DEPARTMENT OF TRANSPORTATION

Speed Limit Change (55 mph to 60 mph) Safety Re-Evaluation

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16. Abstract (Limit: 250 words)

The objective of this study was to evaluate the safety impacts of increasing the speed limit from 55 mph to 60 mph on two-lane, two-way state highway road segments in Minnesota. An empirical Bayes (EB) before-after analysis was used to estimate crash modification factors (CMFs) for both segments and intersections. The segment analysis showed an 8 percent reduction in total crashes that was statistically significant, alongside a significant 15 percent increase in combined fatal, serious injury, and minor injury (KAB) injury crashes. The range of most of the segment CMFs hovered close to 1. The intersection analysis was split into two groups (all traffic control types and thru-stop control only). The aggregate CMFs for all intersections within these two groups showed, on average, between a 10% and 20% statistically significant reduction in total and injury crashes. Analysis was also performed on four subgroups (3- and 4-leg, lighting/no lighting) within the two main intersection groups. Disaggregating the intersections into further groups led to smaller sample sizes that led to higher standard errors showing a widespread range of CMFs around 1 for the individual crash types and severities. The aggregate estimated crash safety effects (for total and injury crashes) for combined segments and intersection sites showed a reduction in total crashes but an increase in the KAB injury crashes.

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Speed Limit Change (55 MPH to 60 MPH) Safety Re-Evaluation

Final Report

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Executive Summary

The objective of this study was to re-evaluate safety impacts of increasing the speed limit from 55 mph to 60 mph on two-lane, two-way state highway road segments in Minnesota. An empirical Bayes (EB) before-after analysis was used to estimate crash modification factors (CMFs) for both segments and intersections. The EB methodology is considered rigorous in that it accounts for the possible bias due to regression to the mean (RTM) and uses safety performance functions (SPFs) to account for changes in exposure and time trends and has been found to reduce the level of uncertainty in the estimates of the safety effect. The CMFs (using EB analysis) were estimated using the expected number of crashes without the treatment along with the number of reported crashes after the treatment. Crash data from 2012 through 2022 was used in the analysis.

The segment analysis showed an 8 percent reduction in total crashes and a 15 percent increase in KAB injury crashes, both statistically significant at the 95% confidence level, alongside significant decreases in combined fatal and all injury (KABC) injury and run-off-road crashes. The range of most of the segment CMFs hovered close to 1. The intersection analysis was split into two groups (all traffic control types and thru-stop control only). The aggregate CMFs for all intersections within these two groups showed, on average, between a 10% and 20% statistically significant reduction in crashes. Analysis was also performed on four subgroups (3- and 4-leg, lighting/no lighting) within the two main intersection groups. Disaggregating the intersections into further groups led to smaller sample sizes that led to higher standard errors showing a widespread range of CMFs around 1 for the individual crash types and severities.

The aggregate analysis conducted using all the segment and intersection data showed an average reduction of 12.7% in total crashes and 7.4% in KABC injury crashes, both statistically significant at the 95% confidence level. KAB injury crashes showed an increase of 4.5% (significant at the 85% confidence level).

The results from this re-evaluation generally showed an improvement in CMFs compared to the previous evaluation (Saleem et al., 2020). For example, the total segment crashes went from showing a 7% increase to showing an 8% reduction. Similarly, the aggregate CMFs for all intersections within the two groups (i.e., all traffic control types and thru-stop control only) also showed statistically significant reduction of between 10% and 20% compared to previous evaluation showing almost minor statistically increases/reduction in crashes. The aggregate estimated crash safety effects (for total and injury crashes) for combined segments and intersection sites showed a reduction in total crashes but an increase in the KAB injury crashes.

The improvement seen in the CMFs in this re-evaluation can be attributed to a larger crash sample being used; however, overall, it can be concluded that that the speed limit increase from 55 mph to 60 mph resulted in fewer overall crashes but potentially more injury crashes.

Chapter 1: Introduction

The Minnesota legislature passed legislation in 2014 mandating the Minnesota Department of Transportation (MnDOT) evaluate a speed limit increase from 55 mph to 60 mph on the two-lane state highway system (see 2014 Laws of Minnesota, Chapter 312, Article 11, Section 36)[1]. Minnesota has approximately 7,000 miles of two-lane, two-way roadways that are affected by this legislation[2]. The legislation[1] required engineering and traffic investigations to determine segments where speed limits could be reasonably and safely increased to 60 mph. The criteria considered to determine possible segments to implement speed limit changes included:

- Number of access points (public roads, residential, commercial, industrial, etc.) below an average of 10 access points per mile
- Shoulder width (regardless of material type) 4' or greater
- Vertical grades remain at or less than 3% (positive or negative) for the majority of the segment
- A clear zone assessment has been made of the corridor and determined to be satisfactory based on engineering judgment
- Total 5-year crash rate and/or fatal and serious injury rate (junction and non-junction crashes) below the statewide average for its ADT range
- Total 5-year crash rate and/or the fatal and serious injury rate (junction and non-junction crashes) below the critical crash rate based on statewide averages for its ADT range
- Horizontal curves properly signed for, or do not have a recent crash problem (average less than 1 crash per year)
- Passing zones meet a 60-mph design standard
- 85th percentile of free flow vehicles above 61 mph
- 10-mph pace has upper boundary above 61 mph

As a result of these investigations, the speed limit was increased to 60 mph on 5,240 miles of the two-lane state highway system. MnDOT had previously increased speeds to 60 mph on 1,550 miles of two-lane highways[2]. When implementation was completed, 81 percent of the two-lane, two-way state highways had a posted speed limit of 60 mph[1].

An initial study of the speed limit changes was completed in 2020 (Saleem et al., 2020), prior to the COVID pandemic and before the speed limit signs were changed for all corridors. The objective of this *Speed Limit Change (55 mph to 60 mph) Safety Evaluation* task was to review and evaluate the safety impacts for two-lane, two-way state highway road segments, considering the additional data and post-

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[1] 2014 Laws of Minnesota, Chapter 312, Article 11, Section 36. https://www.revisor.mn.gov/laws/2014/0/312/

[2] *Evaluation of Certain Trunk Highway Speed Limits. Minnesota Department of Transportation*. 2019. https://www.dot.state.mn.us/govrel/reports/2019/2018%20TH%20Speed%20Limit%20Report-final%20year%20report.pdf

pandemic context since the original evaluation in 2018. Thus, this study evaluated state highway segments where speed limits were changed from 55 mph to 60 mph using a before-and-after evaluation.

Typically, the safety effect of engineering treatments is expressed in the form of crash modification factors (CMFs). The CMF is a multiplicative factor that can be used to estimate the expected number of crashes after implementing a given treatment. With a CMF, the percentage change in crashes due to the treatment is estimated as 100(1-CMF). Hence, a CMF of 1.0 indicates that the engineering treatment did not have any effect on crashes. A CMF of 0.8 indicates that the engineering treatment is expected to reduce crashes by 20%; conversely, a CMF of 1.2 indicates that the engineering change is expected to increase crashes by 20%. In this study, CMFs are estimated for the following locations, crash types, and crash severities:

- Locations:
  - Two-lane, two-way state highway road segments (excluding intersections), and
  - Intersections on two-lane, two-way state highway road segments:
    - 3-Legged intersections with lighting
    - 3-legged intersections with no lighting
    - 4-legged intersections with lighting
    - 4-legged intersections with no lighting
- Crash Types:
  - All types combined (total)
  - Angle crashes
  - Head-on crashes
  - Rear-end crashes
  - Run-off-road crashes
- Crash Severities:
  - Total crashes (also referred to as KABCO crashes)
  - Fatal and all injury crashes (also referred to as KABC crashes)
  - Fatal and serious/suspected injury crashes (also referred to as KAB crashes)

Evaluation of side swipe, same direction crashes at intersections and pedestrian and bicyclist crashes was also considered; however, there were not enough crashes to conduct a reliable statistical evaluation.

Chapter 2: Overview of Evaluation Approach

This evaluation follows a three-step approach:

1. Reviewing existing literature on the safety effectiveness of speed limit and operating speed changes.
2. Identifying data required for this re-evaluation and then gathering and compiling the data in a relational database.
3. Performing a statistical analysis on the roadway, traffic volume, and crash data, including activities to build an analytical file suitable for the statistical analysis.

2.1 Safety Evaluation Methods

The various safety evaluation methods fall under two broad categories: before-after and cross-sectional studies. Before-after studies include all techniques by which one may study the safety effect of some treatment that has been implemented on a group of sites. On the other hand, cross-sectional studies include those where one is comparing the safety of one group of sites having some common feature (treatment of interest) to the safety of a different group of sites not having that feature in order to assess the safety effect of the treatment (Carter *et al.*, 2012).

There is a general consensus in the safety community that well-designed before-after studies provide more reliable estimates of safety effects compared to cross-sectional studies. This is because before-after studies are less prone to confounding (aka other influences) since the study evaluates the same roadway unit used by probably the same users in the before and after period (Elvik, 2011). Confounding, on the other hand, is a big issue in cross-sectional studies and can confuse the association between an exposure and an outcome.

Safety effects derived from before-after studies are based on the change in safety due to the implementation of a treatment. The most practically established approach for before-after evaluations is the empirical Bayesian method (EB). The EB approach associates a reference group (treatment not applied) which is similar to treated sites (treated group) and is introduced to offer referential information for before-after evaluations, as illustrated in Figure 1 (Chen, 2013).

The five groups as identified in Figure 1 form a grid with the dimension of reference and treated groups crossed by dimension of before and after periods. The goal here is to seek a CMF (or crash reduction rate) through a safety comparison between groups 4 and 5. The EB approach estimates the expected safety improvement of the treatment that is being evaluated (Chen, 2013).

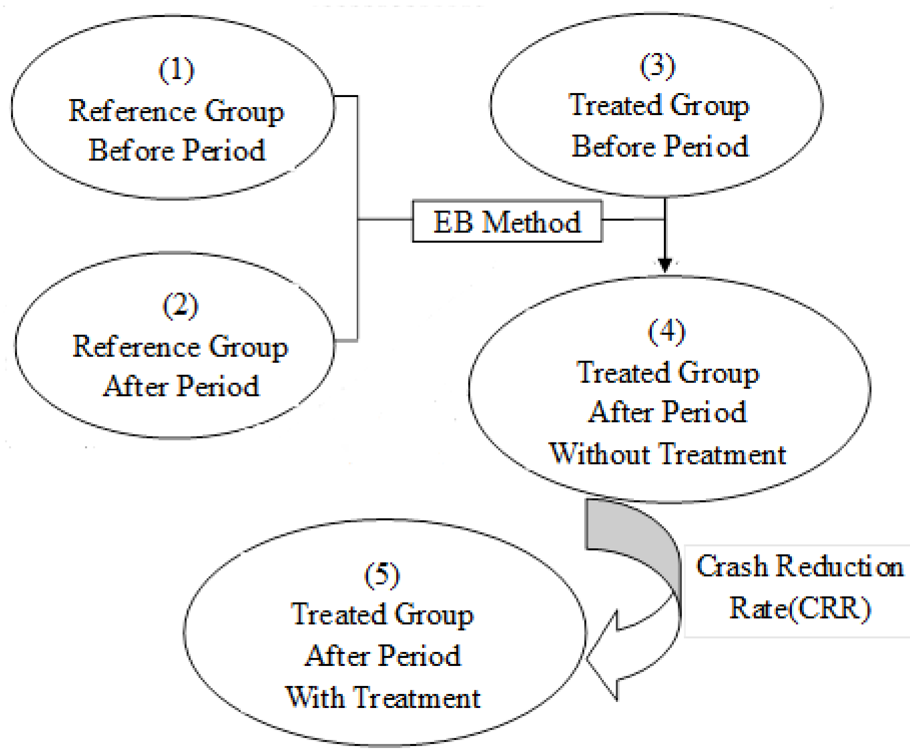

Figure 1. Logical Framework for Before-After Evaluations.

The objective of the EB before-after study is to estimate the number of crashes that would have occurred at an individual treated site in the after period had the treatment not been implemented. The advantage of the EB approach is that it correctly accounts for changes in crash frequencies before and after a treatment that may be due to regression to the mean (RTM). Often, agencies select high crash locations for implementing treatments, and if the possible bias due to RTM is not properly accounted for, the evaluation may overestimate the safety effect of the treatment. In accounting for RTM, the number of crashes expected in the before period without the treatment is estimated as a weighted average of the number of crashes observed in the before period at treated sites and the number of crashes predicted at treated sites based on untreated reference sites with similar characteristics. The 1st edition of the Highway Safety Manual (AASHTO, 2010) considers the EB approach as an effective approach for conducting reliable before-after studies.

Chapter 3: Literature Review

Speed limits are usually set to inform drivers of the highest speed that is appropriate for ideal traffic, road, and weather conditions. A literature review scan shows that many studies were conducted to evaluate the safety impacts of changing speed limits. The results of these studies generally show that increasing speed limits can negatively affect safety. For example, a 2019 IIHS study shows that speed limit increases in the past 25 years are tied to over 3700 deaths in the US (IIHS, 2019). The study found that a 5 mph increase in the maximum speed limit was associated with 8% and 3% increases in fatality rates on interstates/freeways and other roads, respectively.

Sayed and Sacchi (2016) evaluated the safety impacts of increasing speed limits on rural highways in British Columbia (Canada) following a speed limit review initiated by the Ministry of Transportation and Infrastructure (MoTI) of British Columbia in 2013. MoTI conducted over 300 speed surveys to measure 85^{th} percentile operating speeds on approximately 9100 km of rural provincial highway segments. The surveys found that the 85^{th} percentile speed on the surveyed segments was 10 km/h higher than the corresponding posted speed limits. As a result of the review, MoTI recommended increasing speed limits on approximately 1300 km of rural provincial highway segments (65 sections). Majority of the sections had a 10 km/h speed limit increase (216 km of segments went from 80 km/h to 90 km/h, 548 km of segments went from 90 km/h to 100 km/h, 146 km of segments went from 100 km/h to 110 km/h, and 377 km of segments went from 110 km/h to 120 km/h), while a small section of 19.2 km had a 20 km/h speed limit increase going from 80 km/h to 100 km/h. Sayed and Sacchi conducted a full Bayesian before-after evaluation using the approximately 1300 km (65 sections) of rural provincial highway segments recommended for increased speed limits by MoTI as their treatment group along with approximately 1850 km (95 sections) of rural provincial highway segments that did not undergo a speed limit increase as their comparison group. They found speed limit increases associated with a statistically significant 11.1% increase in fatal and injury crashes.

