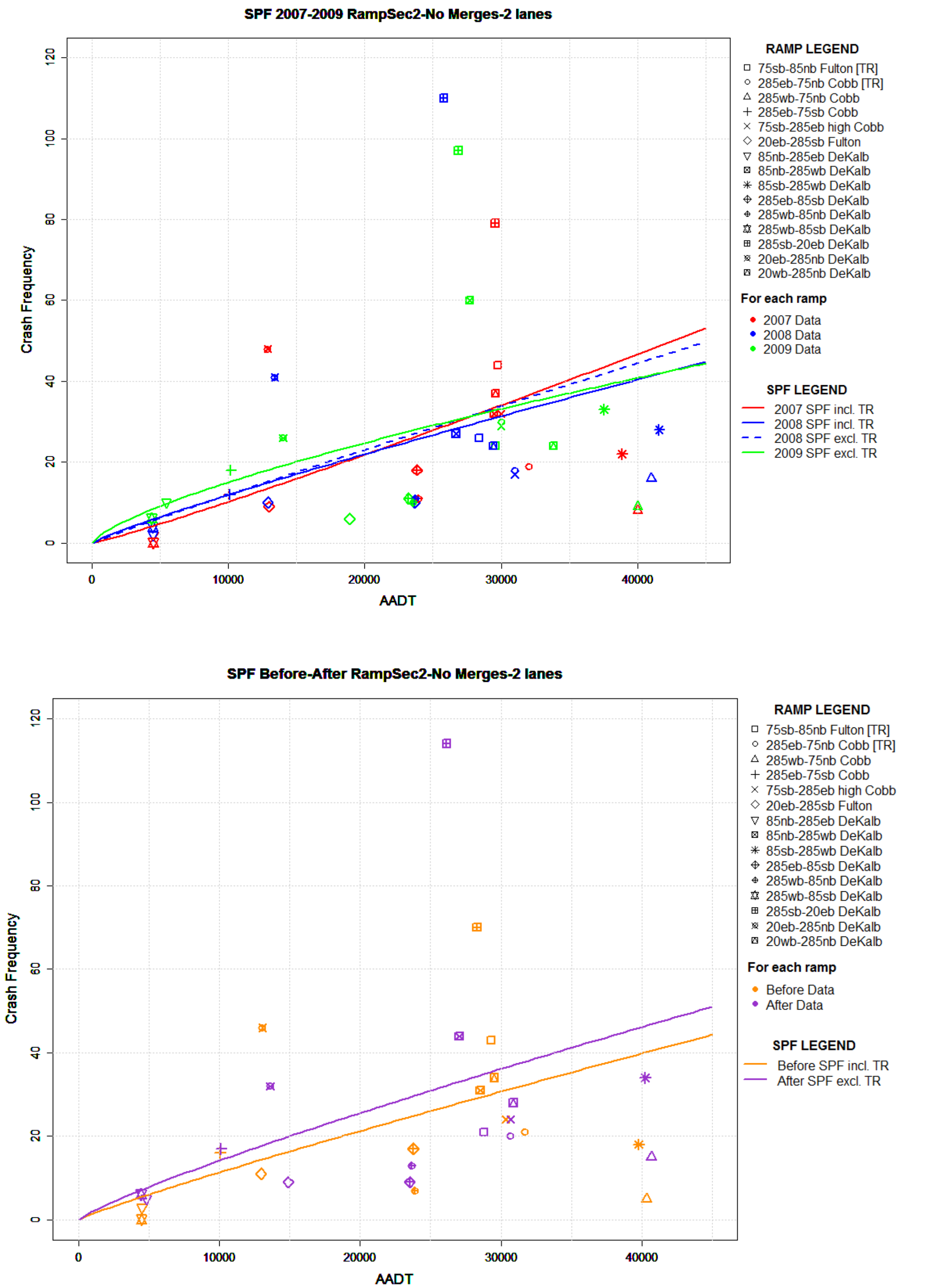
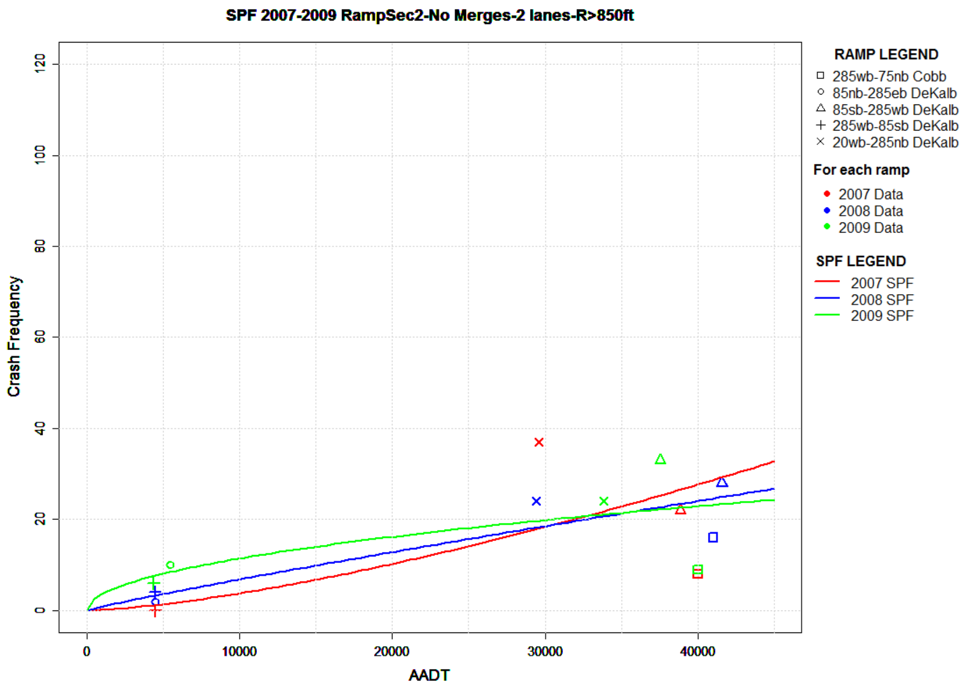


Figure 34 SPFs for Ramp Section 2 – Ramp Condition 0–2 Lanes (*Top* – 2007–2009, *Bottom* – Before–After)

As seen above, there is a general decreasing trend of crashes from 2007 to 2009, as well as from the "before" to "after" periods. In these SPFs, however, the radius of the ramp was not taken into account. Subsequently, a further disaggregation is made to group high-radius ramps separately from low-radius ramps. A high radius is defined as having a radius higher than 850 feet, while a low radius is defined as having a radius less than or equal to 850 feet. This value is based on the AASHTO "Green Book" *(33)* that suggests a minimum radius of 833 feet for a 50-mph roadway at a 6% superelevation rate. The resulting SPFs based on this distinction between radii are shown in Figure 35 and Figure 36 for the high- and low-radius ramps, respectively.



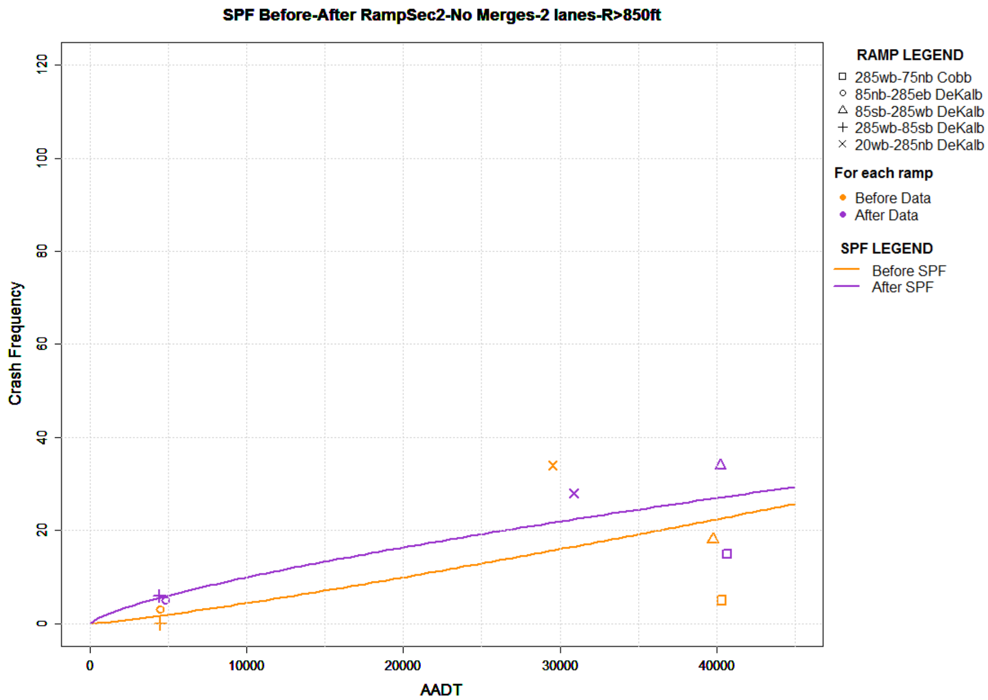


Figure 35 SPFs for Ramp Section 2 – Ramp Condition 0–2 Lanes – High Radius (*Top* – 2007–2009, *Bottom* – Before–After)

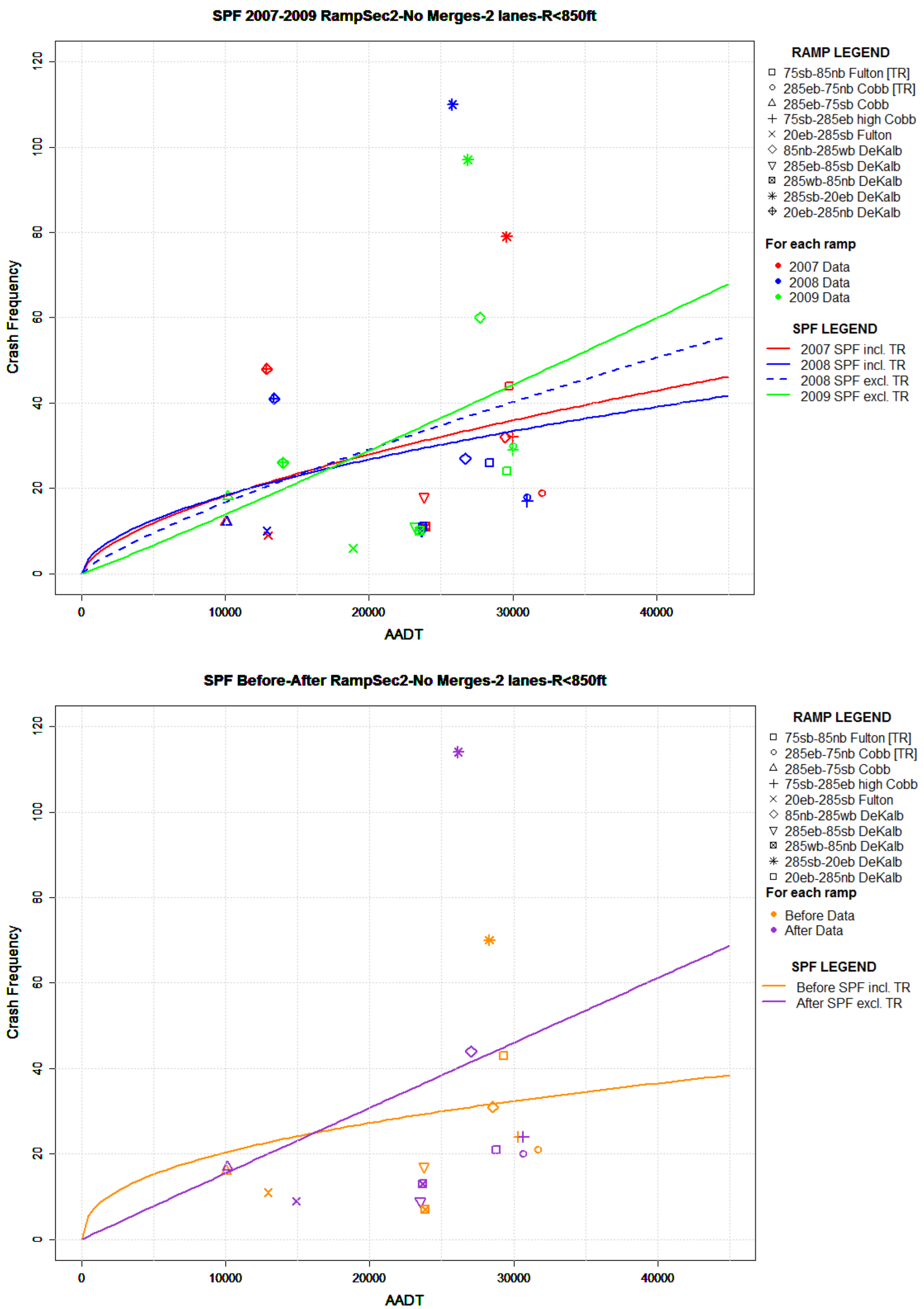
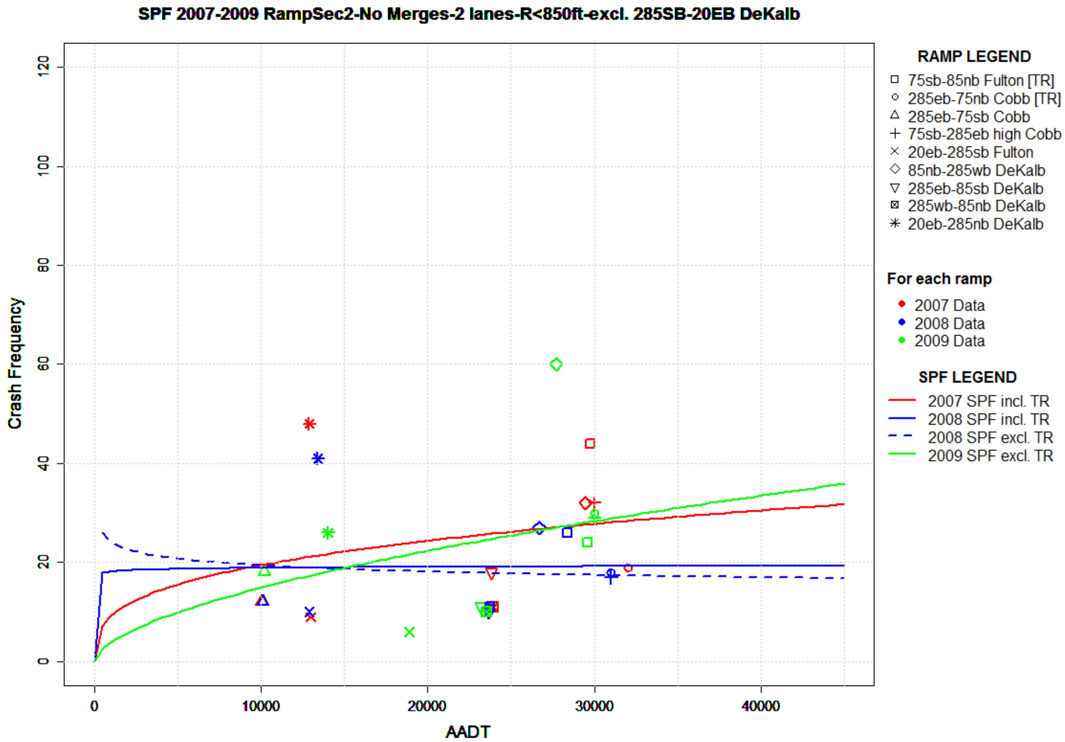


Figure 36 SPFs for Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius (*Top* – 2007–2009, *Bottom* – Before–After)

From Figure 35 and Figure 36, the crash experiences of high- and low-radius ramps are different. Moreover, the treatment ramps both fall under the low-radius ramp category, further supporting the disaggregation of the data. However, in further analyzing the low-radius SPFs, it is also clear that there are several high points that strongly influence the shape of the resulting curves.

In fact, these high points represent the data points of one specific ramp: the I-285 SB to I-20 EB ramp in DeKalb County. Treating these points as outliers, the remodeled SPFs are shown in Figure 37. It is not clear whether or not the points of I-285 SB to I-20 EB DeKalb County ramp should be treated as outliers or not. Rather, in this report both scenarios will be used in evaluating the safety effectiveness of the chevron markings. Additionally, referring back to Figure 34, it can also be argued that the high-radius and low-radius groups should not be treated separately. This is even more evident once the points from the I-285 SB to I-20 EB DeKalb County ramp are excluded (see Figure 38). Similarly, this report will also include this scenario in evaluating the treatment's safety effectiveness.