De Pauw *et al.* (2014) investigated the safety effects of reducing speed limits from 90 km/h to 70 km/h on roads in the Flemish Region of Belgium. The Flemish government, during 2001 and 2002, implemented lower speed limits of a large number of highways in a bid to favorably influence traffic safety. They used four main criteria (one of which had to be met) to select candidate locations: road sections without cycle paths or with cycle lanes close to roadways; road sections with obstacles close to roadway with a high risk of collision; road sections outside urban areas but with high building density and a high number of vulnerable road users; and road sections on which severe crashes occurred in the past. Reduced speed limits were often only restricted at specific sections of roads (e.g., sections between two intersections or sections between two parts of an urban environment) and no enforcement and educational efforts were combined with this change (only traffic signs were updated). De Pauw *et al.* evaluated safety at 61 of the treated road sections with a total length of 116 km. They excluded road sections where other measures (in addition to the speed limit reduction) were performed that could impact speed and safety. Of the 61 road sections in their treated group, 72% were located in rural areas and 80% were categorized as local roads. The comparison group consisted of 19 road sections with a total length of 53 km. They conducted a before-after with comparison group analysis to determine the effectiveness of lowering speed limit at each of the 61 treated sections. They found a decrease in injury crashes at 62% of the treated sections. Disaggregate analysis showed a decrease in injury crashes at intersections for 43% of the treated sections and at segments for 70% of the treated sections. To account for the overall safety effect, they carried out a meta-analysis using the effectiveness at each individual section. The meta-analysis showed a non-significant 5% and 6% reduction in injury and severe injury crashes, respectively.

Jaarsma *et al.* (2011) investigated the safety effects of reducing speed limits from 80 km/h to 60 km/h on rural roads in the Netherlands. Their treatment group consisted of 851 km of minor roads in 20 different rural areas where the speed limit was reduced from 80 km/h to 60 km/h. Minor rural roads in this paper are defined as roads with one lane for two-way traffic along with paved shoulders and a pavement width between 2.5 and 5.5 m. The specific criteria used to select the segments for the treatment group is not mentioned in the paper. The comparison group consisted of 2105 km of comparable roads with 80 km/h speed limit. The results of the before-after with comparison group analysis shows statistically significant 24% and 27% overall reduction in fatal and fatal plus injury crashes, respectively. Disaggregate analysis shows statistically significant reduction of 44% and 55% in fatal and fatal plus injury crashes, respectively at intersections.

Parker (1997) in his study examined the safety effects of raising and lowering speed limits for urban and rural non-limited access highways in 22 States. Experimental sites in this study were selected based on various considerations: sections less than 0.5 mi in length were generally not selected; sections that were recently reconstructed or were subject to construction (apart from regular maintenance) before or after the speed limit changes were not selected; sections with more than one speed limit change during the study period; and sections were selected to represent wide range of urban and rural geographic conditions. The site selection criteria led to selecting three different groups for which safety effects of speed limit changes were evaluated. The first group consisted of 58 experimental sites where speed limits were lowered with a 5-mph speed limit reduction at 14 sites, a 10-mph speed limit reduction at 34 sites, and a 15 or 20 mph speed limit reduction at 10 sites. Using simple before-after analysis, the study finds a 17.29% increase in total crashes for lowering the speed limit by 5 mph, a 3.91% reduction in total crashes for a lowering the speed limit by 10 mph, and a 5.62% reduction in total crashes for lowering the speed limit by 15 or 20 mph. Aggregate analysis over all 58 sites shows a 0.8% and 1.5% increase in total and fatal plus injury crashes, respectively. The second group consisted of 41 experimental sites where speed limits were raised with a 5-mph speed limit increase at 26 sites and a 10 or 15 mph limit increase at 15 sites. Using simple before-after analysis, the study finds an 8.28% reduction in total crashes for a raising the speed limit by 5 mph, and a 15.21% reduction in total crashes for raising the speed limit by 10 or 15 mph. Aggregate analysis over all 41 sites shows a 9.98% and 3.21% reduction in total and fatal plus injury crashes, respectively. The third group consisted of 55 experimental sites, of which, 21 sites had speed limits within 5 mph of the 85th percentile speed (speed limits were raised to within 5 mph of the 85th percentile speed at these sites) and 34 sites had speed limits more than 5 mph below the 85th percentile speed (speed limits were lowered more than 5 mph below the 85th percentile speed at these sites). Using simple before analysis, the study finds an 8.32% reduction in total crashes at sites where the speed limits were raised to within 5 mph of the 85th percentile speed, and a 0.25% increase in total crashes for sites where the speed limits were lowered more than 5 mph below the 85th percentile speed. Furthermore, this study also explored changes in driver behavior with changes in speed limits. The review of the before and after speed data at each site revealed that differences in mean speeds, standard deviations of speeds, 85th percentile speeds, and other percentile speeds were generally less than 2 mi/h and were not related to the amount the posted speed limit was changed.

Acqua and Russo (2011) analyzed 984 km of low volume roadways (AADT < 1000) in Southern Italy. Of the 984 km of the low volume roadways analyzed 232 km are situated on flat/rolling terrains (vertical grade < 6%) and 752 km are situated on mountainous terrains (vertical grade > 6%). The main goal of this study is to calibrate SPFs to predict injury crashes per km per year as a function of volume, mean operating speed, curvature, vertical grade, and roadway width on low volume roadways. Curvature is this study is defined at three levels; low for curve radius between 400 and 500 m, medium for curve radius between 150 and 400m, and high for curve radius less than 150 m. SPFs were calibrated separately for low volume roadways on flat/rolling terrains and low volume roadways on mountainous terrains. Their findings suggest that for a specific combination of roadway width and curvature, the number of injury crashes per km per year increase with speed. Alternatively, they find that there can be a reduction in injury crashes per km per year with no change in speeds but only in specific combinations of roadway width and curvature. One of the examples of various combinations provided in the study where these findings were validated included low curvature roads on flat/rolling terrain with roadway widths of 6 and 9 m. Both of these combinations of roads would see an increase in injury crashes with an increase in speed, however, if the speeds are kept consistent, a decrease in injury crashes can be seen going from a low curvature road with width of 9 m to a low curvature road with a width of 6 m.

Ksaibati *et al.* (2009) in their study developed a rural road safety program for counties in Wyoming. One of the purposes of this program was to help counties identify high-risk low volume rural road locations by developing a methodology for crash prediction at such locations. To develop the crash prediction model, they used data from 36 low volume rural roads. Traffic volume and 85th percentile speed were used as predictor variables. Traffic volumes on the roads analyzed ranged from 35 vehicles/day to 1468 vehicles/day and the 85th percentile speeds on these roads ranged from 30 mph to 70 mph. They found that higher volumes combined with higher speeds will result in more crashes.

Vadeby and Forsman (2018) analyzed the effects of both increased and reduced speed limits as well as changes in actual driving speeds due to the changed speed limits following a review of speed limits on the national rural road network by the Swedish Transport Administration in 2008. The review the Swedish Transport Administration resulted in changed speed limits on approximately 20500 km of rural roads (consisting of two-lane rural roads, three-lane rural roads with alternating passing lanes, and motorways), of which, 2700 km of roads saw an increase in speed limits and 17800 km of roads saw a reduction in speed limits. A reduction in speed limits from 90 km/h to 80 km/h on rural roads resulted in the number of fatalities decreasing by 14 per year, while no significant changes were seen for number of seriously injured. An increase in speed limit from 100 km/h to 120 km/h on motorways was associated with an increase of 15 per year in the number of seriously injured, but no significant changes were seen for the number of deaths. Speed measurement surveys show that a decrease in speed limit with 10 km/h led to a decrease of mean speeds of around 2–3 km/h and an increase of the speed limit with 10 km/h resulted in an increase of mean speed by 3 km/h.

Gayah *et al.* (2018) in their study evaluated the operational and safety impacts of setting posted limits below engineering recommendations using data from rural two- and four-lane roads in Montana. They conducted an empirical Bayes before-after analysis using data from 14 sites (41 miles) where the posted speed limit was reduced from an engineering recommended value to a lower value (comparison group consisted of 38 sites or 131 miles of roadway). The CMFs suggest that setting speed limits 5 mph below the engineering recommended value is associated with a statistically significant reduction in total crashes by 56%, fatal and injury crashes by 40%, and PDO crashes by 57%. Setting speed limits 10 mph below the engineering recommended value is associated with a statistically significant reduction in total crashes by 16% and PDO crashes by 34%, while fatal and injury crashes saw a statistically significant increase of 45%. Setting speed limits 15 mph or more below the engineering recommended value is associated with non-statistically significant increases in total crashes by 21%, fatal and injury crashes by 72%, and PDO crashes by 12%. The operating speed evaluation conducted as a part of this study suggests that drivers tend to comply more closely with the speed limit when the posted speed limit set equal to or just 5 mph below the engineering recommended value. Setting speed limits more than 5 mph below the engineering recommended value saw an increase in both mean and 85th percentile speeds. They also found that intermittent speed enforcement only has nominal effects of operating speeds, while heavy speed enforcements within low-speed limit zones reduces both mean and 85th percentile speeds by about 4 mph increasing the likelihood of speed limit compliance.

Gitelman *et al.* (2017) in their study explored the relationship between travel speeds and accidents, while accounting for traffic exposure and road infrastructure on 179 sections of single-carriage (i.e., rural two-lane) roadways in Israel. They developed two crash prediction models using speed measurements in day and night hours. They found that both in day and night hours, under any road infrastructure condition, the number of injury accidents increases with an increase in the segment mean speed, while controlling for traffic exposure and road infrastructure conditions. The also evaluated the safety impact of speed variance (the standard deviation of the mean speed) and found that the impact trend was inconsistent where an increase in the speed variance was associated with a reduction in day hour accidents and with an increase in night hour accidents.

Monsere *et al.* (2018) in their study analyzed the speed and crash performance changes for 1400 miles of Oregon highways and interstates where speed limits were increased in 2016 by the Oregon legislature. The legislature raised speed limits to 70 mph for cars and 65 mph for trucks on interstates and 65 mph for cars and 55 mph for trucks on rural two-lane highways. They found that average operating speeds at the highways that had a speed limit increase showed a statistically significant 3 mph increase along with increases in both the average and percentage of vehicles exceeding 65, 75, and 85 mph. Their preliminary crash analysis found that both the total and total truck-involved crashes increased at a rate that was expected based on changes in traffic volume and the changes in the control sections. Fatal and severe injury crashes did not appear to increase more than the control section for interstates but did increase for rural two-lane roads. However, overall, on both interstates and rural two-lane highways, there was a reduction in fatal and severe injury crashes involving trucks.

Himes *et al.* (2018) in their study evaluated the crash performance changes for 670 miles of engineering study-qualified rural Virginia interstates where speed limits were increased from 65 to 70 mph in 2010. The paper used an empirical Bayes before-after study to determine Crash Modification Factors for total, injury, run-off-road, and truck-related crashes. “Before” crash data was collected from 2006 to 2009, and “after” crash data was collected from 2011 to 2014. At the aggregate level, none of these focus crash types increased after the speed limit change. However, when data was disaggregated for more in-depth analysis, interchange segments observed statistically significant increases in total, run-off-road, and truck-related crashes. Additionally, roadway improvements such as rumble strip installation, pavement resurfacing, guardrail installation, shoulder activities, pavement markers and markings, and various warning signage improved safety performance of treated segments, though the difference between improved and unimproved roadways was not significant.

Chapter 4: Evaluation Methodology

The EB methodology for before-after studies was used for this evaluation. As mentioned earlier, this methodology is considered rigorous in that it accounts for the possible bias due to the RTM. This procedure uses a reference group of similar but untreated sites, safety performance functions (SPFs) to account for changes in exposure, time trends, and has been found to reduce the level of uncertainty in the estimates of the safety effect.

The following steps are needed to conduct an EB before-after evaluation:

1. Identify a reference group without the treatment, but similar to the treated sites in terms of the major factors that affect crash risk including traffic volume and other site characteristics.
2. Estimate SPFs using data from the reference entities relating crashes to the characteristics of the entity. In some cases, if it is not possible to find a reference group similar to the treatment group, or when the treatment is implemented system-wide, the before data from the treatment entities is used along with reference or comparison entities to estimate the SPFs. In fact, in this evaluation, the before data from the treatment sites were combined with the reference sites for estimating SPFs.
3. In estimating SPFs, calibrate annual calibration factors (ACFs) to account for the temporal effects (e.g., variation in weather, demography, vehicle population, and crash reporting) on safety performance. The ACF for a particular year is the ratio of the observed crashes to the predicted crashes from the SPF.
4. Use the SPFs, ACFs, and site characteristics for each year in the before period for each treatment site to estimate the number of crashes that would be predicted for the before period.
5. Calculate the EB estimate of the expected crashes in the before period at each treatment site as the weighted sum of the actual crashes in the before period and predicted crashes from step 4.
6. For each treatment site, estimate the product of the EB estimate of the expected crashes in the before period and the SPF predictions for the after period divided by the SPF predictions for the before period. This is the EB expected number of crashes in the after period that would have occurred had there been no treatment. The variance of this expected number of crashes is also estimated in this step. The expected number of crashes without the treatment along with the variance of this parameter and the number of reported crashes after the treatment is used to calculate the safety effect of the treatment (θ) along with the standard error, which is an estimate of the precision of the estimate of the safety effect. It is important to note that θ is the same as a CMF.

Based on the safety effect (θ), the percent change in crashes is calculated as $100(1 - \theta)$. Therefore, a value of $\theta = 0.9$ with a standard of error of 0.05 indicates a 10% reduction in crashes with a standard error of 5%. Conversely, a value of $\theta = 1.2$ with a standard of error of 0.1 indicates a 20% increase in crashes with a standard error of 10%. Further details about the equations involved in estimating θ and its standard error are available in Appendix A.

Chapter 5: Data Compilation and Database Development

Steps needed for development of the relational database are shown in Figure 2. Data was first inspected for inconsistencies and anomalies (Step 1). Data collected prior to 2016 was geospatially referenced using MnDOT's Transportation Information System (TIS), while data collected from 2016 to 2022 was referenced by MnDOT's Linear Referencing System (LRS)/Highway Performance Management System (HPMS) and StreetLight speed data collected from 2018 to 2022 was referenced by joining OpenStreetMap (OSM) segments to MnDOT segments through a spatial buffer and weighted allocation based on VMT. To be relatable, data from the three systems were spatially joined in a geographic information system (GIS) (Step 2). Finally, associated roadway, crash, traffic volume, and intersection data are related to the segments with speed limit change (i.e., treatment) and segments with no speed limit change (i.e., reference/non-treatment). Details as to the methods, challenges, and assumptions in the database development can be found in Appendix B.

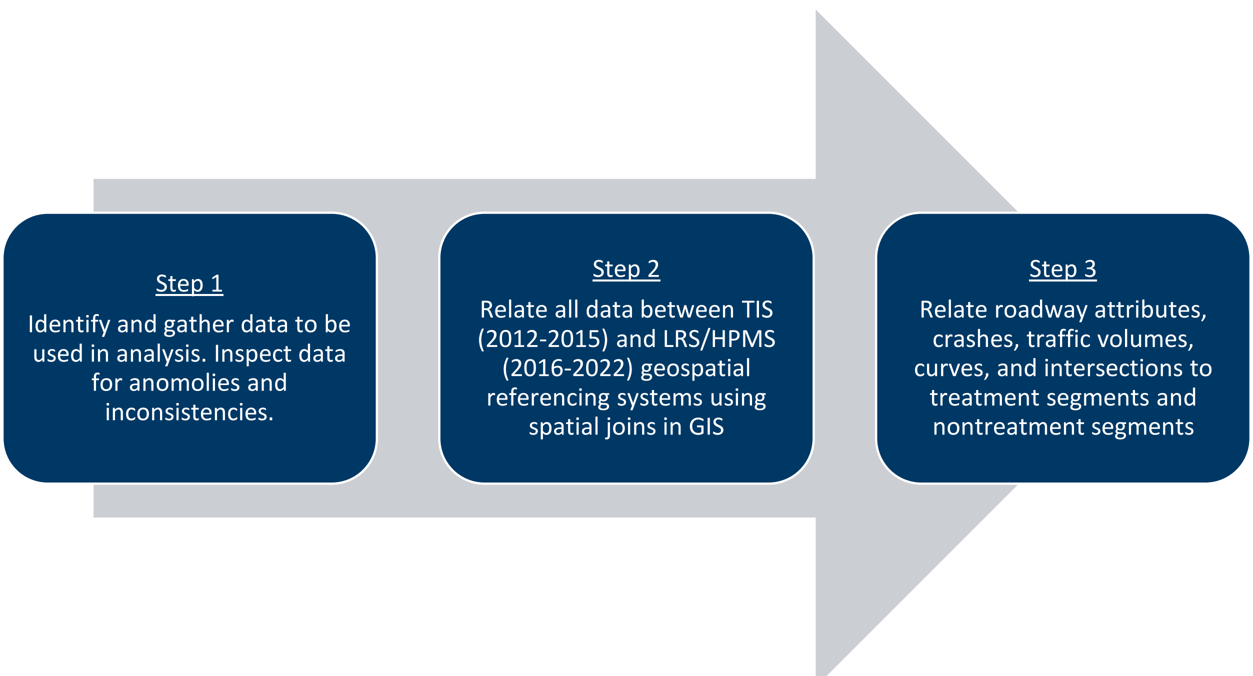

Figure 2. Database Development Approach.

5.1 Descriptive Statistics

Tables 1-8 provide summary statistics for segments and intersections that were used in the analysis. It should be noted that for estimating safety performance functions (SPF), data from reference sites along with before data from treatment sites were used. These SPFs were then used to estimate the EB estimates and the resulting crash modification factors (CMFs). More discussion on SPF and CMF estimation can be found in Section 6 of this report.

Table 1: Segment Summary Statistics

Site Type	Number of Sites	Length (mi)	Average AADT	Average Degree of Curvature
Reference	3451	811.21	4087.73	0.382
Treatment	9693	3073.96	3136.83	0.179

Table 2: Intersection Summary Statistics

Intersection Type	Number of Sites	Average AADT
Reference (3-Leg)	1449	3663.36
Reference (4-Leg)	619	3655.31
Treatment (3-Leg)	3425	3117.76
Treatment (4-Leg)	2697	2462.41

Table 3. Segment Crash Summary Statistics (Reference Sites)

Crash Type	Minimum (/site/year)	Maximum (/site/year)	Average (/Site/Year)	Sum
Total	0	9	0.124	4712
Injury (KABC)	0	4	0.042	1612
Injury (KAB)	0	3	0.023	880
Run off Road	0	6	0.036	1365
Head On	0	3	0.012	451

Table 4. Segment Crash Summary Statistics (Treatment Sites)

Crash Type	Minimum (/site/year)	Maximum (/site/year)	Average (/Site/Year)	Sum
Total	0	10	0.101	10737
Injury (KABC)	0	5	0.037	3909
Injury (KAB)	0	3	0.021	2195
Run off Road	0	6	0.032	3393
Head On	0	3	0.009	1050

Table 5. Intersection Crash Summary Statistics (3-Legged Reference Sites)

Crash Type	Minimum (/site/year)	Maximum (/site/year)	Average (/Site/Year)	Sum
Total	0	7	0.110	1754
Injury (KABC)	0	4	0.039	622
Injury (KAB)	0	3	0.020	311
Angle	0	3	0.014	230
Rear End	0	4	0.030	478

Table 6. Intersection Crash Summary Statistics (4-Legged Reference Sites)

Crash Type	Minimum (/site/year)	Maximum (/site/year)	Average (/Site/Year)	Sum
Total	0	20	0.244	1661
Injury (KABC)	0	6	0.089	605
Injury (KAB)	0	4	0.044	300
Angle	0	5	0.070	475
Rear End	0	15	0.077	527

Table 7. Intersection Crash Summary Statistics (3-Legged Treatment Sites)

Crash Type	Minimum (/site/year)	Maximum (/site/year)	Average (/Site/Year)	Sum
Total	0	7	0.074	2782
Injury (KABC)	0	5	0.029	1089
Injury (KAB)	0	4	0.015	560
Angle	0	3	0.009	335
Rear End	0	6	0.020	739

Table 8. Intersection Crash Summary Statistics (4-Legged Treatment Sites)

Crash Type	Minimum (/site/year)	Maximum (/site/year)	Average (/Site/Year)	Sum
Total	0	18	0.117	3484
Injury (KABC)	0	7	0.047	1382
Injury (KAB)	0	5	0.026	758
Angle	0	6	0.039	1153
Rear End	0	14	0.027	791

Chapter 6: Results and Discussion

As described in Section 4, the evaluation's first step is to estimate a safety performance function (SPF). Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. SPFs were estimated for target crash types and crash severities identified in Section 1. These SPFs and the annual calibration factors (ACFs) are documented in Appendices C and D, respectively.

6.1 Estimated Segment Crash Safety Effects

The estimated crash safety effects for segments are shown in Table 9. For each crash type, the EB expected crashes in the after period had the speed limit change not been implemented are shown along with the actual number of crashes observed in the after period, the CMF, and the standard error of the CMF. It is important to note that the expected crashes in the after period without treatment are provided with a decimal, because it is an estimated quantity, unlike the crashes in the after period that are observed.

The SPFs for segment crashes are presented in Appendix C. The main goodness of fit measure being used is the cumulative residual (CURE) plot. For a reliable SPF, the cumulative residuals are expected to be within the boundaries of the plot. When SPFs were estimated with all segments included (see Table C-1 in Appendix C), most of the cumulative residuals were outside the boundaries (see Figure C-2 in Appendix C for the total crash CURE plot). This strange CURE plot is likely due to the significant number of short segments in the data. To investigate this further, SPFs were estimated by excluding short segments (see Table C-2 in Appendix C). The CURE plot for SPFs developed using segments longer than 0.5 miles resulted in most of the cumulative residuals being within the boundaries indicating that the SPFs are more reliable (see Figure C-3 in Appendix C for total crash CURE plot).

For the segment CMF calculations shown in Table 9, all segments were included, and the SPFs estimated for segments longer than 0.5 miles were used in the prediction for all segments.

Table 9. Estimated Segment Crash Safety Effects

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	4771	5176.01	**0.922***	0.017
Injury (KABC)	1740	1828.48	**0.951****	0.026
Injury (KAB)	1046	907.62	**1.152***	0.040
Head On	424	432.72	**0.979**	0.052
Run Off Road	2157	2554.55	**0.844***	0.022

** Statistically Significant at the 95-percent Confidence Level*

***Statistically Significant at the 90-percent Confidence Level*

The results indicate the increasing the speed limits from 55 mph to 60 mph had minor impacts on segment crashes, especially for the more important injury crashes. The total crashes show a reduction of 7.8% (statistically significant at the 95% confidence level), along with a 4.9% reduction in KABC injury crashes (statistically significant at the 90% confidence level), a 15.2% increase in KAB injury crashes (statistically significant at the 95% confidence level), and a 15.6% reduction in run-off-road crashes (statistically significant at the 95% confidence level).

6.2 Estimated Intersection Crash Safety Effects

Intersections were divided into two different groups (further divided into four different subgroups each) for estimation of crash safety effects. CMFs were estimated for each of the four subgroups, alongside aggregate CMFs for the two groups.

- Intersections on two-lane, two-way state highway road segments – all control types:
    - 3-Legged intersections with lighting (n = 336),
    - 3-legged intersections with no lighting (n = 2760),
    - 4-legged intersections with lighting (n = 310), and
    - 4-legged intersections with no lighting (n = 2132).
- Intersections on two-lane, two-way state highway road segments – thru-stop only:
    - 3-Legged intersections with lighting (n = 331),
    - 3-legged intersections with no lighting (n = 2757),
    - 4-legged intersections with lighting (n = 301), and
    - 4-legged intersections with no lighting (n = 2127).

6.2.1 Intersections Safety Effects (All Traffic Control Types)

The estimated crash safety effects for the four subgroups of intersection with all traffic control types are shown in Tables 10-13. For each crash type, the EB expected crashes in the after period had the speed limit change not been implemented are shown along with the actual number of crashes observed in the after period, the CMF, and the standard error of the CMF.

Table 10. Intersection Safety Effects (3-Leg Intersection with No Lighting – All Control Types)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	768	781.41	**0.981**	0.052
Injury (KABC)	285	308.08	**0.922**	0.075
Injury (KAB)	144	177.62	**0.809***	0.082
Angle	92	68.38	**1.268**	0.320
Rear End	210	182.83	**1.141**	0.122

** Statistically Significant at the 95-percent Confidence Level*

Table 11. Intersection Safety Effects (3-Leg Intersection with Lighting – All Control Types)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	274	328.21	**0.830***	0.084
Injury (KABC)	101	103.54	**0.966**	0.134
Injury (KAB)	59	53.15	**1.085**	0.211
Angle	56	53.07	**1.033**	0.200
Rear End	87	101.58	**0.839**	0.147

** Statistically Significant at the 95-percent Confidence Level*

Table 12. Intersection Safety Effects (4-Leg Intersection with No Lighting – All Control Types)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	762	842.48	**0.903****	0.053
Injury (KABC)	324	362.05	**0.891**	0.079
Injury (KAB)	210	224.89	**0.926**	0.107
Angle	277	291.03	**0.942**	0.109
Rear End	174	163.72	**1.053**	0.129

***Statistically Significant at the 90-percent Confidence Level*

Table 13. Intersection Safety Effects (4-Leg Intersection with Lighting – All Control Types)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	596	1079.80	**0.548***	0.053
Injury (KABC)	223	284.78	**0.776***	0.089
Injury (KAB)	113	140.88	**0.796***	0.101
Angle	247	401.84	**0.607***	0.079
Rear End	180	607.55	**0.280***	0.067

** Statistically Significant at the 95-percent Confidence Level*

The results indicate the increasing the speed limits from 55 mph to 60 mph had varying impacts on intersection crashes at intersections with all traffic control types. Most of the safety effects were statistically insignificant except for total crashes (on 3-leg intersections with lighting – 17.0% reduction; on 4-leg intersections with no lighting – 9.7% reduction; and on 4-leg intersections with lighting – 45.2% reduction), injury (KABC) crashes (on 4-leg intersections with lighting – 22.4% reduction), injury (KAB) crashes (on 3-leg intersections with no lighting – 19.1% reduction; and on 4-leg intersections with lighting – 20.4% reduction), angle crashes (on 4-leg intersections with lighting – 39.3% reduction), and rear end crashes (on 4-leg intersections with lighting – 72.0% reduction) showing statistically significant safety effects at various significance levels.

The CMFs show a wide spread of values showing increases and reduction making it difficult to conclude the effects of speed limit change on the various crashes.

6.2.2 Intersections Safety Effects (Thru-Stop Only)

The estimated crash safety effects for the four subgroups of intersection with thru-stop control are shown in Tables 14-17. For each crash type, the EB expected crashes in the after period had the speed limit change not been implemented are shown along with the actual number of crashes observed in the after period, the CMF, and the standard error of the CMF.

Table 14. Intersection Safety Effects (3-Leg Intersection with No Lighting – Thru-Stop only)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	767	780.75	**0.981**	0.052
Injury (KABC)	284	308.08	**0.919**	0.074
Injury (KAB)	143	177.63	**0.802***	0.082
Angle	92	74.59	**1.179**	0.270
Rear End	210	182.28	**1.144**	0.123

** Statistically Significant at the 95-percent Confidence Level*

Table 15. Intersection Safety Effects (3-Leg Intersection with Lighting – Thru-Stop only)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	257	315.41	**0.809***	0.084
Injury (KABC)	92	104.47	**0.871**	0.126
Injury (KAB)	54	52.84	**0.995**	0.207
Angle	52	49.14	**1.036**	0.205
Rear End	80	101.32	**0.772**	0.142

** Statistically Significant at the 95-percent Confidence Level*

Table 16. Intersection Safety Effects (4-Leg Intersection with No Lighting – Thru-Stop only)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	762	839.21	**0.906****	0.053
Injury (KABC)	324	361.73	**0.892**	0.078
Injury (KAB)	210	222.38	**0.936**	0.108
Angle	277	219.26	**1.255**	0.127
Rear End	174	160.49	**1.074**	0.133

** Statistically Significant at the 95-percent Confidence Level*

Table 17. Intersection Safety Effects (4-Leg Intersection with Lighting – Thru-Stop only)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	572	1063.81	**0.533***	0.053
Injury (KABC)	218	285.57	**0.757***	0.088
Injury (KAB)	111	137.15	**0.802****	0.108
Angle	238	402.24	**0.583***	0.080
Rear End	171	470.87	**0.344***	0.081

** Statistically Significant at the 95-percent Confidence Level*
***Statistically Significant at the 90-percent Confidence Level*

The results indicate the increasing the speed limits from 55 mph to 60 mph had varying impacts on intersection crashes at intersections with all traffic control types. Most of the safety effects were statistically insignificant except for total crashes (on 3-leg intersections with lighting – 19.1% reduction; on 4-leg intersections with no lighting – 9.4% reduction; and on 4-leg intersections with lighting – 46.7% reduction), injury (KABC) crashes (on 4-leg intersections with lighting – 24.3% reduction), injury (KAB) crashes (on 3-leg intersections with no lighting – 19.8% reduction; and on 4-leg intersections with lighting – 19.8% reduction), angle crashes (on 4-leg intersections with lighting – 42.7% reduction), and rear end crashes (on 4-leg intersections with lighting – 65.6% reduction) showing statistically significant safety effects at various significance levels.

The CMFs show a wide spread of values showing increases and reduction making it difficult to conclude the effects of speed limit change on the various crashes.

6.2.3 Aggregate Intersections Safety Effects

The aggregate estimated crash safety effects for the two main groups of intersections (all traffic control types and thru-stop control only) are shown in Tables 18-19. For each crash type, the EB expected crashes in the after period had the speed limit change not been implemented are shown along with the actual number of crashes observed in the after period, the CMF, and the standard error of the CMF.

Table 18. Intersection Safety Effects (All Control Types – 3-leg and 4-leg Combined)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	2400	3031.90	**0.791***	0.033
Injury (KABC)	933	1058.46	**0.880***	0.045
Injury (KAB)	526	596.53	**0.880***	0.056
Angle	672	814.32	**0.821***	0.066
Rear End	651	1055.68	**0.604***	0.087

** Statistically Significant at the 95-percent Confidence Level*

Table 19. Intersection Safety Effects (Thru-Stop only – 3-leg and 4-leg Combined)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	2358	2999.19	**0.785***	0.033
Injury (KABC)	918	1059.85	**0.865***	0.044
Injury (KAB)	518	590.00	**0.876***	0.057
Angle	659	745.23	**0.879****	0.073
Rear End	635	914.96	**0.683***	0.089

** Statistically Significant at the 95-percent Confidence Level*
***Statistically Significant at the 90-percent Confidence Level*

The results indicate increasing the speed limits from 55 mph to 60 mph had varying impacts on aggregate intersection crashes at intersections with all traffic control types and thru-stop control only. For intersections with all traffic control types, a 20.9% reduction was seen in total crashes, alongside 12% reductions in injury (KABC) and injury (KAB) crashes, a 17.9% reduction in angle crashes and a 39.6% reduction is rear end crashes, all statistically significant at the 95% significance level. For intersections with thru-stop control only, a 21.5% reduction was seen in total crashes, alongside a 13.5% reduction in injury (KABC) crashes, a 12.4% reduction in injury (KAB) crashes, a 17.9% reduction in angle crashes and a 39.6% reduction is rear end crashes, all statistically significant at either 90% or 95% significance levels.