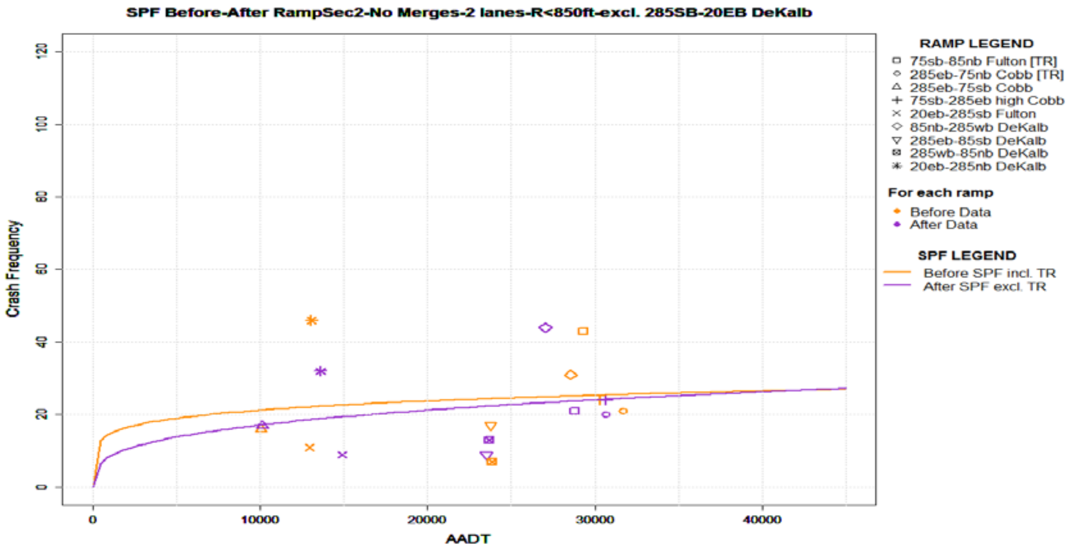


Figure 37 SPFs for Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius – Excluding I-285 SB to I-20 EB DeKalb (*Top* – 2007–2009, *Bottom* – Before–After)

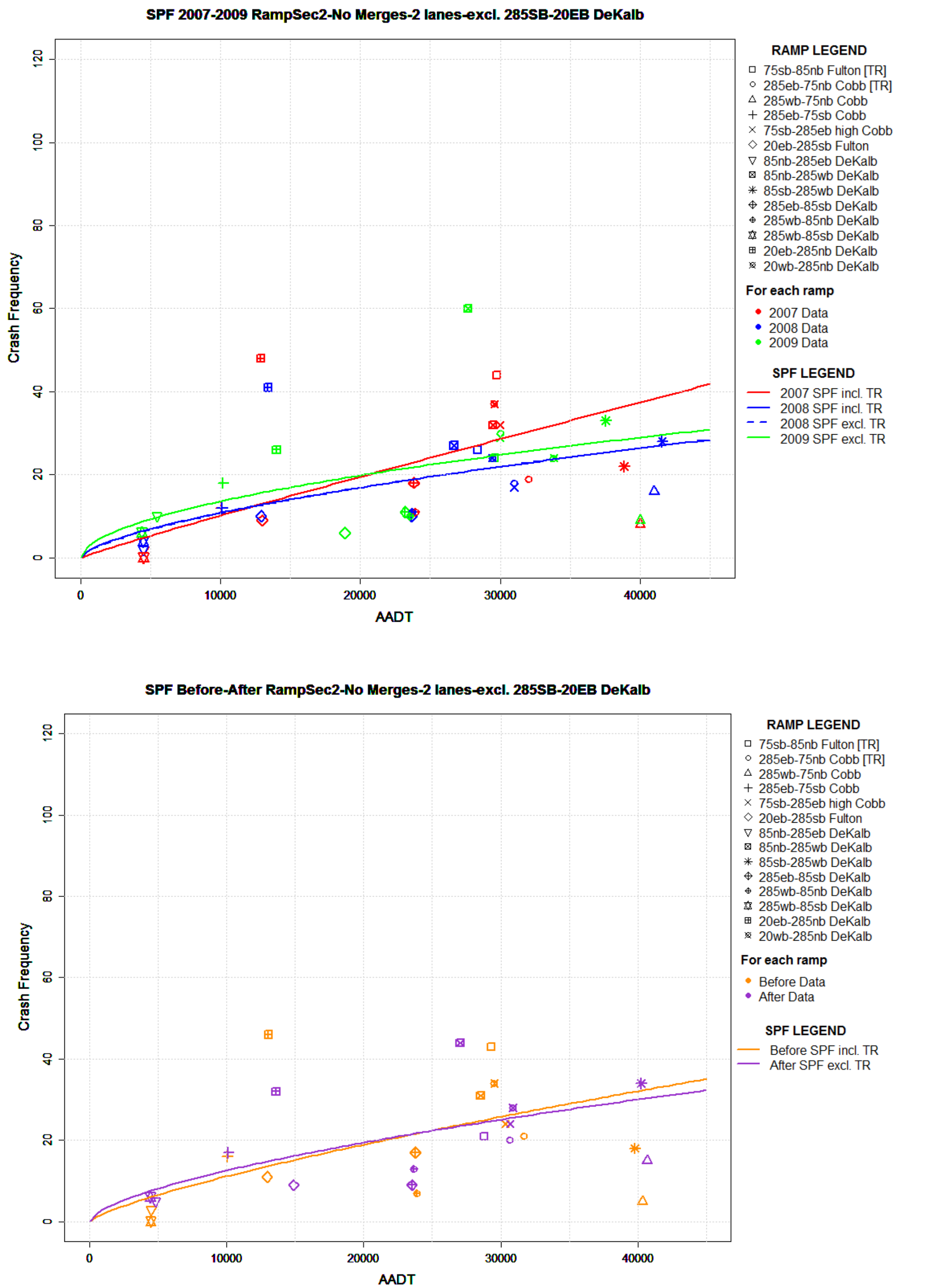


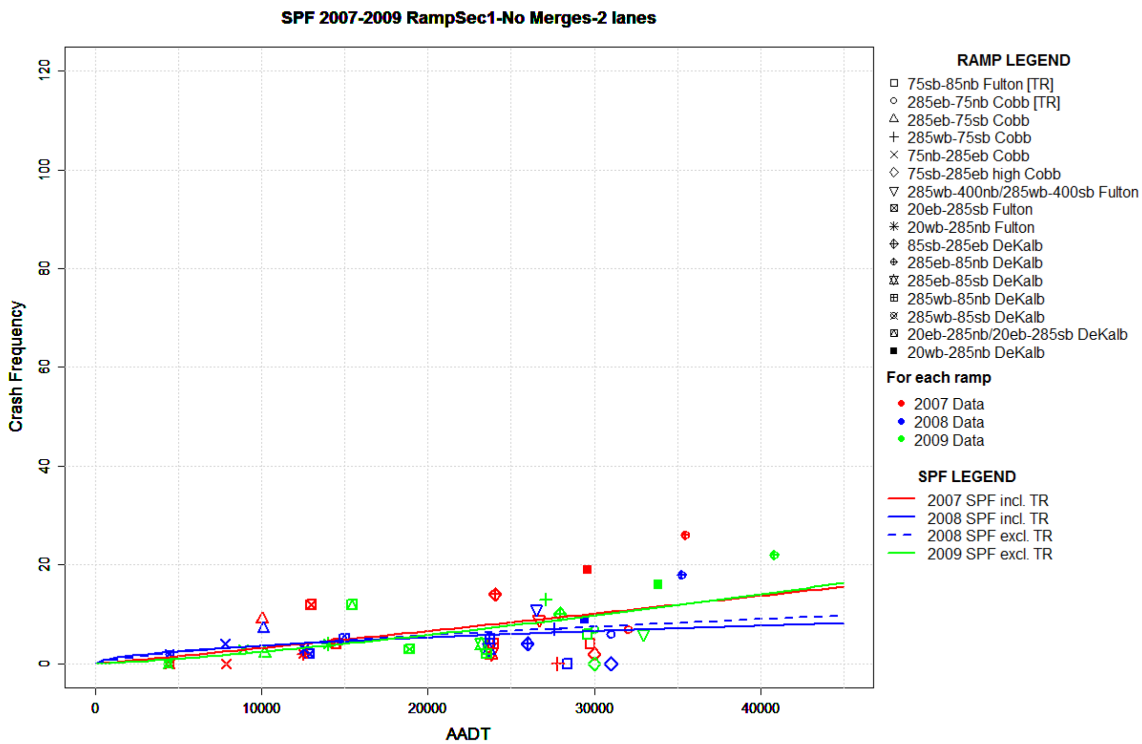
Figure 38 SPFs for Ramp Section 2 – Ramp Condition 0–2 Lanes – Excluding I-285 SB to I-20 EB DeKalb (*Top* – 2007–2008, *Bottom* – Before–After)

In summary, in evaluating the safety effectiveness of the chevron markings with respect to Ramp Section 2, the following three SPF scenarios will be used:

- Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius only
- Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius only (excluding I-285 SB to I-20 EB DeKalb County ramp)
- Ramp Section 2 – Ramp Condition 0–2 Lanes – Both High and Low Radius (excluding I-285 SB to I-20 EB DeKalb County ramp)

5.1.2 Ramp Section 1 – Ramp Condition 0–2 Lanes

Model 2 from Table 8 is also applicable in evaluating the safety effectiveness of the chevron markings. This segment type is of Ramp Section 1, which is the initial segment approaching the main body of the curve or where the chevron markings are located. Similar to the treatment ramps, this segment consists of two-lane ramps that do not experience any merges or diverges. As in Section 5.1.1, six different SPFs were generated for this base condition based on different data sources. These results are shown in Figure 39.



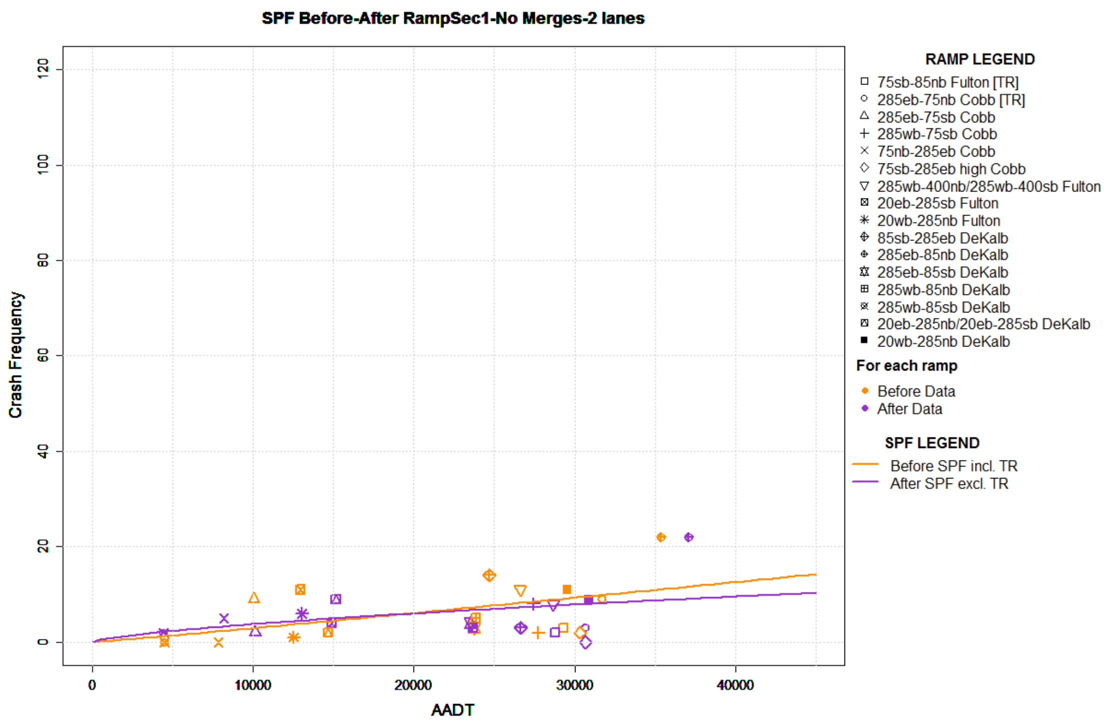


Figure 39 SPFs for Ramp Section 1 – Ramp Condition 0–2 Lanes (*Top* – 2007–2009, *Bottom* – Before–After)

5.2 Safety Effectiveness Evaluation

Once the base conditions have been selected and the base SPFs have been generated, researchers can estimate the safety effectiveness of the treatment. This estimation involves several steps, including estimation of the before-period crash frequency at the treatment sites using the SPFs, estimation of the after-period crash frequency of the treatment sites in the absence of the treatment using the SPFs, estimation of the treatment effectiveness, and estimation of the precision of the treatment effectiveness. A sample calculation of an SPF is provided in Appendix C. The discussion in the following sections focuses on the treatment effectiveness and its precision based on the different base conditions selected.

Treatment effectiveness is generally presented in the form of a crash modification factor. A CMF represents the relative change in crash frequency due to a change in one specific condition (when all other conditions and site characteristics remain constant). It is the ratio of the crash frequency of a site, or a group of sites, under two different conditions (in this case, before and after chevron installation). Therefore, it serves as an estimate of the effect of the treatment, or any particular geometric design or traffic control feature, in crash frequency *(20)*.

The values of CMFs are determined for a specific set of base conditions. Under the base conditions, the value of a CMF is 1.00. CMF values less than 1.00 indicate a reduction in the estimated crash frequency with the treatment in comparison to the base condition. CMF values greater than 1.00 indicate an increase in the estimated crash frequency with the treatment in comparison to the base condition. The relationship between a CMF and the expected percent change in crash frequency is: Percent in Crash Reduction = 100 × (1.00 − CMF).

The following sections discuss the estimated CMFs based on the SPFs developed for the selected base conditions. The results are presented in two manners: (1) a before–after evaluation using the specific 12-month “before” and “after” dates from Section 3.2.4, and (2) a before–after evaluation using data from calendar years 2007 and 2009 while discounting 2008 altogether. In addition to results for all crash severities, results are also presented for fatal-injury crashes only.

5.2.1 Ramp Section 2 – Ramp Condition 0–2 Lanes

All Crash Severities

The treatment effectiveness results estimated by using the 12-month “before” and “after” periods for the three Ramp Section 2 scenarios is presented in Table 9.

Table 10 presents the same estimates using calendar year 2007 and 2009 data. As shown in both tables, the CMFs are smaller (i.e., higher crash reduction) when accounting for only low-radius ramps and including the I-285 SB to I-20 EB DeKalb ramp. This is because the expected crash frequency in the after period in the absence of the treatment is higher than in the other two scenarios, which is due to the influence of the I-285 SB to I-20 EB DeKalb ramp on the SPF. The high crash frequencies on that ramp tend to overestimate the expected crash frequency of the treatment ramps in the after period. When that high crash ramp is excluded, the CMF for low-radius ramps becomes 0.689 when evaluating using before and after periods, indicating a 31.1% crash reduction potential. The 95% confidence interval of this CMF is from 0.428 to 0.949, or a potential crash reduction of between 5 and 57%. When evaluating using 2007 and 2009 data, the CMF becomes 0.850, indicating a 15.0% crash reduction potential. However, the upper limit of the 95% confidence interval of this CMF places it over 1.00, indicating a potential crash increase due to the treatment.

When using all ramps, regardless of radius, but excluding the I-285 SB to I-20 EB DeKalb ramp, the CMFs become 0.667 and 0.998, respectively, for the two evaluation methods. Again, the 95% confidence interval for the 2007 and 2009 evaluation indicates a potential crash increase due to the treatment instead of a reduction.

Table 9 Treatment Effectiveness for Ramp Section 2 – All Crash Severities – Before–After

Base Condition	Final CMF	Variance of CMF	Standard Error of CMF	95% Confidence Interval	
				Upper Limit	Lower Limit
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius	0.453	0.0077	0.0878	0.624	0.281
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius (excl. I-285 SB to I-20 EB DeKalb)	0.689	0.0177	0.1329	0.949	0.428
Ramp Section 2 – Ramp Condition 0–2 Lanes – All Radius (excl. I-285 SB to I-20 EB DeKalb)	0.667	0.0169	0.1300	0.921	0.412

Table 10 Treatment Effectiveness for Ramp Section 2 – All Crash Severities – 2007–2009

Base Condition	Final CMF	Variance of CMF	Standard Error of CMF	95% Confidence Interval	
				Upper Limit	Lower Limit
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius	0.691	0.0153	0.124	0.934	0.448
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius (excl. I-285 SB to I-20 EB DeKalb)	0.850	0.0229	0.151	1.147	0.553
Ramp Section 2 – Ramp Condition 0–2 Lanes – All Radius (excl. I-285 SB to I-20 EB DeKalb)	0.998	0.0323	0.180	1.350	0.646

Fatal/Injury-only Crashes

In terms of fatal/injury-only crashes, the treatment effectiveness for Ramp Section 2 when evaluating using the 12-month “before” and “after” periods is presented in Table 11.