The disaggregate CMFs (Tables 10-17) showed a wide range of increases and reduction in crashes (most of which were statistically insignificant) making it difficult to conclude the effects of speed limit change on the various crashes. The aggregate CMFs (Tables 18-19) show significant reductions for all crash types.

6.3 Estimated Aggregate Segment and Intersection Crash Effects

The aggregate estimated crash safety effects (for total and injury crashes) for combined segments and intersection sites are shown in Table 20. For each crash type, the EB expected crashes in the after period had the speed limit change not been implemented are shown along with the actual number of crashes observed in the after period, the CMF, and the standard error of the CMF.

Table 20. Aggregate Safety Effect (All Segments and Intersections Combined)

Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Total	7171	8207.91	**0.873***	0.017
Injury (KABC)	2673	2886.93	**0.926***	0.024
Injury (KAB)	1572	1504.15	**1.045*****	0.029

** Statistically Significant at the 95-percent Confidence Level*
**** Statistically Significant at the 85-percent Confidence Level*

The results indicate that increasing the speed limits from 55 mph to 60 mph has considerable impact when all the segments and intersections are used to derive an aggregate safety effect. Total crashes show a 12.7% reduction (significant at the 95% confidence level), alongside a 7.4% reduction in the injury (KABC) crashes (significant at the 95% confidence level), and a 4.5% increase in the injury (KAB) crashes (significant at the 85% confidence level).

6.4 Operating Speed Changes

The operating speed was also available for the speed change segments. To analyze the operating speeds before and after the speed limit change, only those segments for which at least 4 quarters of operating speed data was available in the before and after periods were used.

The following two measures were used:

- *Measure 1:* Average operating speed in the after period minus the average operating speed in the before period.
- *Measure 2:* Range of operating speed (95^{th}-Percentile minus 5^{th}-Percentile) in the after period minus the range of operating speed (95th-Percentile minus 5th-Percentile) in the before period minus

For both measures, the speed delta was divided into various sub-categories the various subcategories. The segment mileage associated with each category is listed below:

- Measure 1
    - Speed delta = Negative (58.91 miles)
    - Speed delta = 0 to less than 2 mph (179.07 miles)
    - Speed delta = 2 to less than 5 mph (201.03 miles)
    - Speed delta = Greater than 5 mph (33.27 miles)
- Measure 2
    - Speed delta = Less than -5 mph (77.60 miles)
    - Speed delta = -5 to less than -2 mph (59.29 miles)

- Speed delta = -2 to less than 0 mph (34.67 miles)
- Speed delta = 0 to 2 mph (41.58 miles)
- Speed delta = 2 to 5 mph (82.10 miles)
- Speed delta = Greater than 5 mph (177.05 miles)

The CMFs associated with both measures are presented in Appendix E.

Chapter 7: Conclusions

The objective of this study was to re-evaluate safety impacts of increasing the speed limit from 55 mph to 60 mph on two-lane, two-way state highway road segments. EB analysis was done to estimate CMFs for both segments and intersections.

When interpreting the results, the following should be considered:

- In 2016, Minnesota adopted a new crash reporting system that changed the way some of the crashes were defined.
- For intersections, only the major road AADT was available and used for SPF development.
- The effect of COVID-19 on crashes (the ACFs presented in Appendix D provide an insight into the yearly crash trends).

The segment analysis showed an 8 percent reduction in total crashes and a 15 percent increase in KAB injury crashes, both statistically significant at the 95% confidence level, alongside significant decreases in KABC injury and run-off-road crashes. The range of most of the segment CMFs hovered close to 1. The intersection analysis was split into two groups (all traffic control types and thru-stop control only). The aggregate CMFs for all intersections within these two groups showed, on average, between a 10% and 20% statistically significant reduction in crashes. Analysis was also performed on four subgroups (3- and 4-leg, lighting/no lighting) within the two main intersection groups. Disaggregating the intersections into further groups led to smaller sample sizes that led to higher standard errors showing a widespread range of CMFs around 1 for the individual crash types and severities.

These results generally showed an improvement in CMFs compared to the previous evaluation (Saleem et al., 2020). For example, the total segment crashes went from showing a 7% increase to showing an 8% reduction. Similarly, the aggregate CMFs for all intersections within the two groups (i.e., all traffic control types and thru-stop control only) also show statistically significant reduction of between 10% and 20% compared to previous evaluation showing almost minor statistically increases/reduction in crashes. The aggregate estimated crash safety effects (for total and injury crashes) for combined segments and intersection sites showed a reduction in total crashes but an increase in the KAB injury crashes.

The improvement seen in the CMFs in this re-evaluation can be attributed to a larger crash sample being used; however, overall, it can be concluded that that the speed limit increase from 55 mph to 60 mph resulted in fewer overall crashes but potentially more severe crashes.

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Appendix A:
Empirical Bayes (EB) Methodology

In the EB approach, the estimated change in safety for a given crash type at a site is given by the equation in Figure A-1.

$$\Delta Safety = \lambda - \pi$$

Figure A-1. Equation. Estimated Change in Safety

Where:

λ = Expected number of crashes that would have occurred in the after without the treatment.

π = Number of reported crashes in the after period.

In estimating λ, the effects of regression to the mean and changes in exposure were explicitly accounted for using SPFs. In this effort, the SPFs were estimated using crash data and characteristics of the sites in the reference group (Group 3) and the before-period of the treatment group (Groups 1 and 2). The SPFs were estimated using negative binomial regression. The SPFs were also used to estimate ACFs for each year. The ACFs are defined as the ratio of the total observed crash frequency to the total predicted crash frequency from the SPF are calculated for each year. The ACFs are estimated to account for time trends.

The sum of the annual SPF estimates for the before period (P) was then combined with the count of crashes (x) in the before period at a treatment site to obtain an estimate of the expected number of crashes (m) before the treatment was applied.

$$m = w(P) + (1 - w)(x)$$

Figure A-2. Equation. Empirical Bayes Estimates of Expected Crashes in the Before Period

Where the EB weight, w, was estimated from the mean and variance of the SPF estimate using the equation in Figure A-3.

$$w = \frac{1}{1+kP}$$

Figure A-3. Equation. Empirical Bayes Weight

Where:

k = Overdispersion parameter of the negative binomial distribution.

The expected number of crashes in the after period, λ, was calculated by applying a factor to m as seen in the equation in Figure A-4Figure . This factor was the sum of the annual SPF estimates for the after period (A) divided by P.

$$\lambda = m \times \left(\frac{A}{P}\right)$$

Figure A-4. Equation. Empirical Bayes Estimates of Expected Crashes in the After Period

The estimate of λ and variance of λ, were then summed over all sites to obtain λ_{sum} and $Var(\lambda_{sum})$. λ_{sum} was then compared with the sum of count of crashes observed during the after period over all sites (π_{sum}) to obtain the CMF (θ). The safety effect θ was calculated using the equation in Figure A-5 and the standard error of θ was calculated using the equation in Figure A-6.

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1 + \left(\frac{Var(\lambda_{sum})}{\lambda_{sum}^{2}}\right)}$$

Figure A-5. Equation. CMF

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

Figure A-6. Equation. Standard Error of CMF

The percent change in crashes is calculated as $100(1-\theta)$. Therefore, a value of $\theta = 0.9$ with a standard of error of 0.05 indicates a 10% reduction in crashes with a standard error of 5%. Conversely, a value of $\theta = 1.2$ with a standard of error of 0.1 indicates a 20% increase in crashes with a standard error of 10%.

Appendix B:
Database Development

B.1 Data Sources

Roadway attribute data, crash data, project data, and traffic volume data required for this evaluation are identified and gathered in accordance with the project Master Data Collection Plan. The data used is statewide for the years 2012 to 2022. The data sources used in this evaluation are as follows:

- Roadway attribute data (e.g., lane widths, shoulder widths)
- Traffic volume data (e.g., average number of vehicles per day, year of data collection)
- Speed Study data (e.g., speed limits, speed limit change date)
- Intersection data (e.g., number of approaches, traffic control type)
- Curve data (e.g., curve radius, curve length)
- Crash data (e.g., crash severity, crash type, crash date)

B.2 Roadway Files

Roadway information from 2009 to 2015 is available from the TIS system, whereas the roadway information from 2016 to 2022 is available from the LRS system/HPMS. Travel lane widths were compared between years 2012 and 2022, and any segments that did not match between these years were eliminated from the data set. The following steps identify how data was extracted from the HPMS, LRS, and TIS systems and how it was made cohesive in ArcGIS.

1) Primary Roadway File (2018-2022)

   Roadway information from the LRS system (2018-2022) was located in two files:

   a) An ArcGIS line file that contains basic roadway information in segments, and
   b) A table that contains additional information for the roadway segments (59 columns of data).

   In order to combine the table information with the main roadway ArcGIS file, a "Route Event Layer" was created to join the table data to the roadway segments using the Route ID as a common attribute.

B.3 Volume Files

The volume data from 2009-2022 was obtained from the yearly AADT volume ArcGIS line file[3] files accessed through the MnDOT Geocommons.

In order to eliminate join issues near intersections with the roadway file, the modified volume file was intersected with the study segment file prior to any spatial joins. This eliminated any AADT values from cross streets and roadways not associated with the study.

[3] https://www.dot.state.mn.us/traffic/data/data-products.html#volume

B.4 Speed Study Files

The speed study data was located in three files:

a) An ArcGIS line file that contains information for each speed study segment (2009-2018),
b) A table that contains additional information for the study segments (38 columns of data) (2009-2018), and
c) An ArcGIS line file from StreetLight containing quarterly speed data (averages and percentiles) for study segments (2018-2022)

In the data table, a unique ID was created for each study segment (this was done by creating a unique number for each study, ex: SS1, SS2, etc.). The speed study segment file was joined to the data table using the section description field.

The StreetLight speed data was attached to OpenStreetMap (OSM) highway segments differing from the MnDOT segments used in the rest of the analysis, i.e., one MnDOT highway segment might intersect with multiple StreetLight segments. In order to join StreetLight speed data to the original speed study segment file, OSM segments were buffered (as shown in Figure B-1) and allocated to the MnDOT segments weighted by VMT.

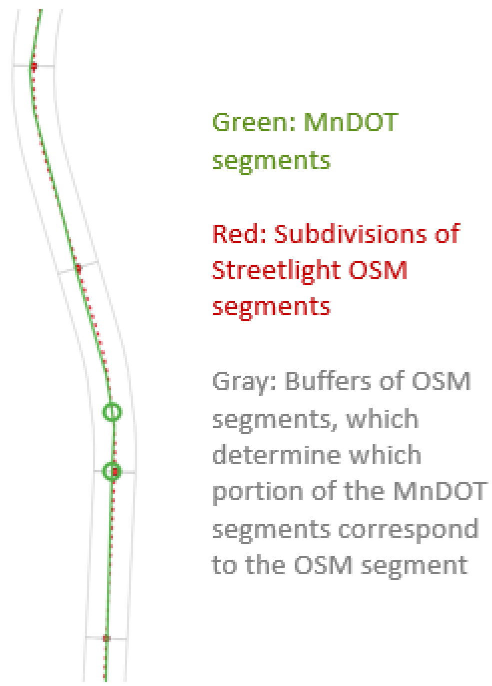

Figure B-1. Buffered StreetLight OSM Segments Compared to MnDOT Segments

B.5 Intersection Files

The intersection data was located in an ArcGIS polygon file. The intersection file had polygons with an average radius of 50 feet from the center of the intersection. For this study, we increased the radius to 250 feet to capture the crash area of influence of the intersection. As such a buffer of 200 feet was added to each intersection.

B.6 Curve Files

The curve data was located in two files:

a) An ArcGIS line file that contains information for each curve (the district safety plan curve file), and
b) An ArcGIS database file that contains additional information for curves (53 columns of data)

The district safety plan curve file is joined to the database file using the unique curve number. The district safety plan curve file with additional data is spatially joined to the ARCGIS file containing basic roadway information prior to creating route event layers allowing for the curve data to be spatially joined and the curve information to be transferred to the roadway file.

Appendix C:
Safety Performance Functions

SPFs were estimated for each of the target crash types and crash severities. The relationship between the crash frequency and the independent variables can be seen in Figure C-1.

$$Crashes = \exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \_\_\_ + \beta_n X_n)$$

Figure C-1. Equation. Sample Safety Performance Function

Where:

α = intercept,

X = independent (exposure) variables, and

β = coefficient estimates.

SPFs for segments and intersections (both all traffic control types and thru-strop control only) are presented in Tables C-1 – C-10.

The main goodness of fit measure being used to assess the SPFs is the cumulative residual (CURE) plot. For a reliable SPF, the cumulative residuals are expected to be within the boundaries of the plot. CURE plots for segment and intersection total crash SPFs are presented in Figures C-2 – C-11.

Table C-1. SPFs for Segment Crashes Developed using All Segments

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Head On Estimate	Run Off Road Estimate
Intercept	-6.706	-7.309	-7.772	-11.402	-7.250
AADT	0.711	0.639	0.611	0.955	0.726
AADT/10000	0.573	0.613	0.395	0.290	-0.071
Degree of Curvature	0.089	0.086	0.098	0.079	0.108
Yearly Factor - 2012	-0.131	0.072	-0.163	0.541	-2.190
Yearly Factor - 2013	-0.011	0.089	-0.095	0.645	-1.909
Yearly Factor - 2014	-0.038	0.039	-0.173	0.583	-2.328
Yearly Factor - 2015	-0.187	-0.052	-0.070	0.548	-2.059
Yearly Factor - 2016	0.007	0.123	0.208	0.427	-0.115
Yearly Factor - 2017	0.043	0.171	0.255	0.286	-0.030
Yearly Factor - 2018	-0.070	0.102	0.080	0.307	-0.061
Yearly Factor - 2019	0.086	0.051	0.065	0.470	-0.274
Yearly Factor - 2020	-0.057	-0.004	0.202	0.402	-0.065
Yearly Factor - 2021	-0.037	0.086	-0.015	0.010	-0.056
Yearly Factor - 2022	0	0	0	0	0
Dispersion	0.834	0.908	0.897	1.580	0.981

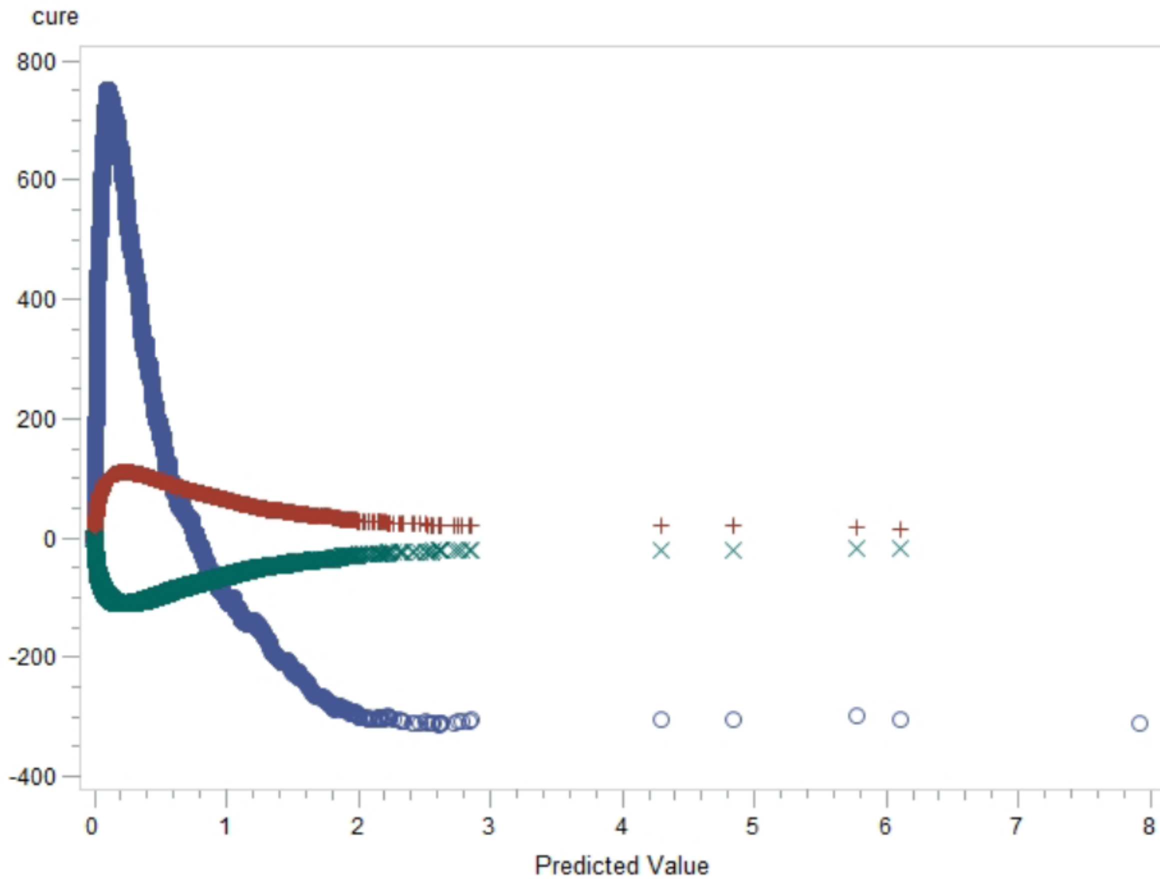

Figure C-2. CURE Plot – SPF for Total Segment Crashes Developed using All Segments

Table C-2. SPFs for Segment Crashes Developed using Segments > 0.5 miles

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Head On Estimate	Run Off Road Estimate
Intercept	-6.595	-6.999	-7.507	-11.300	-7.498
AADT	0.683	0.571	0.582	0.960	0.760
AADT/10000	0.608	0.757	0.498	0.389	-0.135
Degree of Curvature	0.179	0.265	0.496	-0.162	-0.022
Yearly Factor - 2012	-0.234	0.003	-0.218	0.277	-2.488
Yearly Factor - 2013	-0.111	0.130	-0.077	0.439	-2.325
Yearly Factor - 2014	-0.133	0.050	-0.212	0.188	-2.761
Yearly Factor - 2015	-0.243	-0.073	0.000	0.225	-2.300
Yearly Factor - 2016	-0.171	0.045	0.045	0.044	-0.449
Yearly Factor - 2017	-0.101	0.166	0.178	-0.187	-0.366
Yearly Factor - 2018	-0.096	0.156	0.040	0.156	-0.277
Yearly Factor - 2019	0.045	0.178	0.089	0.342	-0.470
Yearly Factor - 2020	-0.099	0.063	0.252	0.113	-0.243
Yearly Factor - 2021	-0.205	-0.137	-0.257	-0.919	-0.243
Yearly Factor - 2022	0	0	0	0	0
Dispersion	0.453	0.538	0.828	1.341	0.753

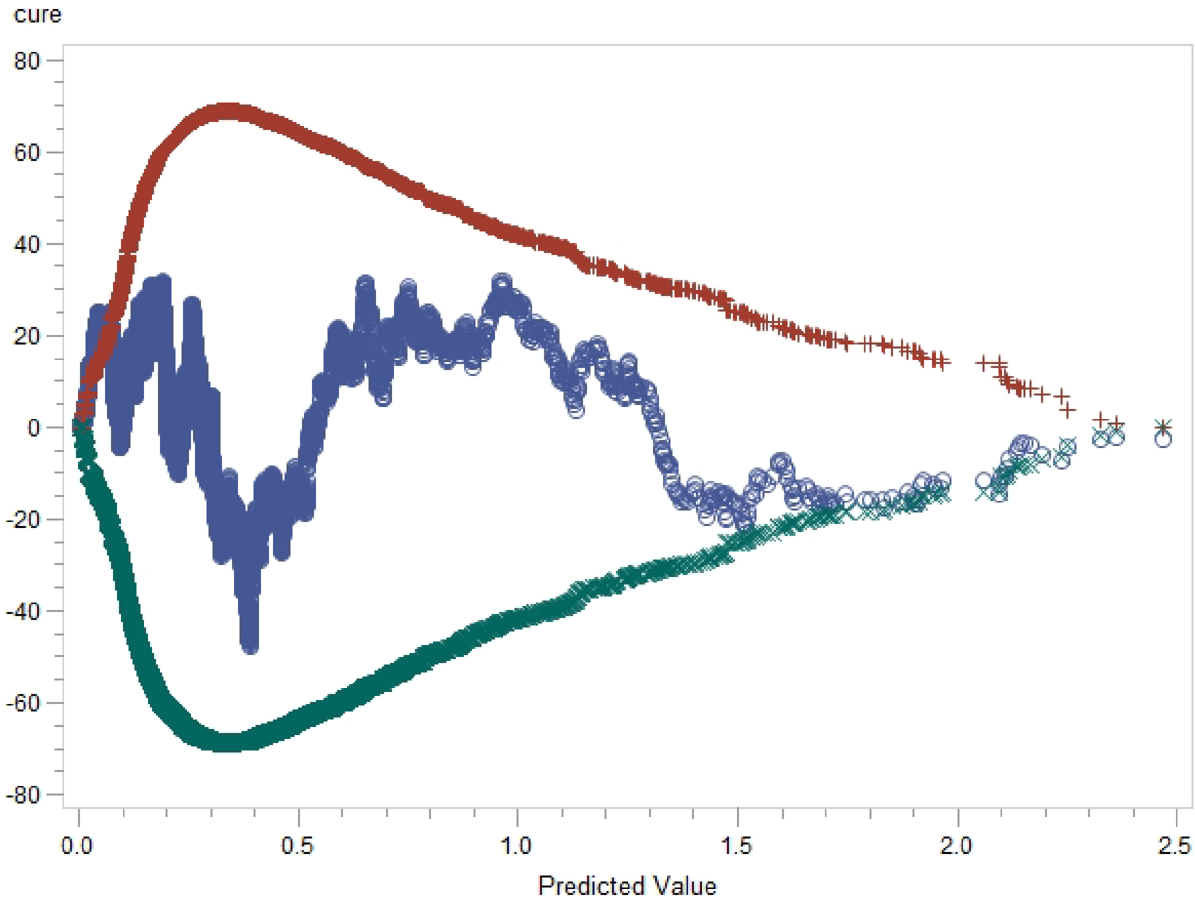

Figure C-3. CURE Plot – SPF for Total Segment Crashes Developed using Segments > 0.5 miles

Table C-3. SPFs for Intersection Crashes (3-Leg Intersections with No Lighting – All Control Types)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-8.9109	-28.9799	-27.5399	-30.8894	-12.5418
Major Road AADT	0.8619	0.7676	0.6763	1.0027	1.3837
Yearly Factor - 2012	0.3745	0.8746	0.4356	0.0556	0.2501
Yearly Factor - 2013	0.4702	0.9456	0.308	-0.1324	0.3641
Yearly Factor - 2014	0.466	0.9409	0.4772	0.1162	0.3722
Yearly Factor - 2015	0.4301	0.9751	0.3454	0.1162	0.4311
Yearly Factor - 2016	-0.0337	0.4804	0.236	-0.3733	0.1633
Yearly Factor - 2017	0.1901	0.7306	0.0788	0.0279	0.4614
Yearly Factor - 2018	0.092	0.5418	0.3335	-0.515	0.1576
Yearly Factor - 2019	0.289	0.4846	0.2851	-0.1512	0.4371
Yearly Factor - 2020	-0.0206	0.6316	0.4011	-0.4943	-0.0447
Yearly Factor - 2021	0.1796	0.6309	0.3523	-0.496	0.0156
Yearly Factor - 2022	0	0	0	0	0
TCF - All Way Stop	-19.0918	-0.6181	-0.7364	-0.8317	-21.6524
TCF - Thru Stop	-0.8708	18.5642	17.6728	17.6924	-3.1142
TCF - Thru Yield	0	0	0	0	0
Dispersion	2.15	2.1653	2.0677	10.1341	2.2668

Note: TCF = Traffic Control Factor

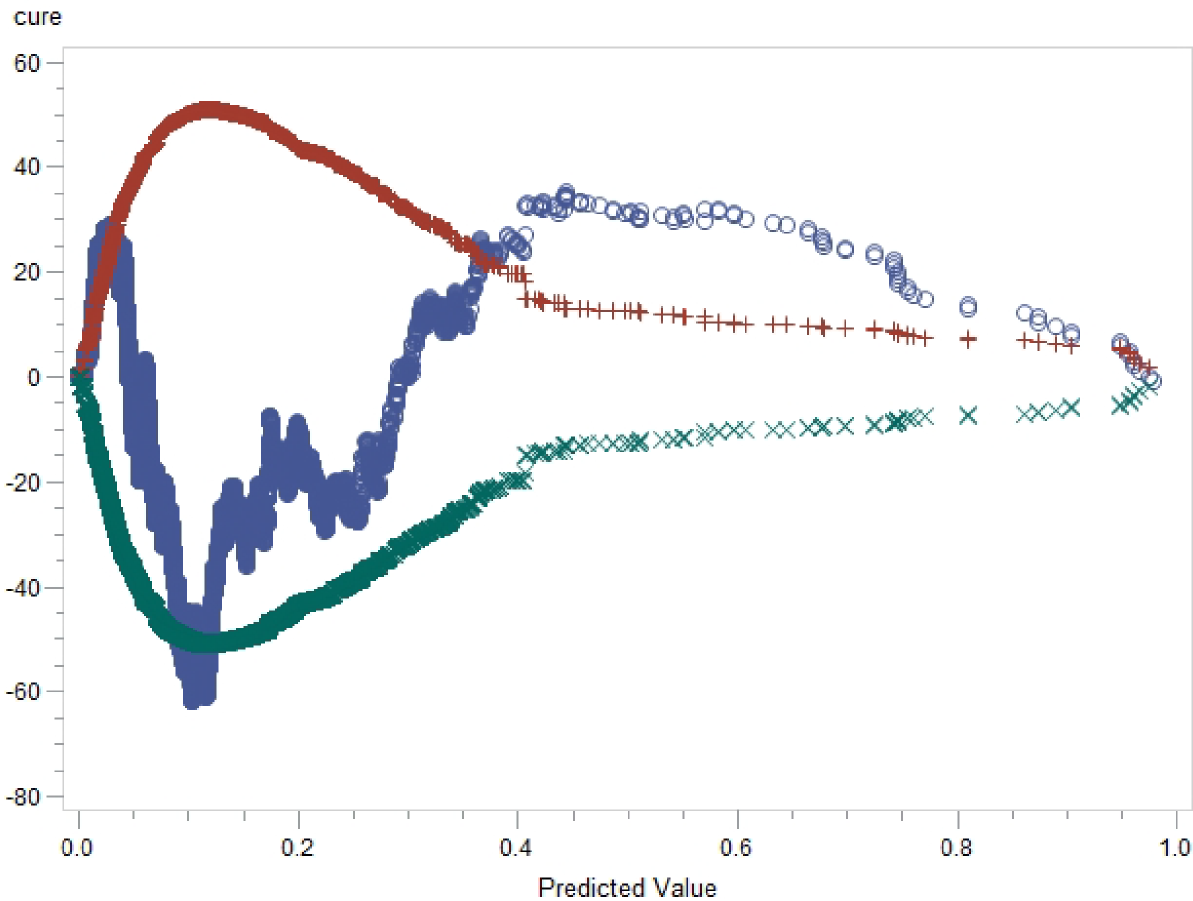

Figure C-4. CURE Plot - SPFs for Total Intersection Crashes (3-Leg Intersections with No Lighting – All Control Types)

Table C-4. SPFs for Intersection Crashes (3-Leg Intersections with Lighting – All Control Types)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-29.3857	-29.8641	-29.8458	-31.3531	-35.2409
Major Road AADT	0.8553	0.7728	0.6865	0.9158	1.2518
Yearly Factor - 2012	0.2443	0.4658	-0.0654	-0.0987	0.3262
Yearly Factor - 2013	-0.0093	0.2553	-0.0589	0.0038	-0.0997
Yearly Factor - 2014	0.0455	-0.1331	0.1281	-0.339	0.1576
Yearly Factor - 2015	0.1955	0.3868	0.6095	-0.1947	0.2604
Yearly Factor - 2016	0.0928	0.1193	0.4136	0.1389	0.1222
Yearly Factor - 2017	-0.0559	0.1049	0.2155	-0.4426	0.2447
Yearly Factor - 2018	-0.2121	-0.0494	-0.0033	-0.049	-0.2818
Yearly Factor - 2019	0.1897	0.2364	0.3716	0.3645	0.0127
Yearly Factor - 2020	-0.3022	-0.2844	-0.3657	0.1982	-0.3869
Yearly Factor - 2021	-0.1127	-0.4551	0.1167	-0.5152	-0.1105
Yearly Factor - 2022	0	0	0	0	0
TCF - All Way Stop	22.2991	0.8726	0.6211	0.7159	4.0804
TCF - Signalized	21.5218	21.6159	21.7777	21.0849	22.6692
TCF - Thru Stop	20.5712	20.6668	20.5197	20.3272	21.6684
TCF - Thru Yield	0	0	0	0	0
Dispersion	1.4754	1.2715	1.8941	1.5135	1.4051

Note: TCF = Traffic Control Factor.