Table 12 presents this treatment effectiveness when evaluating using calendar year 2007 and 2009 data. As shown, the CMFs range from 0.448 to 0.791, indicating a potential crash reduction of 20.9% to 55.2%, depending on the scenario of Ramp Section 2. However, each of these CMFs has a large 95% confidence interval, indicating imprecision. This is due to the small number of fatal/injury-only crashes on these ramps.

Table 11 Treatment Effectiveness for Ramp Section 2 – Fatal/Injury Crashes – Before–After

Base Condition	Final CMF	Variance of CMF	Standard Error of CMF	95% Confidence Interval	
				Upper Limit	Lower Limit
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius	0.448	0.03178	0.1783	0.797	0.098
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius (excl. I-285 SB to I-20 EB DeKalb)	0.711	0.07971	0.2823	1.264	0.157
Ramp Section 2 – Ramp Condition 0–2 Lanes – All Radius (excl. I-285 SB to I-20 EB DeKalb)	0.669	0.07179	0.2679	1.195	0.144

Table 12 Treatment Effectiveness for Ramp Section 2 – Fatal/Injury Crashes – 2007–2009

Base Condition	Final CMF	Variance of CMF	Standard Error of CMF	95% Confidence Interval	
				Upper Limit	Lower Limit
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius	0.659	0.04601	0.2145	1.079	0.238
Ramp Section 2 – Ramp Condition 0–2 Lanes – Low Radius (excl. I-285 SB to I-20 EB DeKalb)	0.768	0.06169	0.2484	1.255	0.281
Ramp Section 2 – Ramp Condition 0–2 Lanes – All Radius (excl. I-285 SB to I-20 EB DeKalb)	0.791	0.06654	0.2580	1.297	0.286

5.2.2 Ramp Section 1 – Ramp Condition 0–2 Lanes

Table 13 presents the treatment effectiveness for Ramp Section 1 considering all crash severities. When evaluated using calendar year 2007 and 2009 data, the chevron markings have an estimated CMF of 1.095 indicating a potential crash increase. However, its 95% confidence interval is very large, indicating a very imprecise estimation of the treatment's effectiveness. Meanwhile, when evaluating using the specified "before" and "after" periods, the chevron markings have a CMF of 0.438, indicating a potential crash reduction of 56.2%. Its 95% confidence interval is still fairly large, ranging from 0.023 to 0.853. However, even its upper limit of 0.853 still indicates a potential crash reduction of 14.7%. An analysis of fatal/injury-only crashes was not performed for this base condition due to small sample size.

Table 13 Treatment Effectiveness for Ramp Section 1 – All Crash Severities

Analysis Type	Final CMF	Variance of CMF	Standard Error of CMF	95% Confidence Interval	
				Upper Limit	Lower Limit
2007 vs. 2009	1.095	0.1576	0.397	1.873	0.317
Before vs. After	0.438	0.0449	0.212	0.853	0.023

6 Conclusions and Recommendations

The safety performance evaluation of the chevron pavement markings installed on two freeway-to-freeway ramps in Atlanta, Georgia, illustrates many of the challenges inherent in these types of analyses. These challenges range from selection of control sites to data quality assurance, as well as the fundamental limitations of analysis of relatively rare events, such as motor vehicle crashes.

In this study, the group of control ramps was selected based on ramps having similar traffic and physical (e.g., geometry and lane configuration) characteristics as the two treatment ramps. This was essential to ensure that there is a representative group of control for use as a reference group to account for regression-to-the-mean trends as well as traffic volume and time trends. Selection of these control ramps represents the first of many tradeoffs in the experimental design. Limiting the selection of the control ramps to those that are very similar to the treatment ramps ensures good comparability but also limits data availability and, thus, the statistical power of the analysis. Conversely, loosening the selection criteria improves statistical power but runs the risk of adding influences that impact the validity of the SPFs for the specific treatment ramps under evaluation.

In this study, researchers undertook a two-pronged approach. For analysis of the impact of demographic and similar data, only a single nearby control ramp was included to ensure that the fleets traversing the ramps were as similar as possible. Unfortunately, development of SPFs using such a limited number of locations would not provide the range of vehicle activity and exposure necessary to effectively develop the necessary regression model. To balance these constraints, the evaluation region was expanded to the central counties of the metropolitan Atlanta area. In this way, the fleets were likely to remain quite similar, but the analysis could incorporate a much wider range of similar freeway ramps. Using this approach, the team ultimately identified and obtained crash data for 43 freeway-to-freeway ramps for use in the SPF analysis.

The researchers explored various ways of extracting the crash data from the available GDOT crash database, but ultimately selected to obtain the data using road names and/or route numbers. Once data were extracted from the database, each incident underwent a thorough quality assurance process that verified the location of the incident through reviewing and reading the corresponding police reports. The quality assurance process was standardized to minimize error and ensure ease of transfer. The team found the examination of the individual police records was both effective and necessary to fully develop the data necessary to conduct these analyses.

Similarly, traffic volume data and roadway characteristic data were obtained and cross-checked through the use of multiple sources, including the GDOT Traffic Server, Atlanta Regional Commission projected volumes for 2015, and Google Earth®. As for the crash data, the team found that these additional quality assurance steps were essential in developing sufficiently precise data to ensure that the resulting analyses were both credible and as accurate as possible.

Once all the data were verified and compiled, they were then disaggregated into the different ramp sections and homogeneous roadway segments. This process was essential to ensure that appropriate SPFs can be developed based on the prepared dataset. With this comprehensive dataset, the team was able to conduct the crash attribute analysis as well as the safety effectiveness evaluation. Significant limitations exist due to the nature of crash data, but the methods used remained consistent throughout the study; hence, the findings of the analyses are expected to be as reliable as the underlying data will allow. Specific findings are presented by major topic in the following sections.

6.1 Overall Effectiveness of Chevron Markings

Regarding the overall effectiveness of the chevron markings, the research team made the following observations based on analysis of the above results:

- The chevron markings are effective for the curved portions of ramps (Ramp Section 2) when evaluated using the before and after periods, regardless of the type of base conditions selected. CMFs for this roadway segment range from 0.453 to 0.689. The lower limit of the 95% confidence interval ranges from 0.281 to 0.428 while the upper limit ranges from 0.624 to 0.949. This indicates that even in the least effective scenario, the treatment still has the potential to reduce crashes by 5.1%.

- When evaluated using calendar year 2007 vs. 2009 data, the chevron markings' effectiveness on Ramp Section 2 is less pronounced. The estimated CMFs are still below 1.00 regardless of the type of base conditions used. However, the upper limit of the 95% confidence intervals places some of these CMFs over 1.00, indicating a potential crash increase. The logic behind evaluating the treatment's effectiveness using calendar year 2007 and 2009 data only is that there appears to be an inherent difference between 2008 data and the data of the other years. It is also possible that the treatment had a more profound effect in 2008 immediately after installation, but its effect has decreased gradually, leading to similar crash frequencies in 2009 as there were in 2007.

- Analysis of fatal/injury-only crash frequency on Ramp Section 2 also showed improvements. The estimated CMFs range from 0.448 to 0.711 when evaluated using before and after periods, and 0.659 to 0.791 when evaluated using the calendar year 2007 and 2009 data. However, the upper limit of the 95% confidence intervals places nearly all of these CMFs over 1.00. The least of the lower limit is 0.098, indicating a large range of variation in these results that is due to the small sample size of such incidents.

- The chevron markings were found to be effective for the approaches to the ramp (Ramp Section 1), the ramp segment where the treatment would generally be installed, when evaluated using the before and after periods. The CMF is estimated to be 0.438 with a 95% confidence interval of 0.023 to 0.853. This is a large range of variation that is likely due to the small sample size in crashes on Ramp Section 1. When evaluated using calendar year 2007 and 2009 data, no tangible benefits were observed. Fatal/injury-only crashes were not evaluated for this ramp segment due to small sample size.

6.2 Crash Attribute Analysis

From the crash attribute analysis of the original treatment and control ramps at the interchange of I-75 and I-85 in Fulton County and the interchange of I-75 and I-285 in Cobb County, the following two statements are highly likely: (1) the treatment location represents an expectancy issue, with low-speed sharp curves on direction ramps connecting high-speed freeways; and (2) the chevron markings appear to have had a significant impact on safety performance, particularly for the I-75 SB to I-85 NB Ramp Section 2 and for the I-285 EB to I-75 NB Ramp Sections 2 and 2A. Furthermore, it does not appear that the chevron markings are addressing a given crash or driver/vehicle attribute more substantially than any other.

The researchers hypothesized that both drivers familiar and unfamiliar with the ramps were involved in crashes, with the majority of crashes being single-vehicle. Literature shows how an expectancy issue may increase the crash likelihood of unfamiliar drivers *(6)*. However, familiar drivers may have an increased likelihood of incidents as well due to "driving with inattention," or mentally being on "auto pilot" *(27–29)*. When driving in such a state, a rapid change, or need for significant input from the driver, may result in a hazardous situation.

While the provided analysis does not prove that the chevron markings address these unfamiliar/familiar driver issues, it does eliminate many other potential explanations, as no single attribute stands out. That is, incidents are reduced under both nighttime and daytime conditions, across the days of the week, under wet and dry conditions, and other attributes. In addition, a mechanism consistent with the given hypothesis may be supported by human factors. For instance, humans are single-channel processors and cannot properly attend to more than one item at a time, but they are capable of rapidly switching attention from one item to another in the driving environment *(6)*. Thus, the chevron markings may essentially serve to switch the familiar drivers from their state of inattention to attention, causing them to focus on the roadway ahead and allowing them to safely traverse the curve. Similarly, the chevron markings may alert the unfamiliar drivers to a potential hazard, allowing the drivers to evaluate the situation and take appropriate actions.

Underlying this discussion is an important attribute of the chevrons; that is, they provide no guidance to the driver on what, if any, action should be taken. It is likely that for a converging chevron treatment to be effective, once the driver is alerted, the required action must be clear and obvious, and the driver must be able to quickly evaluate the situation and take corrective action without further guidance. Interestingly, this chevron attribute may partially explain why the age group of 16- to 20-year-olds experienced minimal improvement in safety. That is, once alerted to a potential hazard, members of this age group are less experienced and less likely to correctly interpret the situation and select an appropriate action. Said another way, a converging chevron treatment would likely be ineffective, and potentially detrimental, if crashes are associated with complexity or confused interpretations of a location. The converging chevrons may only add to that complexity.

6.3 Future Data and Research

The biggest challenge associated with this safety evaluation of the chevron markings was related to the limitations of crash data available to the research team. Data from the Georgia crash databases were carefully assessed to identify those that could be considered reliable over the entire study period. Another big challenge in this evaluation was associated with the availability of only two treatment locations. Despite the uncertainties with the quality of data and the limited availability of treatment locations, the significant changes in crash frequency on both treatment locations indicate that additional research should be conducted.

- The discussion of the findings from the crash attribute analysis represent a potential interpretation of the mechanism by which chevron markings may work. Additional research is required to better understand this treatment and its potential use. This may involve the use of a driving simulator to test assumptions and behaviors, and/or detailed follow-up surveys with drivers involved in incidents on the treatment and other ramps. In addition, future research should explore the characteristics of the converging chevron design to understand, for example, whether the primary driver interaction mechanism is visual or tactile (i.e., the chevrons have a low-level rumble strip feel).

- Given the issues noted with the crash data, improvements and enhancements to the location information of the crash data should be made for future chevron markings performance studies as well as other safety studies. Research can be done to improve the current state of the crash data and enhance the integration of geographic information systems (GIS). The accuracy of coordinate data should also be improved, which could involve outreach initiatives toward police officers who collect these data firsthand and a more robust and efficient data quality assurance process.

- Given the problems noted with the limited number of treatment locations, future chevron markings performance studies should include the installation of the treatment on additional sites. Crash attribute analyses on the two treatment ramps indicate that there may be different crash mechanisms existing between them. Additional treatment sites should help in better understanding this treatment and its potential use. This should increase the robustness of the statistical analysis and improve the significance of the findings. As this study suggests, additional treatment sites should be selected at low-radius ramps where crashes are more prominent on the ramp segment containing the controlling curvature (i.e., Ramp Section 2).

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Appendix A: Ramp Summary Data Sheets

Site Data		
Interchange	I-75/I-85	
Interstate Numbers	I-75	I-85
State Route Numbers	GA 401	GA 403
City	Atlanta	
County	Fulton	
GDOT District	7	
Time Period of Data	Jan. 1st, 2007 – Dec. 31st, 2009	
Total Number of Months Included in Data	36	
Date of Chevron Markings Installation	April 9th, 2008 – April 14th, 2008	
Number of Ramps	2	

Interchange Incident Data by Year

	2007	2008	2009	Total
January	11	2	15	**28**
February	7	9	11	**27**
March	11	7	11	**29**
April	14	10	3	**27**
May[1]	7	8	7	**22**
June	6	2	2	**10**
July	14	6	7	**27**
August	7	4	6	**17**
September	7	3	21	**31**
October	9	8	15	**32**
November	17	13	11	**41**
December	12	10	11	**33**
Total	**122**	**82**	**120**	**324**

Source: Google Earth™, accessed 11/12/2014

Incident, Road Characteristic, and Traffic Volume Data by Ramp Section

Ramp Movement	Roadway Data				Crash & AADT Data									
	Ramp Section[2]	Ramp Condition[2]	Radius (feet)	No. of Lanes	Observed Crash Frequency by Year			AADT by Year			Observed Crash Freq. by Study Period		AADT by Study Period	
					2007	2008	2009	2007	2008	2009	Before	After	Before	After
75sb to 85nb [treatment]	1	0	--	2	4	0	6	29750	28390	29590	3	2	29297	28790
75sb to 85nb [treatment]	2	0	141	2	44	26	24	29750	28390	29590	43	21	29297	28790
75sb to 85nb [treatment]	3	0	--	2	3	0	0	29750	28390	29590	3	0	29297	28790
85sb to 75nb	1	0	--	1	17	6	5	21920	22820	26740	14	9	22220	24127
85sb to 75nb	2	0	305	1	42	45	81	21920	22820	26740	41	61	22220	24127
85sb to 75nb	3	0	--	1	12	5	4	21920	22820	26740	4	7	22220	24127
Totals					**122**	**82**	**120**				**108**	**100**		

[1]Excludes crashes that occurred during week of treatment installment
[2]See definitions of variables in Chapter 3

Site Data		
Interchange	I-75/I-285	
Interstate Numbers	I-75	I-285
State Route Numbers	GA 401	GA 407
City	Atlanta	
County	Cobb	
GDOT District	7	
Time Period of Data	Jan. 1st, 2007 – Dec. 31st, 2009	
Total Number of Months Included in Data	36	
Date of Chevron Markings Installation	April 9th, 2008 – April 14th, 2008	
Number of Ramps	9	

Source: Google Earth™, accessed 11/12/2014

Interchange Incident Data by Year				
	2007	**2008**	**2009**	**Total**
January	31	14	22	**67**
February	21	18	12	**51**
March	16	16	35	**67**
April	23	23	14	**60**
May[1]	12	18	17	**47**
June	12	10	15	**37**
July	30	9	21	**60**
August	11	15	24	**50**
September	18	7	47	**72**
October	27	18	16	**61**
November	19	26	8	**53**
December	39	24	15	**78**
Total	**259**	**198**	**246**	**703**

Incident, Road Characteristic, and Traffic Volume Data by Ramp Section

Ramp Movement	**Roadway Data**				**Crash & AADT Data**									
	Ramp Section[2]	**Ramp Condition**[2]	**Radius (ft.)**	**No. of Lanes**	**Observed Crash Frequency by Year**			**AADT by Year**			**Observed Crash Freq. by Study Period**		**AADT by Study Period**	
					2007	**2008**	**2009**	**2007**	**2008**	**2009**	**Before**	**After**	**Before**	**After**
285eb to 75nb [treatment]	1	0	--	2	7	6	7	32000	31000	30000	9	3	31667	30667
285eb to 75nb [treatment]	2	0	720	2	19	18	30	32000	31000	30000	21	20	31667	30667
285eb to 75nb / 285wb to 75nb [treatment]	2A	0	720	4	20	3	14	72000	72000	70000	18	5	72000	71333
285eb to 75nb / 285wb to 75nb [treatment]	3	0	--	4	3	0	2	69300	69300	67300	3	0	69300	68633
285wb to 75nb	1	0	--	3	21	3	6	67780	68620	67070	12	5	68060	68103
285wb to 75nb	2	0	1825	2	8	16	9	40000	41000	40000	5	15	40333	40667
285eb to 75sb	1	0	--	2	9	7	2	10029	10112	10196	9	2	10057	10140
285eb to 75sb	2	0	575	2	12	12	18	10029	10112	10196	16	17	10057	10140
285eb to 75sb / 285wb to 75sb	2A	1	600	3	8	1	5	20058	20224	20392	6	3	20113	20280