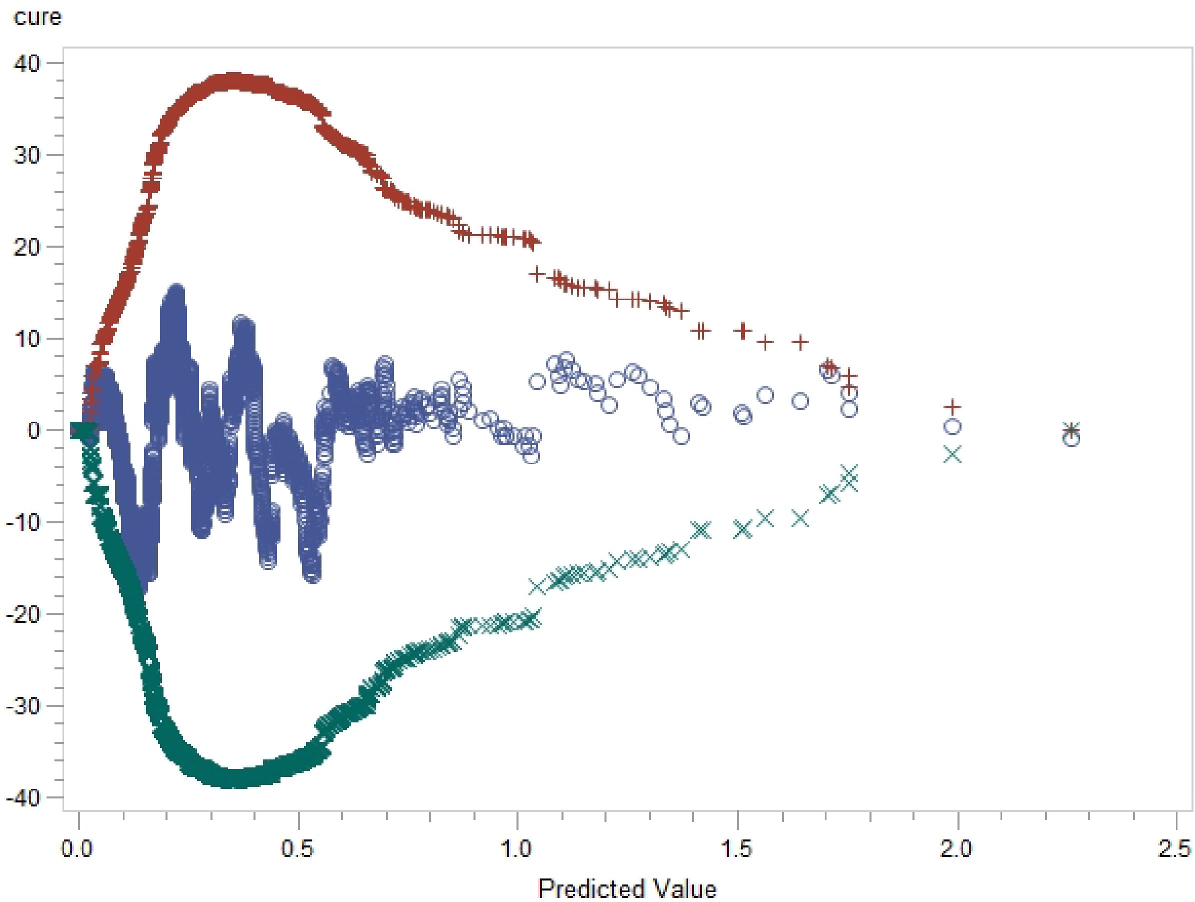

Figure C-5. CURE Plot - SPFs for Total Intersection Crashes (3-Leg Intersections with Lighting – All Control Types)

Table C-5. SPFs for Intersection Crashes (4-Leg Intersections with No Lighting – All Control Types)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-29.7303	-30.2952	-29.7842	-29.7084	-34.8538
Major Road AADT	0.9316	0.866	0.7642	0.7689	1.508
Yearly Factor - 2012	0.1976	0.387	0.0328	0.6186	-0.4377
Yearly Factor - 2013	0.2728	0.5533	0.4406	0.9534	-0.3842
Yearly Factor - 2014	0.1799	0.4135	0.2461	0.5223	-0.3298
Yearly Factor - 2015	0.1672	0.4117	0.1053	0.8062	-0.5369
Yearly Factor - 2016	-0.497	-0.2649	-0.1434	0.3855	-0.7364
Yearly Factor - 2017	-0.2097	-0.3518	-0.3124	0.5541	-0.5105
Yearly Factor - 2018	-0.1683	0.1061	0.0491	0.8056	-0.6174
Yearly Factor - 2019	-0.1264	-0.0675	-1.0111	0.6358	-0.3703
Yearly Factor - 2020	-0.1165	0.2595	-0.0457	1.3833	-1.0696
Yearly Factor - 2021	-0.0032	0.3382	0.3005	0.7129	-0.1496
Yearly Factor - 2022	0	0	0	0	0
TCF - All Way Stop	21.1052	21.3654	21.0754	20.8526	20.1282
TCF - Thru Stop	20.0629	20.0051	19.7725	19.3149	19.2761
TCF - Thru Yield	0	0	0	0	0
Dispersion	1.7866	1.9349	2.4659	5.753	2.3307

Note: TCF = Traffic Control Factor.

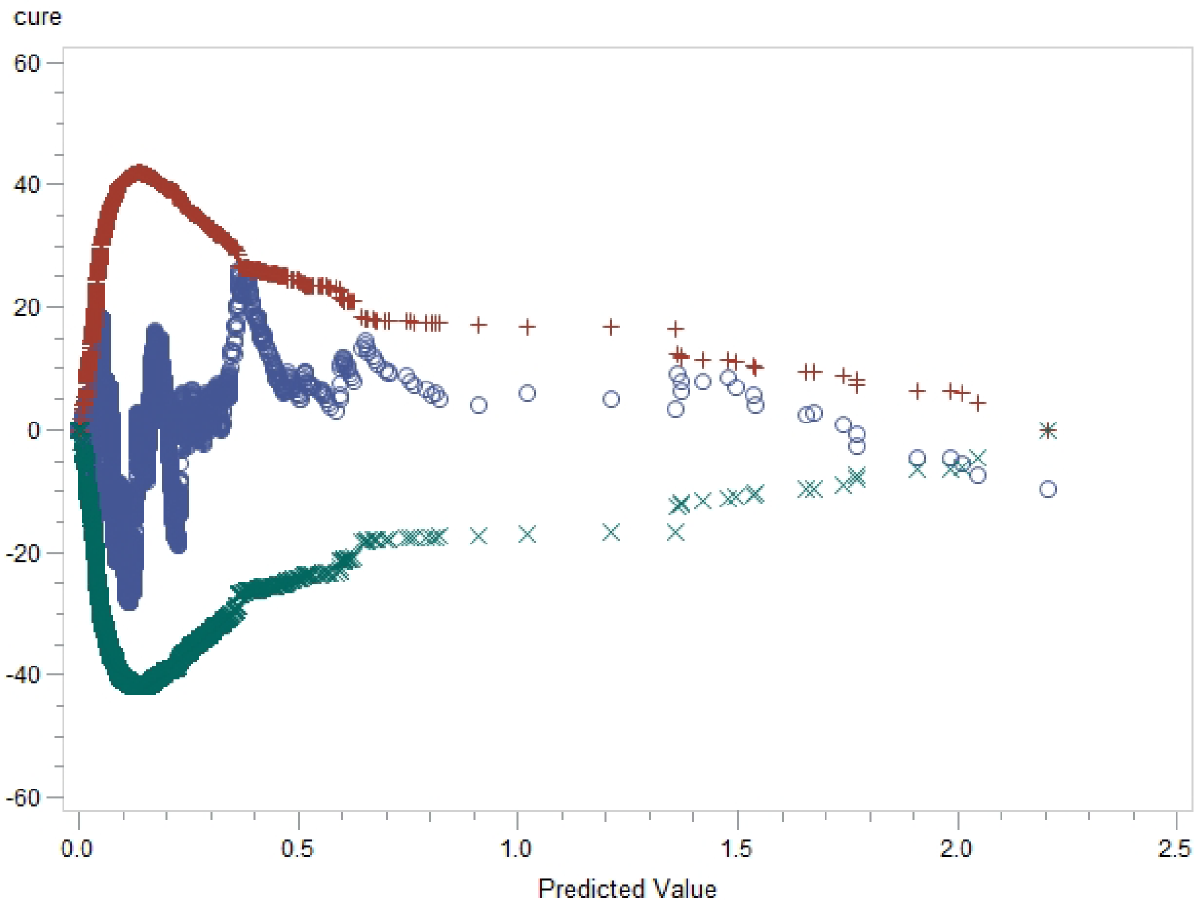

Figure C-6. CURE Plot - SPFs for Total Intersection Crashes (4-Leg Intersections with No Lighting – All Control Types)

Table C-6. SPFs for Intersection Crashes (4-Leg Intersections with Lighting – All Control Types)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-7.9017	-7.7595	-6.8918	-6.9639	-14.1834
Major Road AADT	0.8326	0.7096	0.5524	0.6456	1.3048
Yearly Factor - 2012	-0.0299	-0.011	-0.3441	-0.455	-0.3931
Yearly Factor - 2013	0.0732	0.1143	-0.2775	-0.3364	0.7049
Yearly Factor - 2014	-0.0642	-0.0384	-0.2623	-0.5978	0.5867
Yearly Factor - 2015	0.0505	0.1594	0.0236	-0.4659	0.7815
Yearly Factor - 2016	-0.1708	-0.2007	-0.3106	-0.3207	0.4765
Yearly Factor - 2017	-0.2124	-0.3074	-0.1997	-0.5039	0.5655
Yearly Factor - 2018	-0.2489	-0.2709	-0.3917	-0.4315	0.1783
Yearly Factor - 2019	-0.2132	-0.2277	-0.5267	-0.2401	0.1929
Yearly Factor - 2020	-0.1984	-0.1125	-0.0748	-0.1008	-0.4305
Yearly Factor - 2021	-0.2176	-0.2241	-0.0341	-0.4363	0.0455
Yearly Factor - 2022	0	0	0	0	0
TCF - All Way Stop	0.1365	-0.1776	-0.1124	0.4831	-22.0773
TCF - Signalized	0.8531	0.6886	0.3926	0.2875	1.3976
TCF - Roundabout	1.103	1.1666	1.7008	1.4418	0.5358
TCF - Thru Stop	0	0	0	0	0
Dispersion	1.8966	1.1427	0.7838	2.6891	1.7279

Note: TCF = Traffic Control Factor.

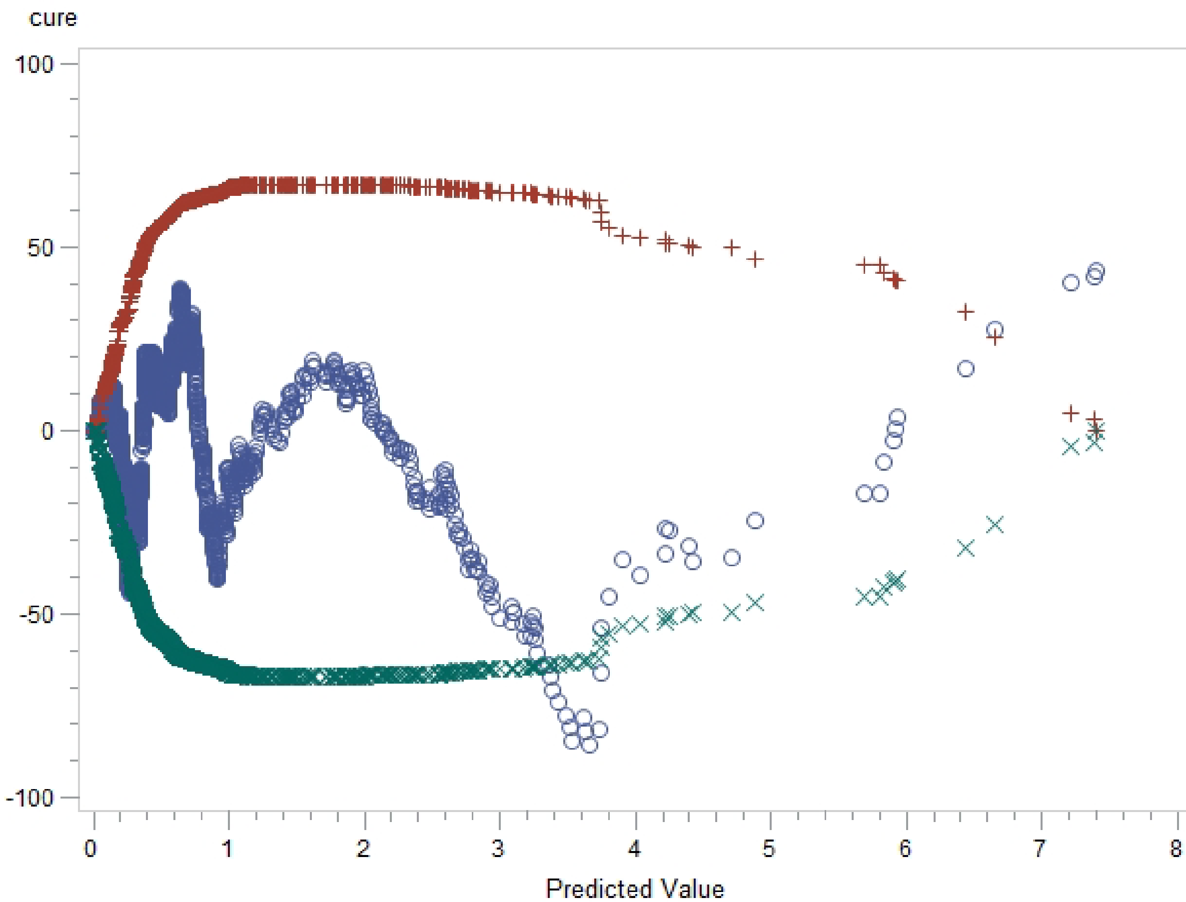

Figure C-7. CURE Plot - SPFs for Total Intersection Crashes (4-Leg Intersections with Lighting – All Control Types)

Table C-7. SPFs for Intersection Crashes (3-Leg Intersections with No Lighting – Thru-Stop only)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-9.7792	-10.4157	-9.867	-12.927	-15.6498
Major Road AADT	0.8616	0.7676	0.6763	1.0027	1.383
Yearly Factor - 2012	0.3751	0.8746	0.4356	0.0556	0.2521
Yearly Factor - 2013	0.4708	0.9456	0.308	-0.1324	0.3661
Yearly Factor - 2014	0.4667	0.9409	0.4772	0.1162	0.3741
Yearly Factor - 2015	0.4309	0.9751	0.3454	0.1162	0.4334
Yearly Factor - 2016	-0.0394	0.4804	0.236	-0.3733	0.1458
Yearly Factor - 2017	0.1908	0.7306	0.0788	0.0279	0.4641
Yearly Factor - 2018	0.092	0.5418	0.3335	-0.515	0.1574
Yearly Factor - 2019	0.289	0.4846	0.2851	-0.1512	0.437
Yearly Factor - 2020	-0.0206	0.6316	0.4011	-0.4943	-0.0447
Yearly Factor - 2021	0.1796	0.6309	0.3523	-0.496	0.0154
Yearly Factor - 2022	0	0	0	0	0
Dispersion	2.1512	2.1653	2.0677	10.1341	2.2791

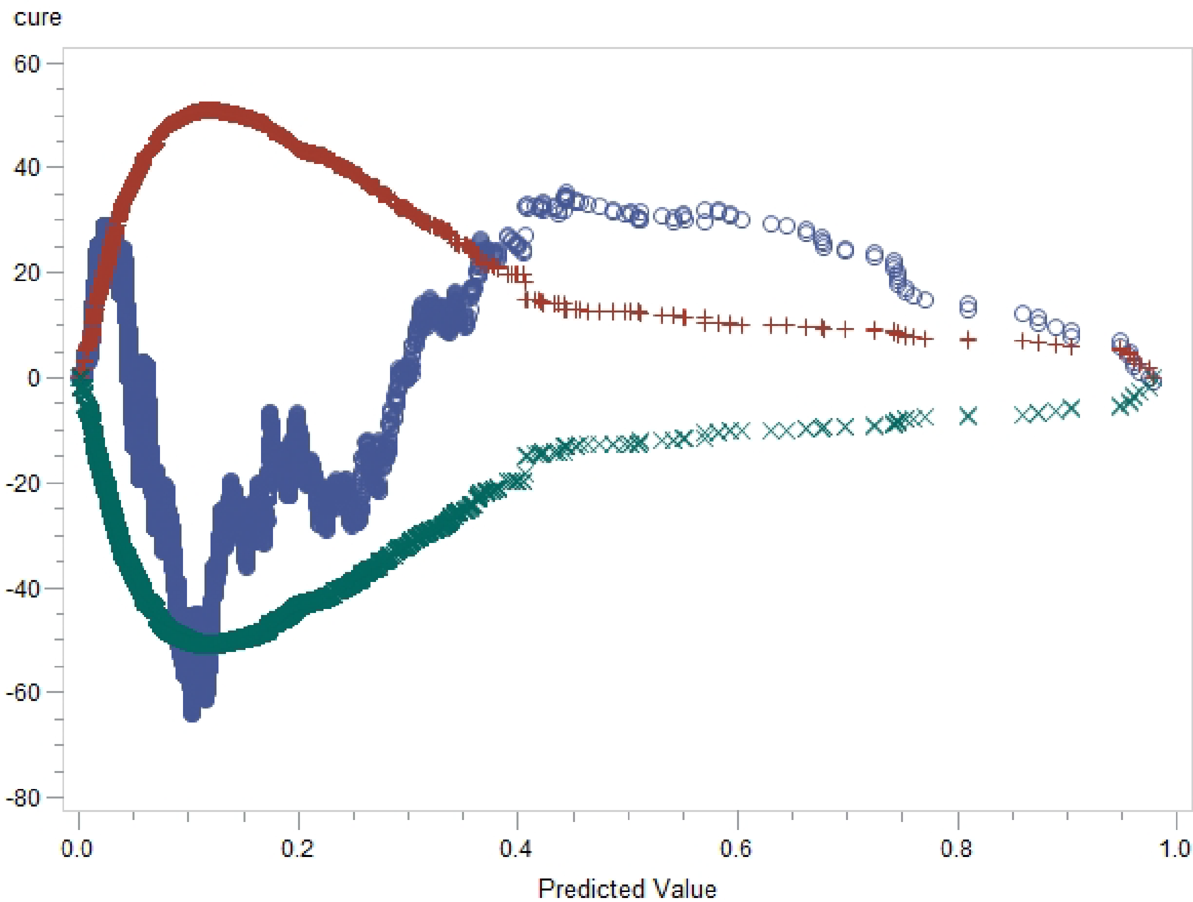

Figure C-8. CURE Plot - SPFs for Total Intersection Crashes (3-Leg Intersections with No Lighting – Thru-Stop Only)

Table C-8. SPFs for Intersection Crashes (3-Leg Intersections with Lighting – Thru-Stop only)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-8.8526	-9.2974	-9.491	-11.0061	-13.6798
Major Road AADT	0.8583	0.79	0.7128	0.9192	1.2606
Yearly Factor - 2012	0.2687	0.4287	-0.1357	-0.1107	0.3747
Yearly Factor - 2013	0.0097	0.2066	-0.0782	-0.0084	-0.0494
Yearly Factor - 2014	0.0573	-0.173	0.1074	-0.3498	0.1668
Yearly Factor - 2015	0.2167	0.3125	0.558	-0.2599	0.3015
Yearly Factor - 2016	0.1198	0.062	0.3114	0.0815	0.1514
Yearly Factor - 2017	-0.0814	-0.031	-0.0344	-0.5295	0.2201
Yearly Factor - 2018	-0.1888	-0.0839	-0.0853	-0.1132	-0.2353
Yearly Factor - 2019	0.2009	0.2032	0.2998	0.359	0.0203
Yearly Factor - 2020	-0.3697	-0.2795	-0.3619	-0.1127	-0.3597
Yearly Factor - 2021	-0.0828	-0.4526	0.1127	-0.5141	-0.021
Yearly Factor - 2022	0	0	0	0	0
Dispersion	1.5236	1.434	2.277	1.3747	1.575

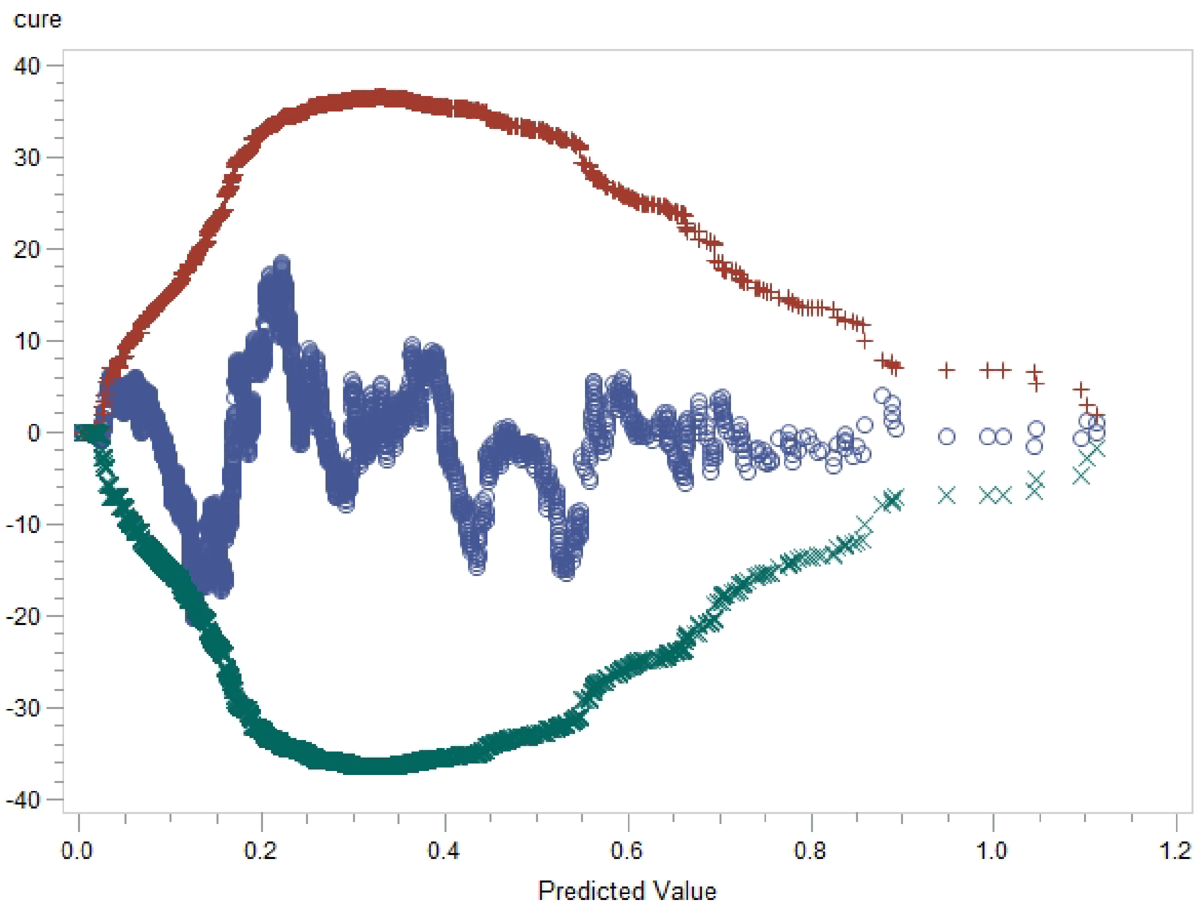

Figure C-9. CURE Plot - SPFs for Total Intersection Crashes (3-Leg Intersections with Lighting – Thru-Stop Only)

Table C-9. SPFs for Intersection Crashes (4-Leg Intersections with No Lighting – Thru-Stop only)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-9.7431	-10.3981	-10.1226	-	-15.7412
Major Road AADT	0.9427	0.8816	0.7805	-	1.5292
Yearly Factor - 2012	0.1855	0.3723	0.0264	-	-0.44
Yearly Factor - 2013	0.2649	0.5483	0.4339	-	-0.3863
Yearly Factor - 2014	0.1713	0.3987	0.2202	-	-0.3316
Yearly Factor - 2015	0.1533	0.3837	0.0719	-	-0.5372
Yearly Factor - 2016	-0.4995	-0.2666	-0.1469	-	-0.7397
Yearly Factor - 2017	-0.2164	-0.3597	-0.3212	-	-0.5194
Yearly Factor - 2018	-0.1918	0.0989	0.0415	-	-0.7209
Yearly Factor - 2019	-0.1838	-0.1495	-1.0144	-	-0.4974
Yearly Factor - 2020	-0.1167	0.2584	-0.0468	-	-1.0768
Yearly Factor - 2021	-0.031	0.2804	0.1952	-	-0.1549
Yearly Factor - 2022	0	0	0	-	0
Dispersion	1.7503	1.8443	2.4711	-	2.3252

For Angle crashes: Use Total crash SPF with the crash proportion of Angle crashes to Total crashes

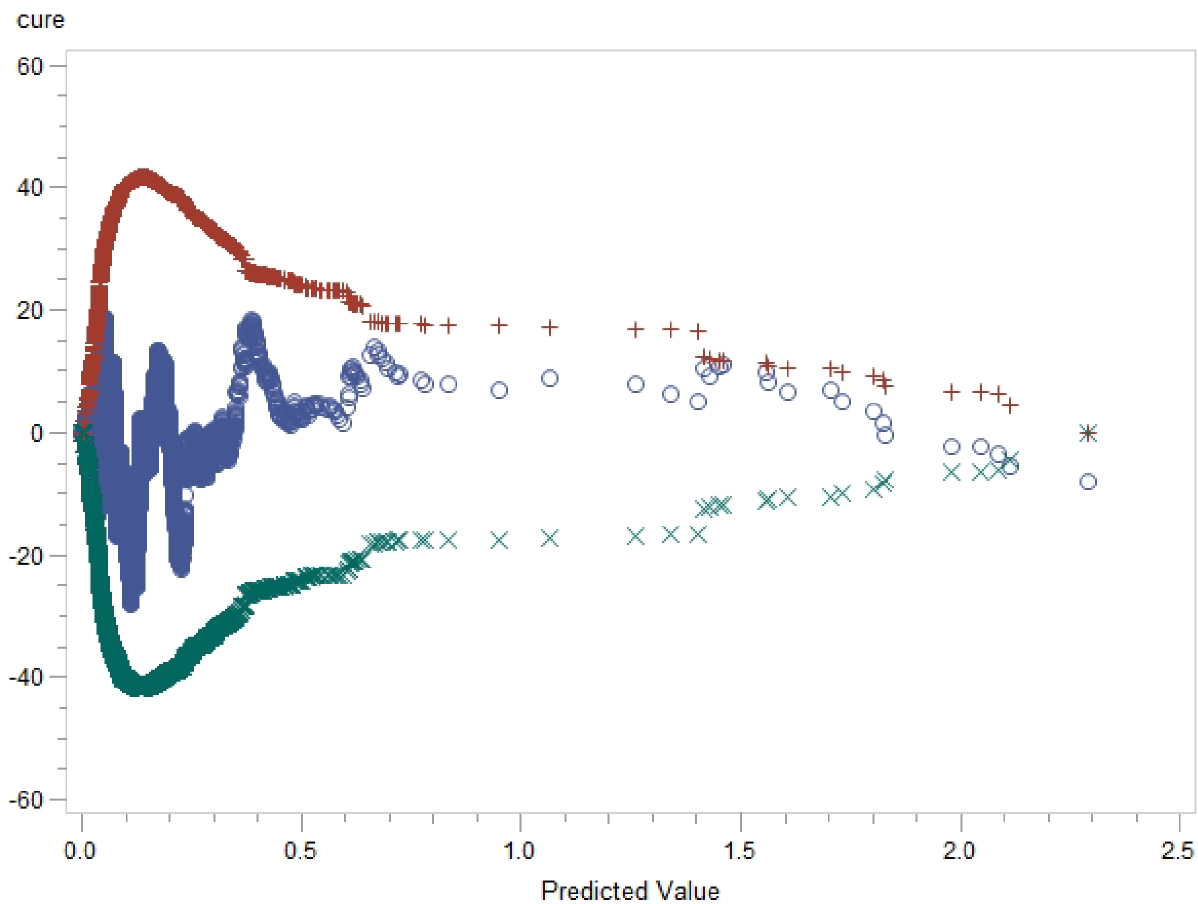

Figure C-10. CURE Plot - SPFs for Total Intersection Crashes (4-Leg Intersections with No Lighting – Thru-Stop Only)

Table C-10. SPFs for Intersection Crashes (4-Leg Intersections with Lighting – Thru-Stop only)

Parameter	Total Estimate	Injury (KABC) Estimate	Injury (KAB) Estimate	Angle Estimate	Rear End Estimate
Intercept	-7.9977	-7.949	-7.4657	-7.4159	-14.3786
Major Road AADT	0.8452	0.7377	0.5962	0.6951	1.3049
Yearly Factor - 2012	-0.038	-0.0929	-0.2142	-0.4062	0.5746
Yearly Factor - 2013	0.0779	0.072	-0.0881	-0.3109	1.0119
Yearly Factor - 2014	-0.1035	-0.1694	-0.0628	-0.6656	0.71
Yearly Factor - 2015	0.0069	0.0955	0.232	-0.4365	0.9097
Yearly Factor - 2016	-0.1624	-0.2077	-0.0498	-0.2577	0.7343
Yearly Factor - 2017	-0.2023	-0.2748	0.0908	-0.4638	0.8617
Yearly Factor - 2018	-0.3128	-0.3684	-0.2302	-0.3759	0.2407
Yearly Factor - 2019	-0.205	-0.3168	-0.3099	-0.0992	0.4633
Yearly Factor - 2020	-0.216	-0.1015	0.1321	-0.0603	-0.4995
Yearly Factor - 2021	-0.1715	-0.1951	0.2801	-0.4236	0.3319
Yearly Factor - 2022	0	0	0	0	0
Dispersion	1.9338	1.1263	0.9343	3.173	1.2034