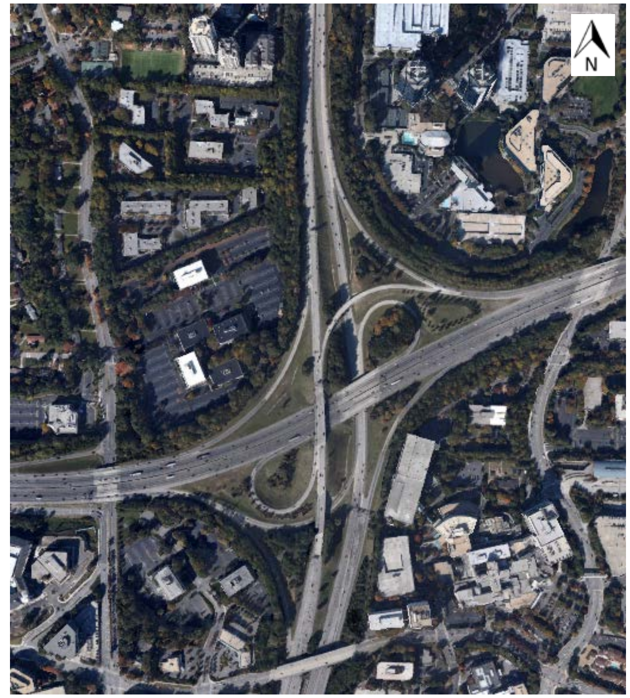
285eb to 75sb / 285wb to 75sb	3	1	--	2	4	3	1	15950	16080	16215	5	2	15993	16125
285wb to 75sb	1	0	--	2	0	7	13	27780	27620	27070	2	8	27727	27437
285wb to 75sb	2	2	600	2	35	34	43	10029	10112	10196	38	29	10057	10140
75nb to 285eb	1	0	--	2	0	4	3	7870	7820	8910	0	5	7853	8183
75nb to 285eb	2	3	920	2	10	18	22	11960	11890	13540	10	25	11937	12440
75nb to 285eb	2A	1	--	2	2	1	4	28790	28620	32030	2	2	28733	29757
75nb to 285eb	3	0	--	2	2	1	0	28790	28620	32030	3	0	28733	29757
75nb to 285wb	1	0	--	1	0	1	3	9720	9540	11150	0	2	9660	10077
75nb to 285wb	2	0	207	1	6	2	3	9720	9540	11150	6	2	9660	10077
75nb to 285wb	3	0	--	1	7	3	4	9720	9540	11150	6	3	9660	10077
75sb to 285eb low	1	0	--	1	1	1	1	9480	11230	10050	0	2	10063	10837
75sb to 285eb low	2	0	210	1	22	10	3	9480	11230	10050	18	12	10063	10837
75sb to 285eb low	3	0	--	1	3	3	6	9480	11230	10050	3	1	10063	10837
75sb to 285eb high	1	0	--	2	2	0	0	30000	31000	30000	2	0	30333	30667
75sb to 285eb high	2	0	590	2	32	17	29	30000	31000	30000	24	24	30333	30667
75sb to 285eb high	3	0	--	2	2	4	3	30000	31000	30000	5	1	30333	30667
75sb to 285wb	1	5	--	2	7	5	2	23581	22845	22108	6	5	23336	22599
75sb to 285wb	2	3	1050	2	13	10	8	6300	6260	6140	11	9	6287	6220
75sb to 285wb (after diverge/merge)	3	0	--	2	4	8	5	6300	6260	6140	4	9	6287	6220
Totals					**259**	**198**	**246**				**244**	**211**		

[1]Excludes crashes that occurred during week of treatment installment
[2]See definitions of variables in Chapter 3

Site Data		
Interchange	SR-400/I-285	
Interstate Numbers	--	I-285
State Route Numbers	GA 400	GA 407
City	Atlanta	
County	Fulton	
GDOT District	7	
Time Period of Data	Jan. 1st, 2007 – Dec. 31st, 2009	
Total Number of Months Included in Data	36	
Date of Chevron Markings Installation	n/a	
Number of Ramps	8	

Interchange Incident Data by Year

	2007	2008	2009	Total
January	8	8	6	**22**
February	10	4	5	**19**
March	8	15	2	**25**
April	5	5	5	**15**
May[1]	9	8	4	**21**
June	10	7	2	**19**
July	10	3	5	**18**
August	13	5	2	**20**
September	9	3	5	**17**
October	5	9	2	**16**
November	7	6	3	**16**
December	5	4	9	**18**
Total	**99**	**77**	**50**	**226**



Source: Google Earth™, accessed 11/12/2014

Incident, Road Characteristic, and Traffic Volume Data by Ramp Section

Ramp Movement	Roadway Data				Crash & AADT Data									
	Ramp Section[2]	Ramp Condition[2]	Radius (feet)	No. of Lanes	Observed Crash Frequency by Year			AADT by Year			Observed Crash Freq. by Study Period		AADT by Study Period	
					2007	2008	2009	2007	2008	2009	Before	After	Before	After
285eb to 400nb / 285eb to 400sb	1	0	--	1	4	8	6	30000	29830	30060	5	6	29943	29907
285eb to 400nb	2	0	485	1	2	4	3	25520	25370	26940	3	3	25470	25893
285eb to 400nb	3	0	--	1	3	5	2	25520	25370	26940	3	4	25470	25893
285eb to 400sb	2	0	795	1	0	0	0	7656	7611	8082	0	0	7641	7768
285eb to 400sb	3	0	--	1	0	0	0	7656	7611	8082	0	0	7641	7768
285wb to 400nb / 285wb to 400sb	1	0	--	2	9	11	6	26670	26520	32950	11	8	26620	28663
285wb to 400nb	2	0	1020	1	1	1	6	26160	26010	26060	2	1	26110	26027

285wb to 400nb	3	0	--	1	1	0	0	26160	26010	26060	1	0	26110	26027
285wb to 400sb	2	0	505	1	0	0	0	8090	8040	8040	0	0	8073	8040
285wb to 400sb	3	0	--	1	3	0	0	8090	8040	8040	2	0	8073	8040
400sb to 285wb	1	0	--	1	24	8	3	24020	23880	25900	25	5	23973	24553
400sb to 285wb	2	0	1070	1	4	1	1	24020	23880	25900	4	1	23973	24553
400sb to 285wb	3	0	--	1	2	1	1	24020	23880	25900	2	0	23973	24553
400sb to 285eb	1	0	--	1	29	23	9	23820	23680	23850	26	18	23773	23737
400sb to 285eb	2	0	165	1	6	6	7	23820	23680	23850	3	7	23773	23737
400sb to 285eb	3	0	--	1	1	1	2	23820	23680	23850	1	1	23773	23737
400nb to 285eb	1	0	--	1	2	1	2	9530	8680	8790	2	2	9247	8717
400nb to 285eb	2	0	880	1	1	1	0	9530	8680	8790	2	0	9247	8717
400nb to 285eb	3	0	--	1	4	0	0	9530	8680	8790	3	0	9247	8717
400nb to 285wb	1	0	--	1	0	2	0	6270	5170	5940	0	2	5903	5427
400nb to 285wb	2	0	171	1	3	1	2	6270	5170	5940	3	2	5903	5427
400nb to 285wb	3	0	--	1	0	3	0	6270	5170	5940	1	2	5903	5427
Totals						**99**		**77**	**50**		**99**	**62**		

[1]Excludes crashes that occurred during week of treatment installment
[2]See definitions of variables in Chapter 3

Site Data		
Interchange	I-20/I-285	
Interstate Numbers	I-20	I-285
State Route Numbers	GA 402	GA 407
City	Atlanta	
County	Fulton	
GDOT District	7	
Time Period of Data	Jan. 1st, 2007 – Dec. 31st, 2009	
Total Number of Months Included in Data	36	
Date of Chevron Markings Installation	n/a	
Number of Ramps	8	

Source: Google Earth™, accessed 11/12/2014

Interchange Incident Data by Year				
	2007	**2008**	**2009**	**Total**
January	12	7	9	**28**
February	8	10	5	**23**
March	11	8	7	**26**
April	7	5	5	**17**
May[1]	8	10	3	**21**
June	12	2	1	**15**
July	11	8	6	**25**
August	7	9	1	**17**
September	16	6	8	**30**
October	6	9	4	**19**
November	7	8	6	**21**
December	8	7	1	**16**
Total	**113**	**89**	**56**	**258**

Incident, Road Characteristic, and Traffic Volume Data by Ramp Section

Ramp Movement	**Roadway Data**				**Crash & AADT Data**									
	Ramp Section[2]	**Ramp Condition[2]**	**Radius (feet)**	**No. of Lanes**	**Observed Crash Frequency by Year**			**AADT by Year**			**Observed Crash Freq. by Study Period**		**AADT by Study Period**	
					2007	**2008**	**2009**	**2007**	**2008**	**2009**	**Before**	**After**	**Before**	**After**
285nb to 20wb	1	0	0	1	2	0	3	7400	7500	7600	0	0	7433	7533
285nb to 20wb	2	0	800	1	2	1	2	7400	7500	7600	2	2	7433	7533
285sb to 20wb	1	0	0	1	31	11	1	15000	16000	17000	23	9	15333	16333
285sb to 20wb	2	0	440	1	8	12	6	15000	16000	17000	11	10	15333	16333
285nb to 20wb / 285sb to 20wb	2A	0	0	2	3	12	7	22400	23500	24600	7	12	22767	23867
285nb to 20wb / 285sb to 20wb	3	1	0	2	8	3	3	22400	23500	24600	7	5	22767	23867
285sb to 20eb	1	0	0	1	3	1	1	12490	12550	14120	2	1	12510	13073
285sb to 20eb	2	0	1325	1	1	2	0	12490	12550	14120	1	1	12510	13073

285nb to 20eb	1	0	0	1	2	3	2	14090	14010	16840	1	3	14063	14953
285nb to 20eb	2	0	1000	1	1	3	1	14090	14010	16840	2	2	14063	14953
285sb to 20eb / 285nb to 20eb	2A	0	0	2	3	5	0	25440	25290	30300	6	2	25390	26960
285sb to 20eb / 285nb to 20eb	3	0	0	2	1	1	0	25440	25290	30300	0	1	25390	26960
20eb to 285sb	1	0	0	2	12	2	3	12990	12910	18890	11	4	12963	14903
20eb to 285sb	2	0	772	2	9	10	6	12990	12910	18890	11	9	12963	14903
20eb to 285sb	3	1	0	1	5	0	1	12990	12910	18890	2	1	12963	14903
20eb to 285nb	1	0	0	1	6	8	2	20700	20500	20980	8	6	20633	20660
20eb to 285nb	2	0	185	1	2	3	3	20700	20500	20980	3	1	20633	20660
20eb to 285nb	3	0	0	1	0	1	0	20700	20500	20980	0	1	20633	20660
20wb to 285nb	1	0	0	2	2	3	4	12500	12550	14000	1	6	12517	13033
20wb to 285nb	2	1	1545	1	4	3	1	12500	12550	14000	4	3	12517	13033
20wb to 285nb	3	0	0	1	1	1	5	12500	12550	14000	0	2	12517	13033
20wb to 285sb	1	0	0	1	5	3	2	10180	10120	11900	3	4	10160	10713
20wb to 285sb	2	5	1430	1	1	1	2	10180	10120	11900	1	2	10160	10713
20wb to 285sb	3	0	0	1	1	0	1	6787	6747	7933	0	1	6773	7142
Totals					**113**	**89**	**56**				**106**	**88**		

[1]Excludes crashes that occurred during week of treatment installment
[2]See definitions of variables in Chapter 3

Site Data		
Interchange	I-85/I-285	
Interstate Numbers	I-85	I-285
State Route Numbers	GA 403	GA 407
City	Atlanta	
County	DeKalb	
GDOT District	7	
Time Period of Data	Jan. 1st, 2007 – Dec. 31st, 2009	
Total Number of Months Included in Data	36	
Date of Chevron Markings Installation	n/a	
Number of Ramps	8	

Interchange Incident Data by Year				
	2007	**2008**	**2009**	**Total**
January	61	19	43	**123**
February	27	19	45	**91**
March	37	23	70	**130**
April	32	34	21	**87**
May[1]	25	6	47	**78**
June	21	18	15	**54**
July	41	22	21	**84**
August	18	35	32	**85**
September	15	12	47	**74**
October	32	38	59	**129**
November	36	79	32	**147**
December	55	55	38	**148**
Total	**400**	**360**	**470**	**1230**

Source: Google Earth™, accessed 11/12/2014

Incident, Road Characteristic, and Traffic Volume Data by Ramp Section

Ramp Movement	**Roadway Data**				**Crash & AADT Data**										
	Ramp Section[2]	**Ramp Condition**[2]	**Radius (feet)**	**No. of Lanes**	**Observed Crash Frequency by Year**			**AADT by Year**			**Observed Crash Freq. by Study Period**		**AADT by Study Period**	
					2007	**2008**	**2009**	**2007**	**2008**	**2009**	**Before**	**After**	**Before**	**After**
85nb to 285eb / 85nb to 285wb	1	0	0	3	8	7	7	35930	32560	33780	5	11	34807	32967
85nb to 285eb	2	0	1790	2	2	2	10	4518	4493	5468	3	5	4510	4818
85nb to 285eb / 85sb to 285eb	2A	5	0	4	5	7	5	30120	29950	36450	5	5	30063	32117
85nb to 285eb / 85sb to 285eb	3	1	0	2	13	5	12	23855	23720	28868	9	10	23810	25436
85nb to 285wb	2	0	747	2	32	27	60	29463	26699	27700	31	44	28541	27033
85nb to 285wb	3	0	0	3	3	9	4	68353	61942	64263	5	8	66216	62716
85sb to 285wb	1	5	0	2	35	12	26	50519	54041	48802	29	21	51693	52295
85sb to 285wb	2	0	1660	2	22	28	33	38861	41570	37540	18	34	39764	40227
85sb to 285wb	3	0	0	2	11	26	18	38861	41570	37540	10	31	39764	40227
85sb to 285eb	1	0	0	2	14	4	10	24040	25990	27940	14	3	24690	26640
85sb to 285eb	2	3	730	2	65	77	104	25602	25457	30982	63	94	25554	27299

285eb to 85nb (before merge)	1	0	0	2	26	18	22	35450	35240	40800	22	22	35380	37093
285eb to 85nb (after merge)	2	3	820	2	80	57	96	49985	49688	57528	60	77	49886	52302
285eb to 85nb	3	0	0	4	27	31	16	65980	65589	75937	19	31	65849	69038
285eb to 85sb	1	0	0	2	2	3	4	23820	23680	23210	3	4	23773	23523
285eb to 85sb	2	0	630	2	18	10	11	23820	23680	23210	17	9	23773	23523
285eb to 85sb	3	0	0	2	8	5	4	23820	23680	23210	6	6	23773	23523
285wb to 85nb	1	0	0	2	4	5	2	23928	23738	23550	5	3	23865	23676
285wb to 85nb	2	0	625	2	11	11	10	23928	23738	23550	7	13	23865	23676
285wb to 85nb	3	0	0	2	11	10	10	23928	23738	23550	10	13	23865	23676
285wb to 85sb (before merge)	1	0	0	2	0	2	0	4502	4476	4387	0	2	4493	4446
285wb to 85sb (before merge)	2	0	860	2	0	4	6	4502	4476	4387	0	6	4493	4446
285wb to 85sb (after merge)	3	3	0	2	3	0	0	13326	13248	12985	2	0	13300	13160
Totals					**400**	**360**	**470**				**343**	**452**		

[1]Excludes crashes that occurred during week of treatment installment
[2]See definitions of variables in Chapter 3

Site Data		
Interchange	I-20/I-285	
Interstate Numbers	I-20	I-285
State Route Numbers	GA 402	GA 407
City	Atlanta	
County	DeKalb	
GDOT District	7	
Time Period of Data	Jan. 1st, 2007 – Dec. 31st, 2009	
Total Number of Months Included in Data	36	
Date of Chevron Markings Installation	n/a	
Number of Ramps	8	

Source: Google Earth™, accessed 11/12/2014

Interchange Incident Data by Year

	2007	**2008**	**2009**	**Total**
January	56	18	31	**105**
February	22	17	14	**53**
March	27	14	26	**67**
April	23	20	17	**60**
May[1]	11	14	35	**60**
June	12	11	14	**37**
July	29	17	15	**61**
August	18	41	21	**80**
September	13	16	40	**69**
October	26	25	46	**97**
November	29	56	11	**96**
December	47	39	16	**102**
Total	**313**	**288**	**286**	**887**

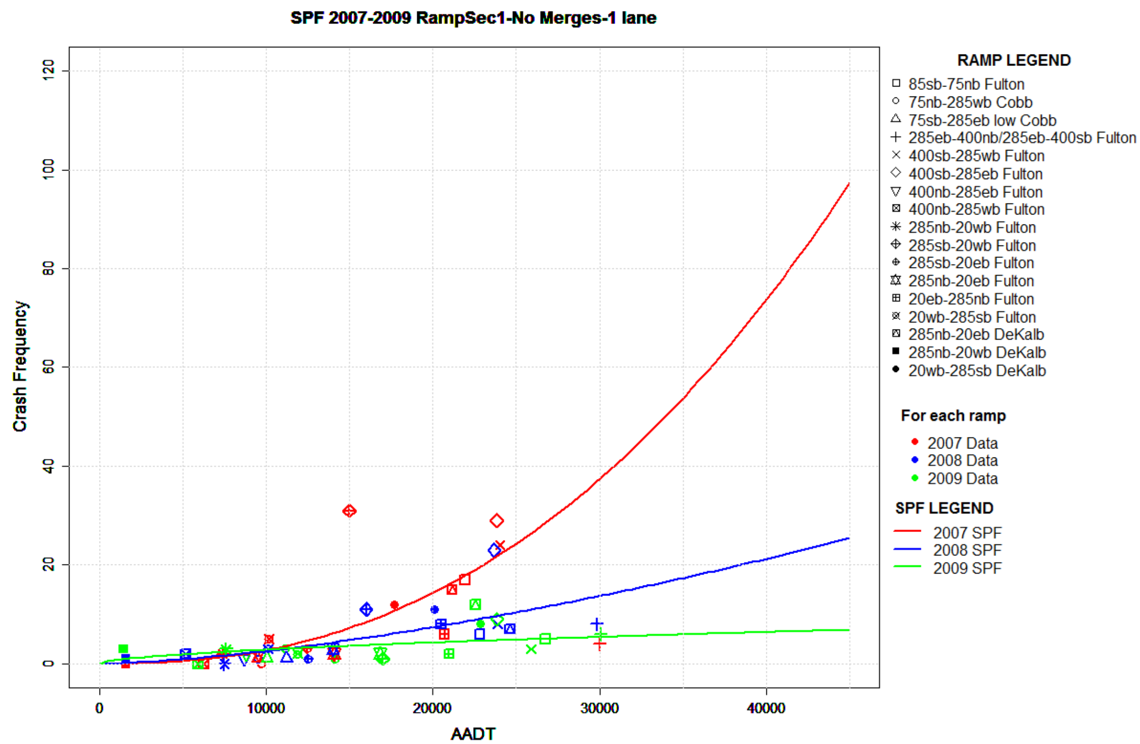
Incident, Road Characteristic, and Traffic Volume Data by Ramp Section

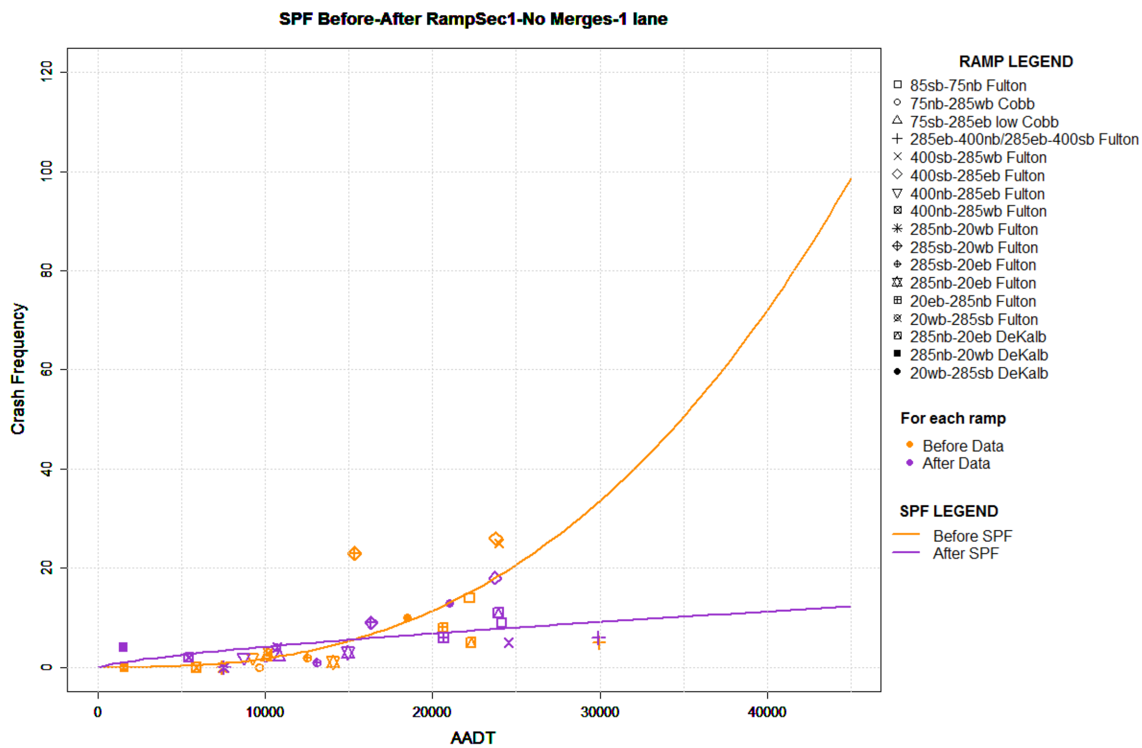
Ramp Movement	**Roadway Data**				**Crash & AADT Data**									
	Ramp Section[2]	**Ramp Condition**[2]	**Radius (feet)**	**No. of Lanes**	**Observed Crash Frequency by Year**			**AADT by Year**			**Observed Crash Freq. by Study Period**		**AADT by Study Period**	
					2007	**2008**	**2009**	**2007**	**2008**	**2009**	**Before**	**After**	**Before**	**After**
285nb to 20eb	1	0	0	1	15	7	12	21160	24640	22560	5	11	22320	23947
285nb to 20eb	2	0	1260	1	19	11	12	21160	24640	22560	14	13	22320	23947
285nb to 20eb / 285sb to 20eb	2A	0	1030	3	2	4	6	50720	50430	49420	1	5	50623	50093
285nb to 20eb / 285sb to 20eb	3	0	0	3	9	5	2	50720	50430	49420	6	4	50623	50093
285sb to 20eb / 285sb to 20wb	1	0	0	3	12	8	13	46610	42740	42630	5	13	45320	42703
285sb to 20eb	2	0	450	2	79	110	97	29560	25790	26860	70	114	28303	26147
285sb to 20wb	2	1	1040	2	13	8	8	17050	16950	15770	8	11	17017	16557
285sb to 20wb	3	0	0	1	2	0	1	17050	16950	15770	2	0	17017	16557
285nb to 20wb	1	0	0	1	0	1	3	1610	1600	1450	0	4	1607	1550
285nb to 20wb	2	0	148	1	1	0	2	1610	1600	1450	1	2	1607	1550
285nb to 20wb	3	0	0	1	0	1	1	1610	1600	1450	1	1	1607	1550

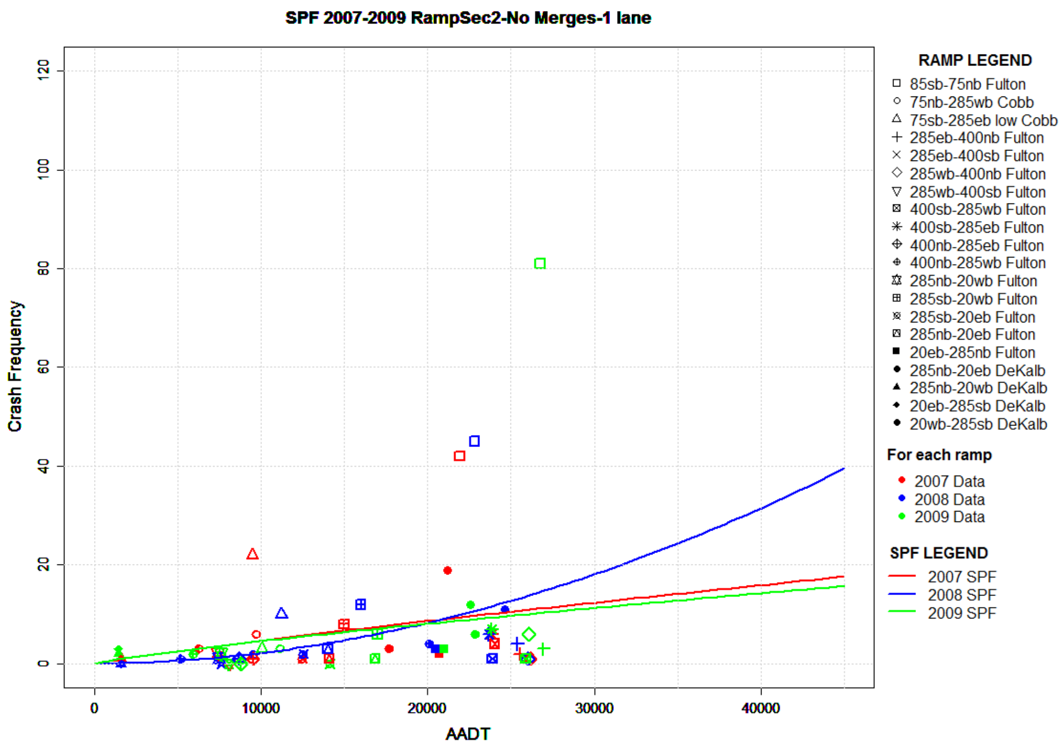
20eb to 285nb / 20eb to 285sb	1	0	0	2	4	5	12	14500	15000	15460	2	9	14667	15153
20eb to 285nb	2	0	780	2	48	41	26	12890	13400	14010	46	32	13060	13603
20eb to 285nb / 20wb to 285nb	2A	0	0	4	13	16	11	42480	42820	47843	15	12	42593	44494
20eb to 285nb / 20wb to 285nb	3	0	0	4	22	17	21	42480	42820	47843	19	19	42593	44494
20eb to 285sb	2	0	680	1	1	0	3	1610	1600	1450	1	0	1607	1550
20eb to 285sb (After merge)	2A	3	0	1	0	1	0	24710	24570	24080	1	0	24663	24407
20eb to 285sb (After merge)	3	0	0	1	1	2	1	24710	24570	24080	0	2	24663	24407
20wb to 285nb	1	0	0	2	19	9	16	29590	29420	33833	11	9	29533	30891
20wb to 285nb	2	0	1005	2	37	24	24	29590	29420	33833	34	28	29533	30891
20wb to 285sb	1	0	0	1	12	11	8	17687	20099	22840	10	13	18491	21013
20wb to 285sb	2	0	220	1	3	4	6	17687	20099	22840	2	5	18491	21013
20wb to 285sb	3	0	0	1	1	2	1	17687	20099	22840	1	2	18491	21013
Totals					**313**	**287**	**286**				**255**	**309**		

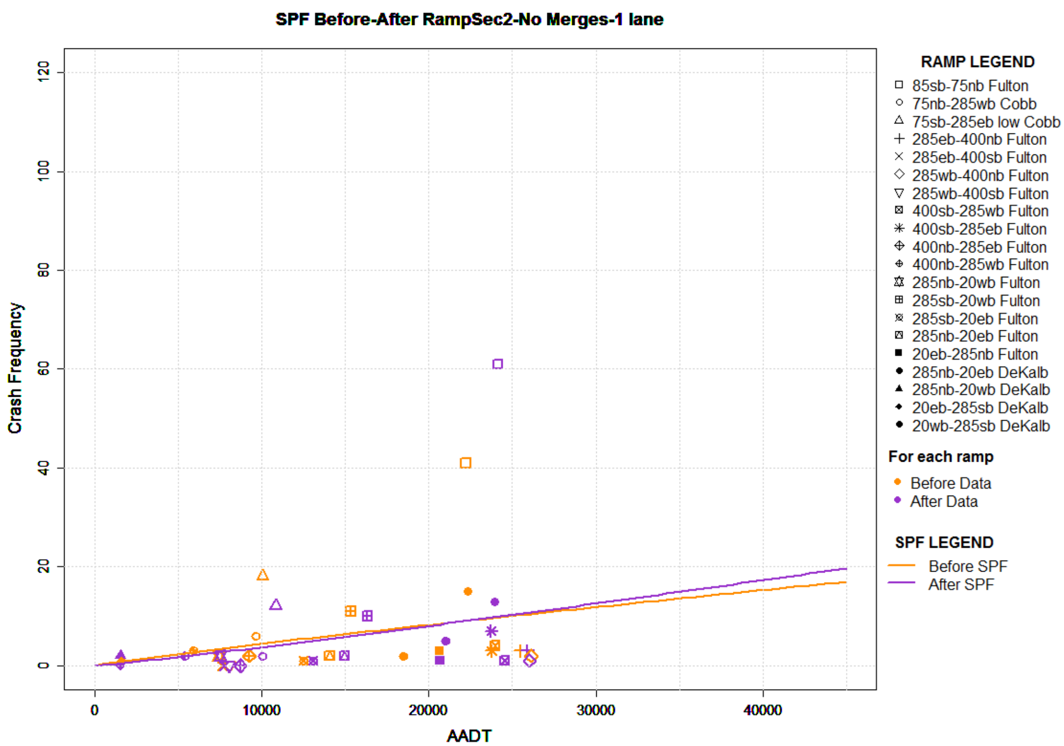
[1]Excludes crashes that occurred during week of treatment installment
[2]See definitions of variables in Chapter 3

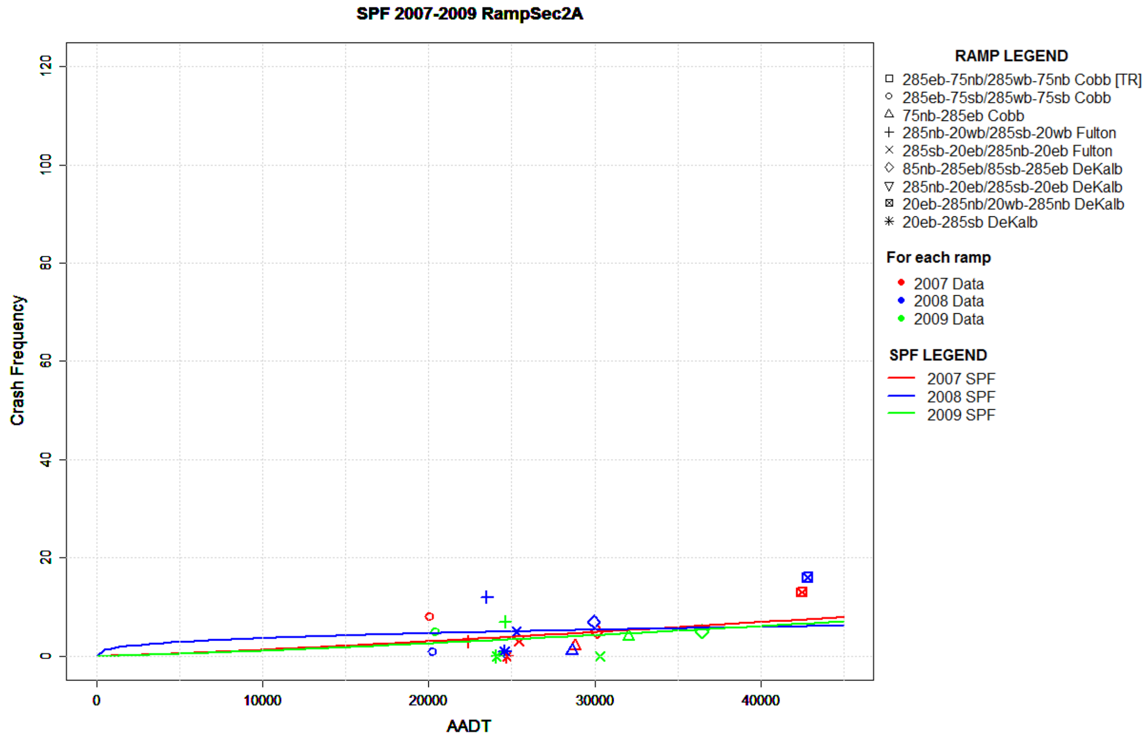
Appendix B: Additional SPFs Generated

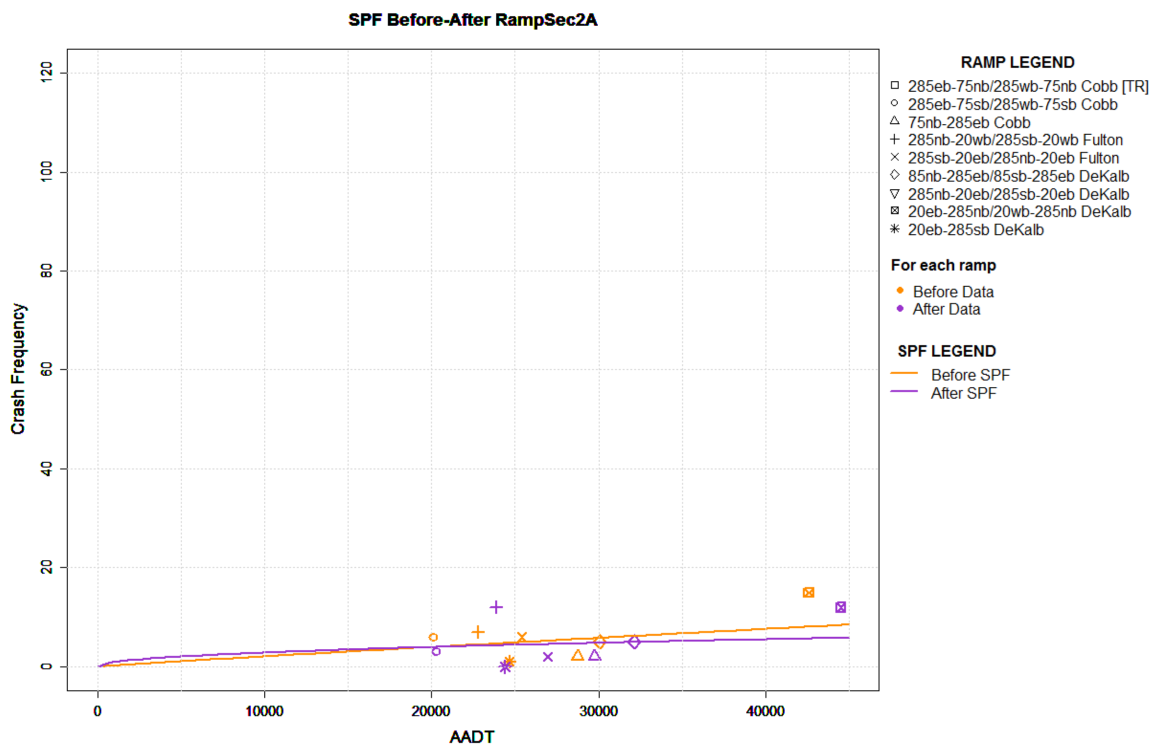

SPF 2007-2009 RampSec1-No Merges-1 lane
Crash Frequency
AADT
0
10000
20000
30000
40000
0
20
40
60
80
100
120
RAMP LEGEND
85sb-75nb Fulton
75nb-285wb Cobb
75sb-285eb low Cobb
285eb-400nb/285eb-400sb Fulton
400sb-285wb Fulton
400sb-285eb Fulton
400nb-285eb Fulton
400nb-285wb Fulton
285nb-20wb Fulton
285sb-20wb Fulton
285sb-20eb Fulton
285nb-20eb Fulton
20eb-285nb Fulton
20wb-285sb Fulton
285nb-20eb DeKalb
285nb-20wb DeKalb
20wb-285sb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF
2008 SPF
2009 SPF

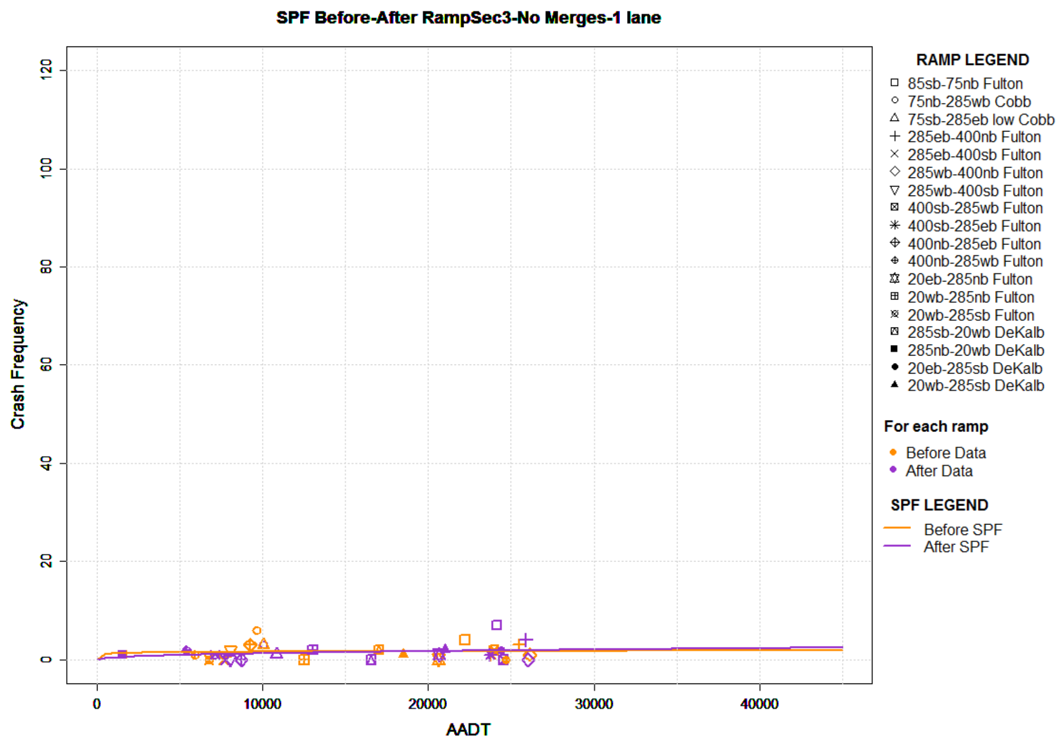

SPF Before-After RampSec1-No Merges-1 lane
Crash Frequency
AADT
0
10000
20000
30000
40000
0
20
40
60
80
100
120
RAMP LEGEND
85sb-75nb Fulton
75nb-285wb Cobb
75sb-285eb low Cobb
285eb-400nb/285eb-400sb Fulton
400sb-285wb Fulton
400sb-285eb Fulton
400nb-285eb Fulton
400nb-285wb Fulton
285nb-20wb Fulton
285sb-20wb Fulton
285sb-20eb Fulton
285nb-20eb Fulton
20eb-285nb Fulton
20wb-285sb Fulton
285nb-20eb DeKalb
285nb-20wb DeKalb
20wb-285sb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF
After SPF


SPF 2007-2009 RampSec2-No Merges-1 lane
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
85sb-75nb Fulton
75nb-285wb Cobb
75sb-285eb low Cobb
285eb-400nb Fulton
285eb-400sb Fulton
285wb-400nb Fulton
285wb-400sb Fulton
400sb-285wb Fulton
400sb-285eb Fulton
400nb-285eb Fulton
400nb-285wb Fulton
285nb-20wb Fulton
285sb-20wb Fulton
285sb-20eb Fulton
285nb-20eb Fulton
20eb-285nb Fulton
285nb-20eb DeKalb
285nb-20wb DeKalb
20eb-285sb DeKalb
20wb-285sb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF
2008 SPF
2009 SPF

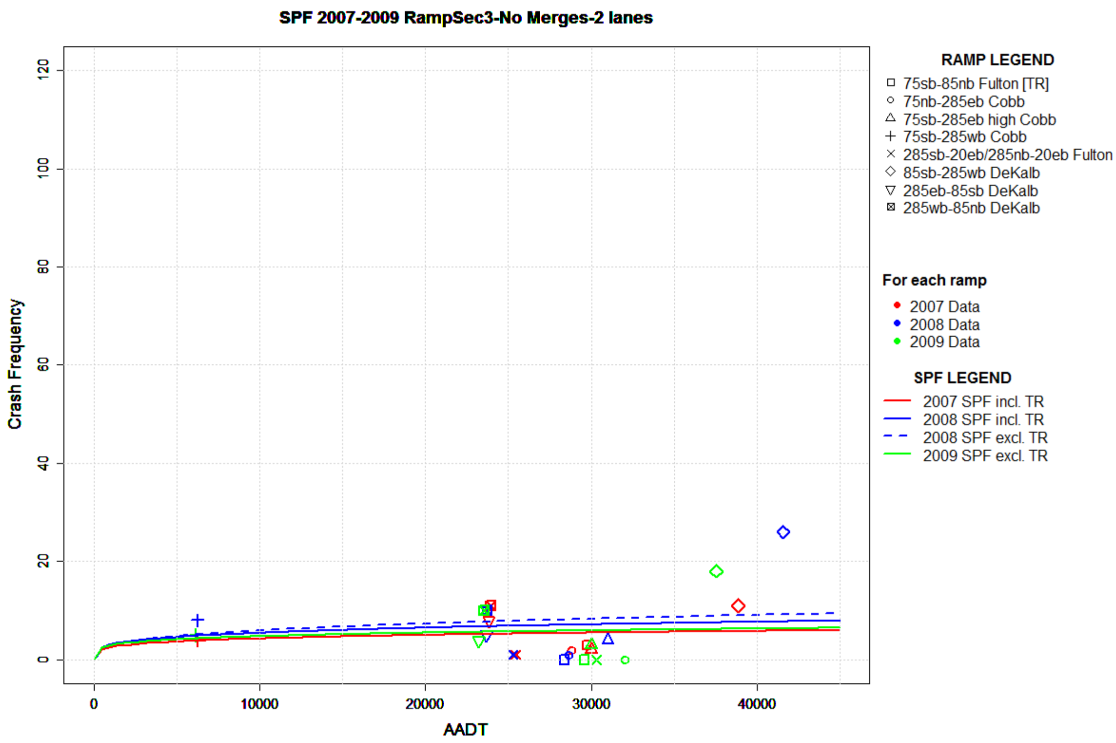

SPF Before-After RampSec2-No Merges-1 lane
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
85sb-75nb Fulton
75nb-285wb Cobb
75sb-285eb low Cobb
285eb-400nb Fulton
285eb-400sb Fulton
285wb-400nb Fulton
285wb-400sb Fulton
400sb-285wb Fulton
400sb-285eb Fulton
400nb-285eb Fulton
400nb-285wb Fulton
285nb-20wb Fulton
285sb-20wb Fulton
285sb-20eb Fulton
285nb-20eb Fulton
20eb-285nb Fulton
285nb-20eb DeKalb
285nb-20wb DeKalb
20eb-285sb DeKalb
20wb-285sb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF
After SPF

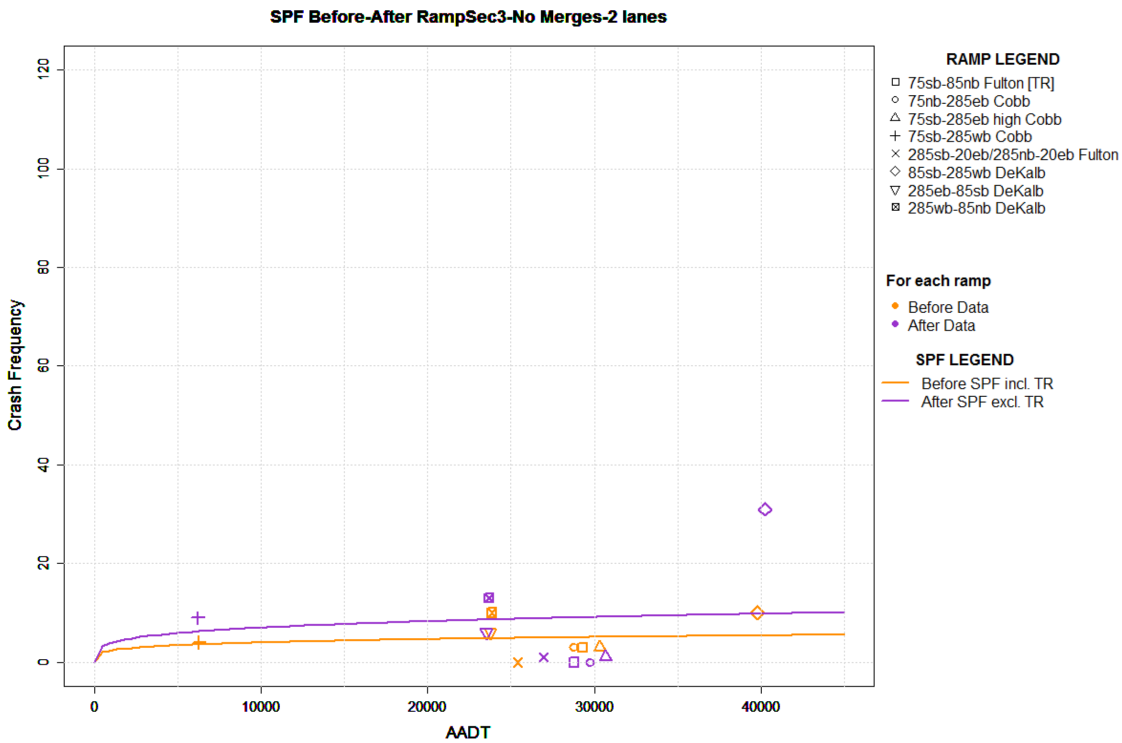

SPF 2007-2009 RampSec2A
Crash Frequency
AADT
RAMP LEGEND
285eb-75nb/285wb-75nb Cobb [TR]
285eb-75sb/285wb-75sb Cobb
75nb-285eb Cobb
285nb-20wb/285sb-20wb Fulton
285sb-20eb/285nb-20eb Fulton
85nb-285eb/85sb-285eb DeKalb
285nb-20eb/285sb-20eb DeKalb
20eb-285nb/20wb-285nb DeKalb
20eb-285sb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF
2008 SPF
2009 SPF


SPF Before-After RampSec2A
Crash Frequency
AADT
RAMP LEGEND
285eb-75nb/285wb-75nb Cobb [TR]
285eb-75sb/285wb-75sb Cobb
75nb-285eb Cobb
285nb-20wb/285sb-20wb Fulton
285sb-20eb/285nb-20eb Fulton
85nb-285eb/85sb-285eb DeKalb
285nb-20eb/285sb-20eb DeKalb
20eb-285nb/20wb-285nb DeKalb
20eb-285sb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF
After SPF

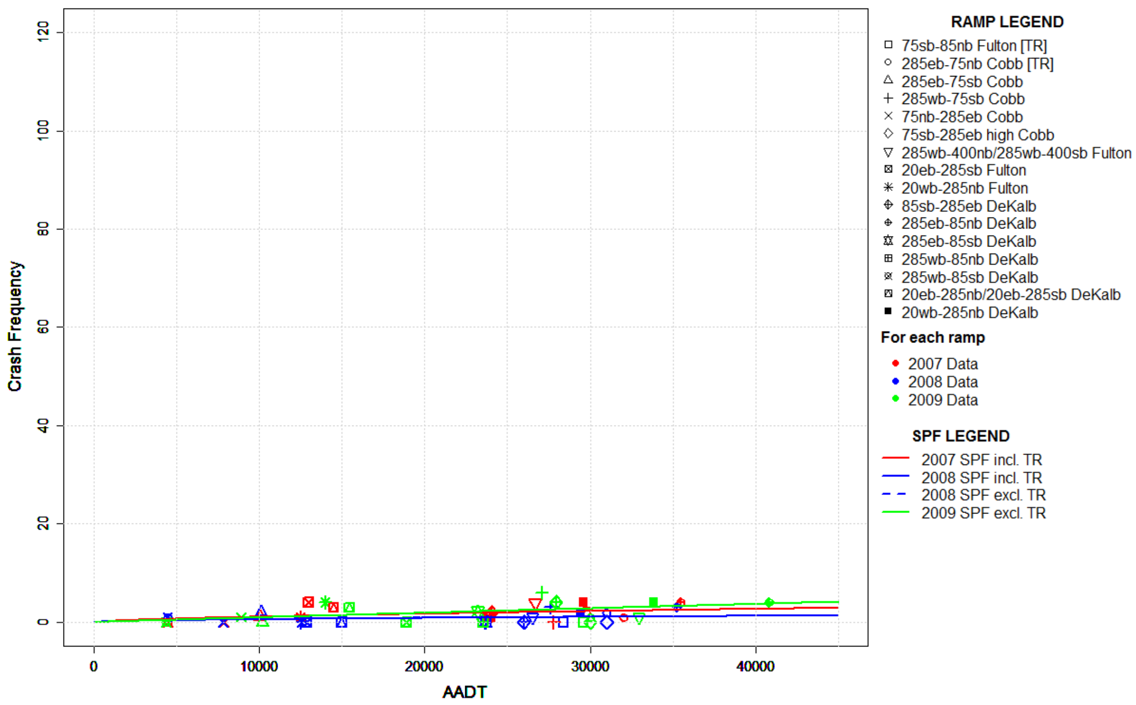


SPF Before-After RampSec3-No Merges-1 lane
Crash Frequency
0
20
40
60
80
100
120
0
10000
20000
30000
40000
AADT
RAMP LEGEND
85sb-75nb Fulton
75nb-285wb Cobb
75sb-285eb low Cobb
285eb-400nb Fulton
285eb-400sb Fulton
285wb-400nb Fulton
285wb-400sb Fulton
400sb-285wb Fulton
400sb-285eb Fulton
400nb-285eb Fulton
400nb-285wb Fulton
20eb-285nb Fulton
20wb-285nb Fulton
20wb-285sb Fulton
285sb-20wb DeKalb
285nb-20wb DeKalb
20eb-285sb DeKalb
20wb-285sb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF
After SPF

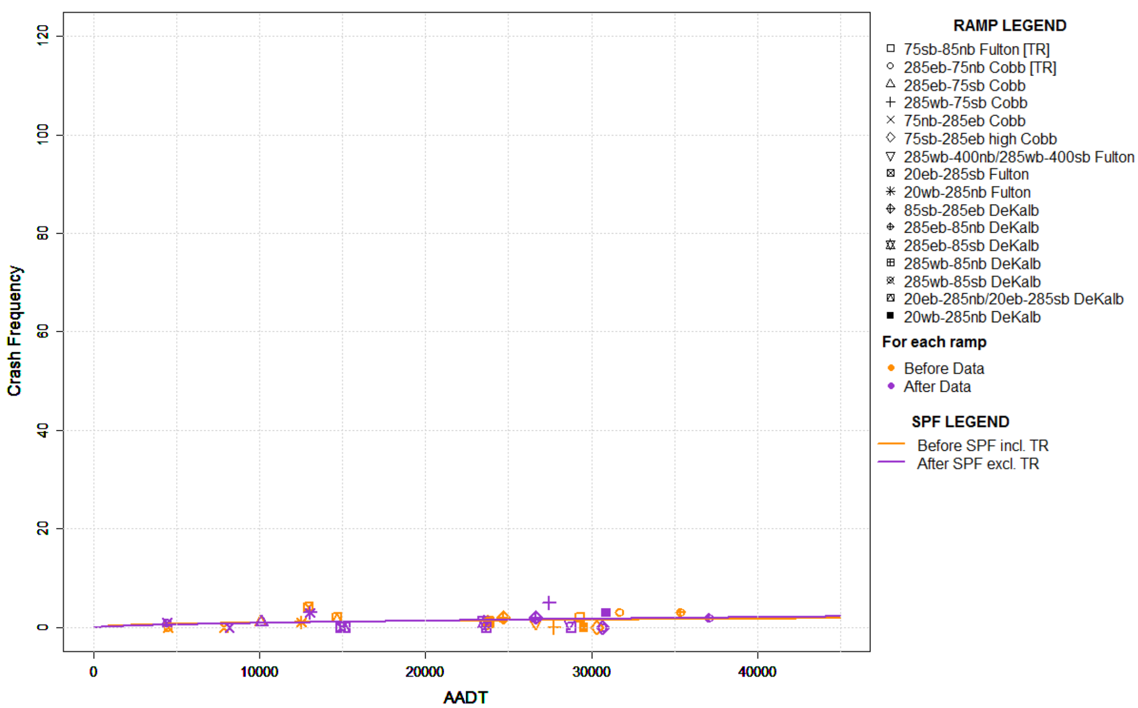

SPF 2007-2009 RampSec3-No Merges-2 lanes
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
75sb-85nb Fulton [TR]
75nb-285eb Cobb
75sb-285eb high Cobb
75sb-285wb Cobb
285sb-20eb/285nb-20eb Fulton
85sb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF incl. TR
2008 SPF incl. TR
2008 SPF excl. TR
2009 SPF excl. TR

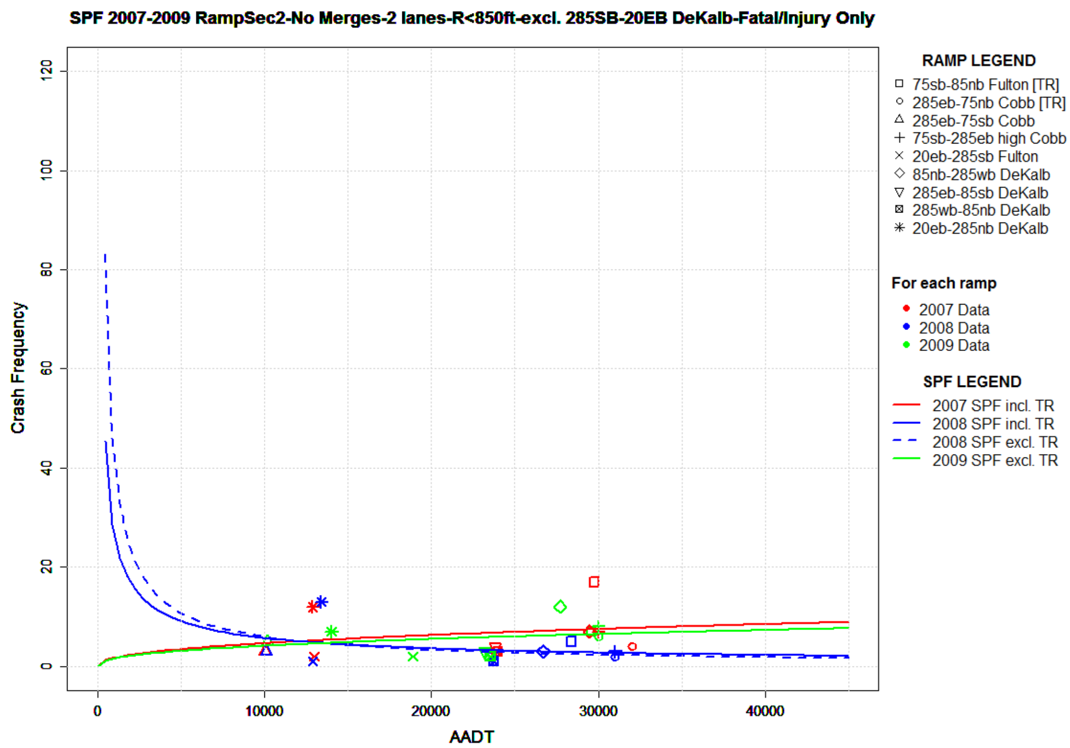

SPF Before-After RampSec3-No Merges-2 lanes
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
75sb-85nb Fulton [TR]
75nb-285eb Cobb
75sb-285eb high Cobb
75sb-285wb Cobb
285sb-20eb/285nb-20eb Fulton
85sb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF incl. TR
After SPF excl. TR

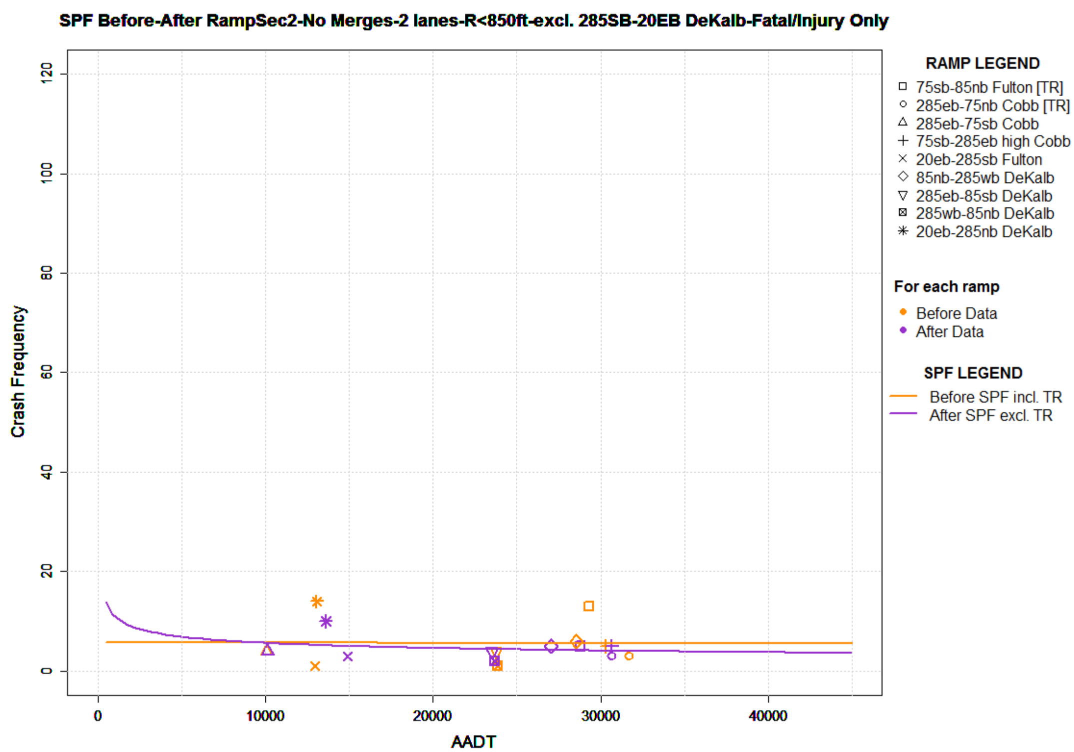
SPF 2007-2009 RampSec1-No Merges-2 lanes-Fatal/Injury Only

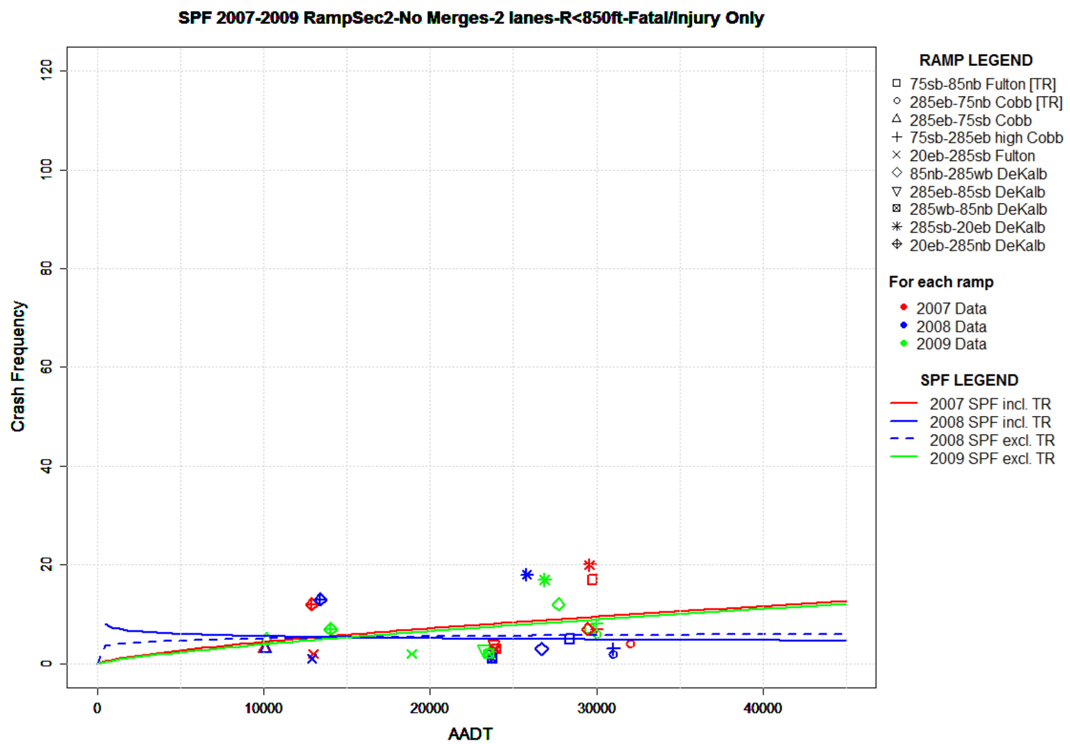


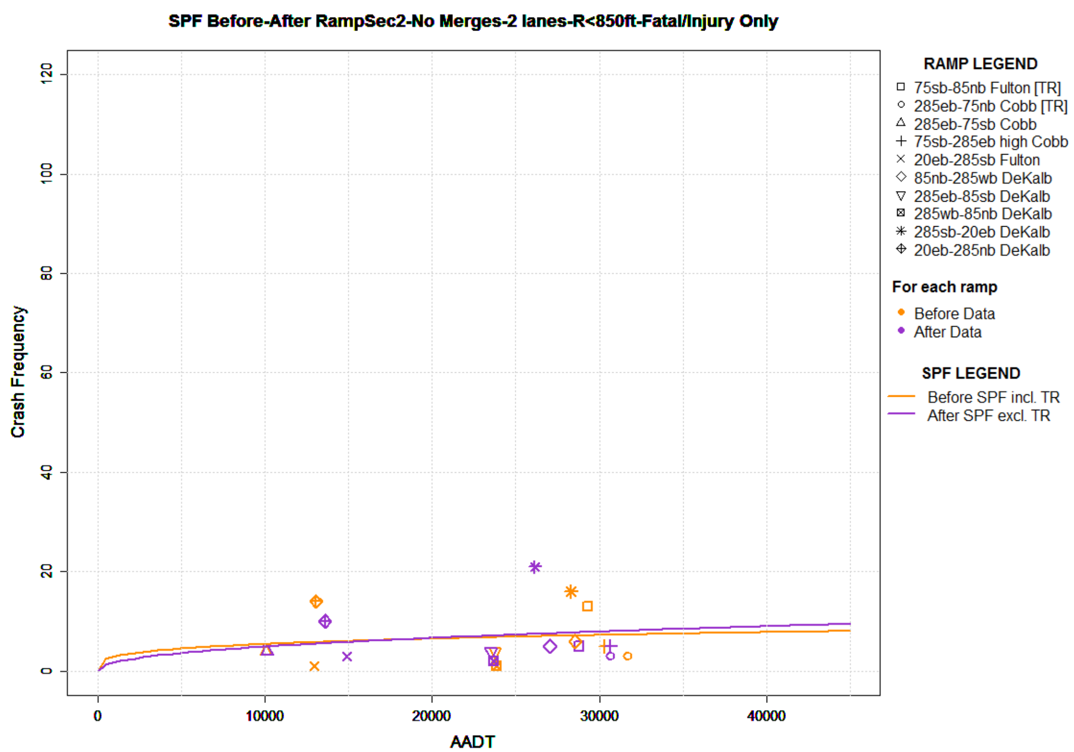
SPF Before-After RampSec1-No Merges-2 lanes-Fatal/Injury Only

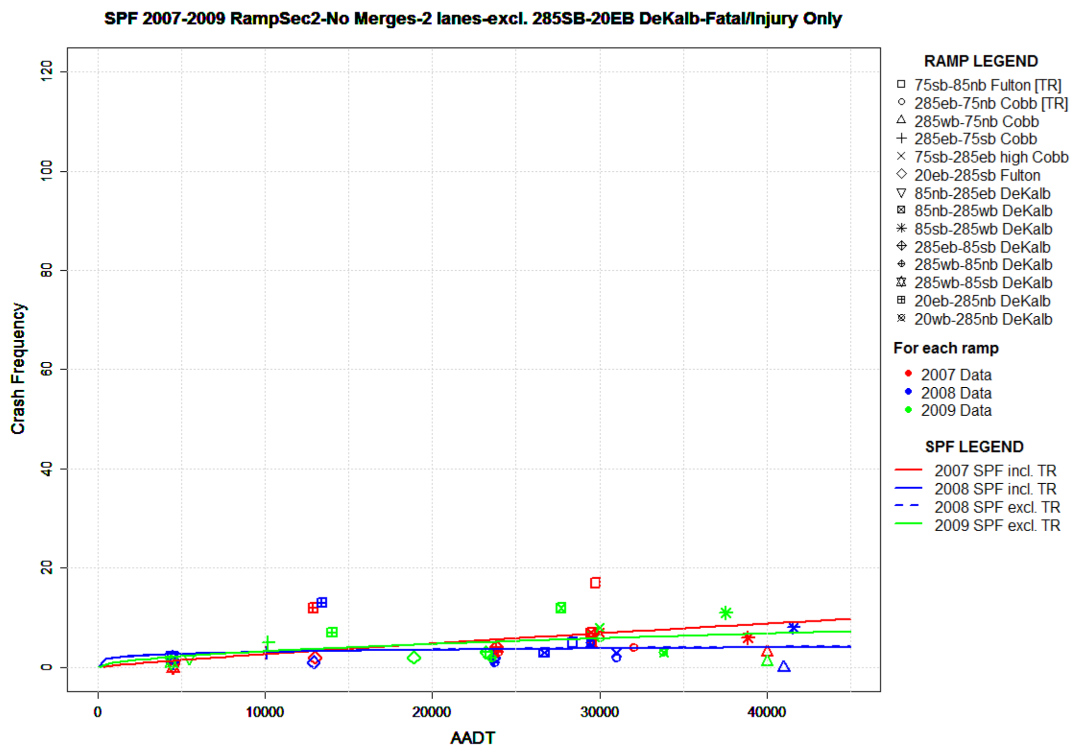


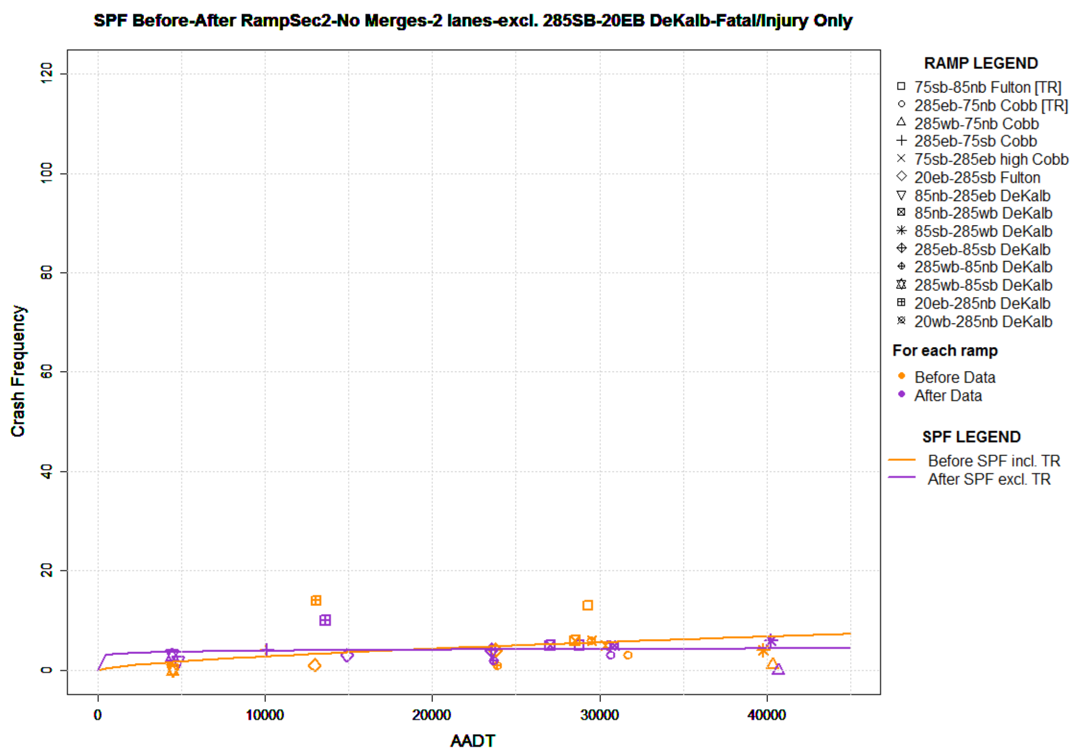

SPF 2007-2009 RampSec2-No Merges-2 lanes-R<850ft-excl. 285SB-20EB DeKalb-Fatal/Injury Only
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
75sb-85nb Fulton [TR]
285eb-75nb Cobb [TR]
285eb-75sb Cobb
75sb-285eb high Cobb
20eb-285sb Fulton
85nb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
20eb-285nb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF incl. TR
2008 SPF incl. TR
2008 SPF excl. TR
2009 SPF excl. TR


SPF Before-After RampSec2-No Merges-2 lanes-R<850ft-excl. 285SB-20EB DeKalb-Fatal/Injury Only
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
75sb-85nb Fulton [TR]
285eb-75nb Cobb [TR]
285eb-75sb Cobb
75sb-285eb high Cobb
20eb-285sb Fulton
85nb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
20eb-285nb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF incl. TR
After SPF excl. TR


SPF 2007-2009 RampSec2-No Merges-2 lanes-R<850ft-Fatal/Injury Only
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
75sb-85nb Fulton [TR]
285eb-75nb Cobb [TR]
285eb-75sb Cobb
75sb-285eb high Cobb
20eb-285sb Fulton
85nb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
285sb-20eb DeKalb
20eb-285nb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF incl. TR
2008 SPF incl. TR
2008 SPF excl. TR
2009 SPF excl. TR


SPF Before-After RampSec2-No Merges-2 lanes-R<850ft-Fatal/Injury Only
Crash Frequency
AADT
0
20
40
60
80
100
120
0
10000
20000
30000
40000
RAMP LEGEND
75sb-85nb Fulton [TR]
285eb-75nb Cobb [TR]
285eb-75sb Cobb
75sb-285eb high Cobb
20eb-285sb Fulton
85nb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
285sb-20eb DeKalb
20eb-285nb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF incl. TR
After SPF excl. TR


SPF 2007-2009 RampSec2-No Merges-2 lanes-excl. 285SB-20EB DeKalb-Fatal/Injury Only
Crash Frequency
0
20
40
60
80
100
120
0
10000
20000
30000
40000
AADT
RAMP LEGEND
75sb-85nb Fulton [TR]
285eb-75nb Cobb [TR]
285wb-75nb Cobb
285eb-75sb Cobb
75sb-285eb high Cobb
20eb-285sb Fulton
85nb-285eb DeKalb
85nb-285wb DeKalb
85sb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
285wb-85sb DeKalb
20eb-285nb DeKalb
20wb-285nb DeKalb
For each ramp
2007 Data
2008 Data
2009 Data
SPF LEGEND
2007 SPF incl. TR
2008 SPF incl. TR
2008 SPF excl. TR
2009 SPF excl. TR


SPF Before-After RampSec2-No Merges-2 lanes-excl. 285SB-20EB DeKalb-Fatal/Injury Only
Crash Frequency
0
20
40
60
80
100
120
0
10000
20000
30000
40000
AADT
RAMP LEGEND
75sb-85nb Fulton [TR]
285eb-75nb Cobb [TR]
285wb-75nb Cobb
285eb-75sb Cobb
75sb-285eb high Cobb
20eb-285sb Fulton
85nb-285eb DeKalb
85nb-285wb DeKalb
85sb-285wb DeKalb
285eb-85sb DeKalb
285wb-85nb DeKalb
285wb-85sb DeKalb
20eb-285nb DeKalb
20wb-285nb DeKalb
For each ramp
Before Data
After Data
SPF LEGEND
Before SPF incl. TR
After SPF excl. TR

Appendix C: Sample Calculations for Empirical Bayes Safety Analysis

This Appendix presents a sample calculation for conducting the empirical Bayes safety analysis, arriving at the calculation of the CMF and its significance. The sample calculation will be done using the following base condition: Ramp Section 2 – Ramp Condition 0–2 Lanes – Radius < 850 ft. – Excludes I-285 SB to I-20 EB DeKalb County. Only the evaluation using the before and after periods are shown here. Calculations using other base conditions, SPFs, and different evaluation time periods can use the same procedure.

STEP 1: Basic Input Data

The basic input data for the safety effectiveness evaluation, including the yearly observed crash data and before and after period observed crash data for the two treatment ramps, are presented below:

Site No	Site Name	County	Roadway Data			
			Ramp Section	Ramp Condition	Radius in Feet	No of Lanes
2	75sb to 85nb [treatment]	121	2	0	141	2
8	285eb to 75nb [treatment]	67	2	0	720	2

Site No	Crash & AADT Data									
	Observed Crash Frequency by Year			AADT			Observed Crash Frequency by Study Period		Before AADT	After AADT
	2007	2008	2009	2007	2008	2009	BEFORE	AFTER		
2	44	26	24	29750	28390	29590	43	21	29297	28790
8	19	18	30	32000	31000	30000	21	20	31667	30667

STEP 2: Select the applicable SPFs.

These SPFs were developed based on the crash and traffic volume data obtained for the treatment and control ramps. For more discussion on it, please refer to Chapter 5.

These SPFs are for the following base conditions: Ramp Section 2 – Ramp Condition 0–2 Lanes – Radius < 850 ft. – Excludes I-285 SB to I-20 EB DeKalb County

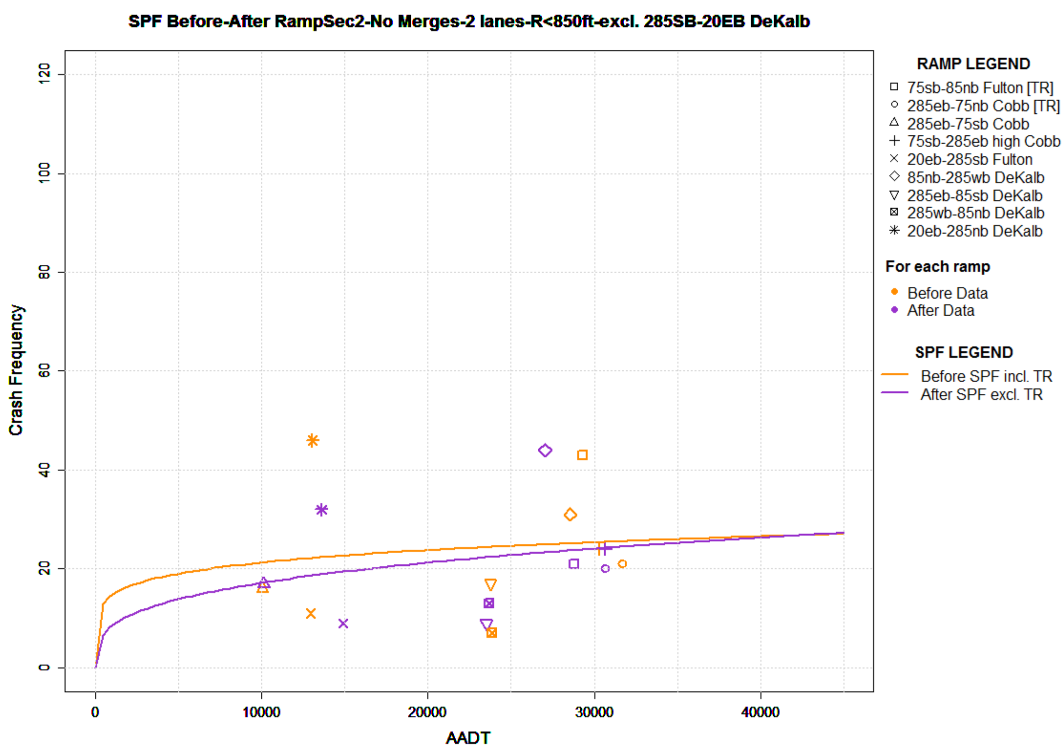
The Before-Period SPF is the following:

$N_{BEFORE} = e^{1.5856 + (0.1598 * lnAADT)}$ with an over-dispersion parameter, k = 0.2475

The After-Period SPF is the following:

$N_{AFTER} = e^{0.01044 + (0.3076 * lnAADT)}$ with an over-dispersion parameter, k = 0.2513

The SPF plots are presented below:



STEP 3: Using the above SPF and the before AADTs, calculate the predicted average crash frequency during the Before Period.

For the I-75 SB to I-85 NB ramp, using an AADT of 29,297, the predicted average crash frequency during the Before Period is:

$$N_{predicted\ before-site2} = e^{1.5856\ +(0.1598*\ln(29297))} = 25.3\ crashes$$

Similarly, for the I-285 EB to I-75 NB ramp, using an AADT of 31,667, the predicted average crash frequency during the Before Period is 25.6 crashes.

The sum of these predicted average crash frequencies is 50.9 crashes, which will be used in later calculations.

STEP 4: Calculate the weighted adjustment, w, for each treatment site for the Before Period.

The weight, w, for each site, is determined as:

$$w = \frac{1}{1 + k * N_{predicted}}$$

Thus, for the I-75 SB to I-85 NB ramp, the weighted adjustment is:

$$w_{site2} = \frac{1}{1 + 0.2475 * 25} = 0.1379$$

For the I-285 EB to I-75 NB ramp, the weighted adjustment is:

$$w_{site8} = \frac{1}{1 + 0.2475 * 26} = 0.1364$$

STEP 5: Using the calculated weighted adjustments, calculate the expected average crash frequency in the Before Period.

This is calculated as:

$$N_{expected} = w\, N_{predicted} + (1 - w)N_{observed}$$

Thus, for the I-75 SB to I-85 NB ramp, the expected average crash frequency in the Before Period is:

$$N_{expected,B} = 0.1379 * 25 + (1 - 0.1379) * 43 = 40.55\ crashes.$$

This is very close to the observed number of crashes of 43, indicating that the SPF was able to model the crashes accurately in the Before Period.

Similarly, for the I-285 EB to I-75 NB ramp, the expected average crash frequency in the Before Period is calculated to be 21.62 crashes. This, again, is very close to the observed number of crashes of 21, indicating that the SPF was able to model the crashes accurately in the Before Period.

The sum of these expected average crash frequencies is 62.18 crashes, which will be used in later calculations.

STEP 6: Using the above SPF and the after AADTs, calculate the predicted average crash frequency during the After Period.

For the I-75 SB to I-85 NB ramp, using an AADT of 28,790, the predicted average crash frequency during the After Period is:

$$N_{predicted\ after-site2} = e^{0.01044\ +(0.3076*\ln(28790))} = 23.8\ crashes$$

Similarly, for the I-285 EB to I-75 NB ramp, using an AADT of 30,667, the predicted average crash frequency during the Before Period is 24.2 crashes.

The sum of these predicted average crash frequencies is 48 crashes, which will be used in later calculations.

STEP 7: Calculate an adjustment factor, r, to account for the differences between the Before and After Period SPFs.

The adjustment factor is determined as:

$$r = \frac{N_{predicted\ after}}{N_{predicted\ before}}$$

For the I-75 SB to I-85 NB ramp, the adjustment factor is: 23.8/25.3 = 0.941

For the I-285 EB to I-75 NB ramp, the adjustment factor is: 24.2/25.6 = 0.945

As a group of treatment ramps, the adjustment factor is: 48/50.9 = 0.943

STEP 8: Calculate the expected average crash frequency in the After Period in the absence of the treatment.

This is calculated as:

$$N_{expected,A} = N_{expected,B} * \ r$$

For the I-75 SB to I-85 NB ramp, the expected average crash frequency in the After Period is: 40.55 * 0.941 = 38.16 crashes.

For the I-285 EB to I-75 NB ramp, the expected average crash frequency in the After Period is: 21.62 * 0.945 = 20.43 crashes.

To get the overall expected average crash frequency, the sum of the two calculated values is simply taken: 38.16 + 20.43 = 58.59 crashes.

STEP 9: Calculate the variance of the overall expected average crash frequency.

This is determined by calculating the variance of the expected average crash frequency for each site and then taking their sum.

The variance of the expected average crash frequency for each site, *i*, is determined as:

$$Var\left(N_{expected,A,i}\right) = (r_i)^2 * N_{expected,B} * (1 - w_i)$$

For the I-75 SB to I-85 NB ramp, this variance is calculated as:

$= (0.941)^2 * 40.55 * (1 – 0.1379) = 30.95$

For the I-285 EB to I-75 NB ramp, this variance is calculated as:

$= (0.945)^2 * 21.62 * (1 – 0.1364) = 16.67$

Therefore, the variance of the overall expected average crash frequency is:

30.95 + 16.67 = 47.62

STEP 10: Calculate the Crash Modification Factor associated with the treatment.

The CMF is calculated as follows:

$$CMF = \frac{\frac{\sum N_{Observed,A}}{\sum N_{Expected,A}}}{1 + \frac{Var(overall)}{\left(\sum N_{Expected,A}\right)^2}} = \frac{\frac{41}{58.59}}{1 + \frac{47.62}{58.59^2}} = 0.689$$

STEP 11: Calculate the precision of the CMF, including the variance, the standard error, and the 95% confidence interval.

$$Var(CMF) = \frac{(CMF^2) * \left[\frac{1}{N_{Observed,A}} + \frac{Var(overall)}{(\sum N_{Expected,A})^2}\right]}{\left[1 + \frac{Var(overall)}{(\sum N_{Expected,A})^2}\right]^2}$$

$$Var(CMF) = \frac{(0.689^2) * \left[\frac{1}{41} + \frac{47.62}{58.59^2}\right]}{\left[1 + \frac{47.62}{58.59^2}\right]^2} = 0.0176$$

$$SE(CMF) = \sqrt{Var(CMF)} = \sqrt{0.0176} = 0.133$$

95% Confidence Interval Upper Limit = CMF + (1.96 * SE(CMF)) = 0.689 + (1.96 * 0.133) = 0.949

95% Confidence Interval Lower Limit = CMF – (1.96 * SE(CMF)) = 0.689 – (1.96 * 0.133) = 0.428