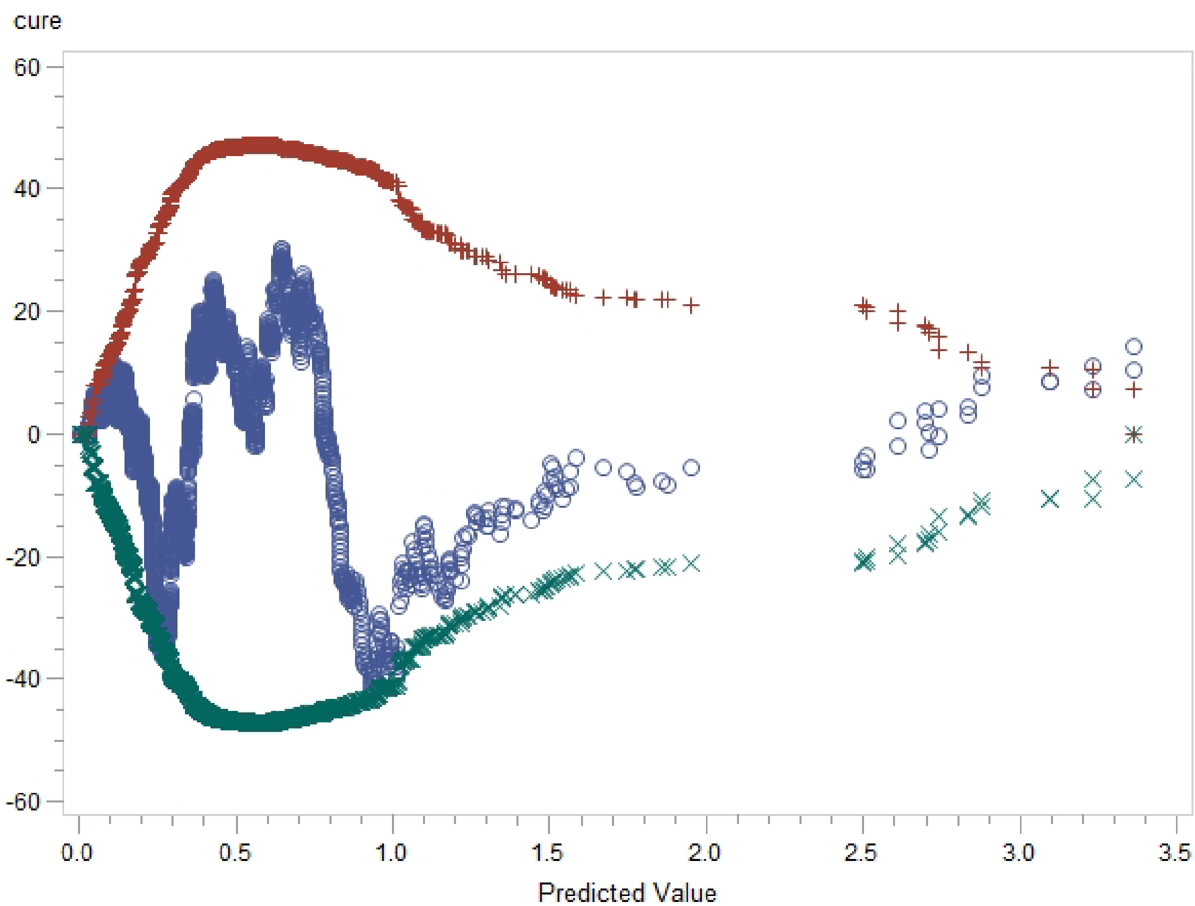

Figure C-11. CURE Plot - SPFs for Total Intersection Crashes (4-Leg Intersections with Lighting – Thru-Stop Only)

Appendix D:
Annual Calibration Factors

The SPFs presented in Appendix C were used to estimate annual calibration factors (ACFs). The ACFs are defined as the ratio of the total observed crash frequency to the total predicted crash frequency from the SPF and are calculated for each year. The ACFs are estimated to account for time trends. The ACFs are presented in Tables D-1 – D-10.

Table D-1. ACFs for Segment Crashes (SPFs Developed using All Segments)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Head On	Run Off Road
ACF 2012	0.967	0.986	0.995	0.995	0.997
ACF 2013	0.973	0.991	0.995	1.001	0.994
ACF 2014	0.979	0.993	0.995	0.999	0.996
ACF 2015	0.965	0.980	0.989	0.991	0.998
ACF 2016	0.972	0.986	0.992	0.991	0.983
ACF 2017	0.974	0.986	0.990	0.988	0.977
ACF 2018	0.974	0.978	0.987	1.002	0.986
ACF 2019	0.956	0.990	0.990	1.003	0.982
ACF 2020	0.951	0.979	0.987	0.990	0.976
ACF 2021	0.948	0.979	0.993	0.996	0.974
ACF 2022	0.964	0.977	0.990	1.009	0.992

Table D-2. ACFs for Segment Crashes (SPFs Developed using Segments > 0.5 miles – ACFs Based on Data from All Segments)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Head On	Run Off Road
ACF 2012	0.990	0.998	1.003	0.999	1.000
ACF 2013	0.998	0.998	0.999	0.999	0.998
ACF 2014	1.008	1.004	1.002	1.006	0.999
ACF 2015	0.989	0.996	0.990	0.994	0.999
ACF 2016	1.017	1.007	1.006	0.998	1.003
ACF 2017	1.005	0.998	0.998	0.987	0.999
ACF 2018	1.000	0.986	0.987	1.004	1.000
ACF 2019	0.997	1.004	0.996	1.014	0.997
ACF 2020	0.983	0.992	0.992	0.990	0.991
ACF 2021	0.987	1.002	1.016	1.014	0.989
ACF 2022	0.989	0.990	0.993	1.021	0.992

Table D-3. ACFs for Intersection Crashes (3-Leg Intersections with No Lighting – All Control Types)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.992	0.997	0.996	1.002	0.986
ACF 2013	1.003	0.996	0.999	0.982	0.985
ACF 2014	1.013	1.005	1.003	1.008	0.988
ACF 2015	0.991	0.996	1.001	1.008	0.988
ACF 2016	1.004	1.003	1.004	0.978	0.978
ACF 2017	1.007	1.007	1.001	1.018	0.983
ACF 2018	0.991	1.007	1.009	0.951	0.955
ACF 2019	0.998	1.015	1.005	0.989	0.928
ACF 2020	0.991	0.984	0.990	0.974	0.919
ACF 2021	0.998	0.991	0.994	0.985	0.979
ACF 2022	0.979	0.989	0.993	0.929	0.922

Table D-4. ACFs for Intersection Crashes (3-Leg Intersections with Lighting – All Control Types)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.977	0.991	0.999	0.995	0.991
ACF 2013	1.000	1.004	0.999	0.998	0.981
ACF 2014	0.991	0.999	0.996	1.007	0.975
ACF 2015	1.026	1.023	0.992	1.005	1.021
ACF 2016	0.967	0.980	0.992	0.983	0.974
ACF 2017	1.011	1.011	1.041	1.006	0.972
ACF 2018	1.012	1.009	1.005	1.001	1.043
ACF 2019	0.982	0.975	0.985	0.972	1.024
ACF 2020	1.059	0.968	0.975	1.038	1.007
ACF 2021	0.951	0.985	0.974	0.992	0.974
ACF 2022	1.068	0.979	0.974	1.003	1.061

Table D-5. ACFs for Intersection Crashes (4-Leg Intersections with No Lighting – All Control Types)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.993	0.998	1.002	1.001	0.947
ACF 2013	0.995	1.002	1.006	1.004	0.955
ACF 2014	0.987	0.993	0.993	0.995	0.941
ACF 2015	0.988	1.003	1.004	1.004	0.964
ACF 2016	1.026	1.007	0.993	0.987	1.084
ACF 2017	1.038	0.986	0.988	0.988	1.107
ACF 2018	1.026	0.991	0.981	0.996	0.992
ACF 2019	0.988	0.967	1.003	0.993	0.831
ACF 2020	0.886	0.942	0.976	0.891	0.817
ACF 2021	0.985	0.983	0.990	1.011	0.845
ACF 2022	0.914	0.948	0.966	0.967	0.690

Table D-6. ACFs for Intersection Crashes (4-Leg Intersections with Lighting – All Control Types)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	1.005	0.995	1.005	0.946	1.188
ACF 2013	0.951	0.996	1.004	0.975	0.815
ACF 2014	1.101	1.042	0.988	1.044	1.089
ACF 2015	1.003	1.020	0.998	1.002	1.002
ACF 2016	1.030	0.998	0.993	0.988	1.005
ACF 2017	1.060	0.963	1.005	1.034	1.017
ACF 2018	1.078	1.015	1.011	0.974	1.189
ACF 2019	1.129	1.053	1.010	0.971	1.274
ACF 2020	0.994	0.947	0.999	0.999	1.198
ACF 2021	0.929	0.949	0.979	1.008	0.895
ACF 2022	1.069	1.042	1.046	1.084	1.138

Table D-7. ACFs for Intersection Crashes (3-Leg Intersections with No Lighting – Thru-Stop only)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.992	0.997	0.996	1.002	0.986
ACF 2013	1.003	0.996	0.999	0.982	0.985
ACF 2014	1.013	1.005	1.003	1.008	0.988
ACF 2015	0.991	0.996	1.001	1.008	0.988
ACF 2016	1.005	1.003	1.004	0.978	0.976
ACF 2017	1.007	1.007	1.001	1.018	0.983
ACF 2018	0.991	1.007	1.009	0.951	0.955
ACF 2019	0.998	1.015	1.005	0.989	0.928
ACF 2020	0.991	0.984	0.990	0.974	0.919
ACF 2021	0.998	0.991	0.994	0.984	0.979
ACF 2022	0.979	0.989	0.993	0.929	0.922

Table D-8. ACFs for Intersection Crashes (3-Leg Intersections with Lighting – Thru-Stop only)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.990	0.993	0.997	1.002	0.995
ACF 2013	1.011	1.011	1.014	1.004	0.994
ACF 2014	1.001	1.007	1.012	1.011	0.977
ACF 2015	1.037	1.017	1.007	1.001	1.030
ACF 2016	0.984	0.984	0.994	0.990	0.982
ACF 2017	0.983	0.986	0.997	0.998	0.938
ACF 2018	1.022	1.016	1.001	0.998	1.061
ACF 2019	0.971	0.973	0.971	0.982	1.010
ACF 2020	0.998	0.975	0.984	0.988	1.001
ACF 2021	0.954	0.993	0.990	0.998	0.990
ACF 2022	1.055	0.991	0.985	1.010	1.051

Table D-9. ACFs for Intersection Crashes (4-Leg Intersections with No Lighting – Thru-Stop only)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.994	1.000	1.003	-	0.943
ACF 2013	0.997	1.004	1.008	-	0.950
ACF 2014	0.988	0.995	0.993	-	0.936
ACF 2015	0.991	1.005	1.005	-	0.959
ACF 2016	1.028	1.009	0.994	-	1.082
ACF 2017	1.038	0.986	0.988	-	1.102
ACF 2018	1.027	0.992	0.981	-	1.002
ACF 2019	0.992	0.969	1.003	-	0.839
ACF 2020	0.885	0.944	0.976	-	0.805
ACF 2021	0.987	0.984	0.989	-	0.831
ACF 2022	0.914	0.949	0.966	-	0.675

For Angle crashes: Use Total crash ACFs

Table D-10. ACFs for Intersection Crashes (4-Leg Intersections with Lighting – Thru-Stop only)

Crash Type	Total	Injury (KABC)	Injury (KAB)	Angle	Rear End
ACF 2012	0.999	0.983	0.993	0.952	1.141
ACF 2013	0.992	1.003	1.014	0.973	0.966
ACF 2014	1.030	1.020	0.989	1.030	0.945
ACF 2015	0.973	1.002	1.002	1.007	0.989
ACF 2016	1.044	0.993	0.998	1.024	1.002
ACF 2017	1.026	0.985	0.994	1.040	1.008
ACF 2018	1.048	1.024	1.030	0.984	1.043
ACF 2019	1.069	1.033	1.012	1.005	1.062
ACF 2020	0.971	0.955	0.987	0.976	0.935
ACF 2021	1.002	0.989	0.989	1.068	0.914
ACF 2022	1.032	1.032	1.007	1.040	1.044

Appendix E:
Estimated Segment Crash Safety Effects Based on Operating Speed Data

For segments, CMFs were also estimated based on two speed delta measures:

- *Measure 1:* Average operating speed in the after period minus the average operating speed in the before period.
- *Measure 2:* Range of operating speed (95th-Percentile minus 5th-Percentile) in the after period minus the range of operating speed (95th-Percentile minus 5th-Percentile) in the before period minus

For this specific analysis, only those segments for which at least 4 quarters of operating speed data was available in the before and after periods were used limiting the sample of segments that could be included.

For both measures, the speed delta was divided into four sub-categories:

- Measure 1
  - Speed delta = Negative (58.91 miles)
  - Speed delta = 0 to less than 2 mph (179.07 miles)
  - Speed delta = 2 to less than 5 mph (201.03 miles)
  - Speed delta = Greater than 5 mph (33.27 miles)
- Measure 2
  - Speed delta = Less than -5 mph (77.60 miles)
  - Speed delta = -5 to less than -2 mph (59.29 miles)
  - Speed delta = -2 to less than 0 mph (34.67 miles)
  - Speed delta = 0 to 2 mph (41.58 miles)
  - Speed delta = 2 to 5 mph (82.10 miles)
  - Speed delta = Greater than 5 mph (177.05 miles)

The estimated crash safety effects for both scenarios (for total and injury crashes) are shown in Tables E-1 and E-2. For each crash type, the EB expected crashes in the after period had the speed limit change not been implemented are shown along with the actual number of crashes observed in the after period, the CMF, and the standard error of the CMF.

Table E-1. Estimated Segment Crash Safety Effects (Speed Delta Measure 1)

Speed Delta	Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Negative	Total	37	48.99	0.753**	0.130
0 to less than 2 mph	Total	230	250.35	0.918	0.066
2 to less than 5 mph	Total	237	271.37	0.873*	0.061
Greater than 5 mph	Total	27	32.59	0.825	0.166
Negative	Injury (KABC)	14	16.38	0.851	0.233
0 to less than 2 mph	Injury (KABC)	76	79.67	0.953	0.114
2 to less than 5 mph	Injury (KABC)	93	87.16	1.066	0.116
Greater than 5 mph	Injury (KABC)	10	10.26	0.968	0.313
Negative	Injury (KAB)	6	12.84	0.464*	0.192
0 to less than 2 mph	Injury (KAB)	50	58.53	0.853	0.126
2 to less than 5 mph	Injury (KAB)	62	58.10	1.065	0.143
Greater than 5 mph	Injury (KAB)	8	6.91	1.145	0.418

** Statistically Significant at the 95-percent Confidence Level*

***Statistically Significant at the 90-percent Confidence Level*

Table E-2. Estimated Segment Crash Safety Effects (Speed Delta Measure 2)

Speed Delta	Crash Type	Crashes in After Period	Expected Crashes in After Period without Treatment	CMF	Standard Error of CMF
Less than -5 mph	Total	81	107.30	0.754*	0.088
-5 to less than -2 mph	Total	79	86.51	0.911	0.111
-2 to less than 0 mph	Total	42	45.76	0.914	0.151
0 to less than 2 mph	Total	62	57.69	1.071	0.149
2 to less than 5 mph	Total	112	125.48	0.891	0.091
Greater than 5 mph	Total	155	180.56	0.858**	0.074
Less than -5 mph	Injury (KABC)	33	34.26	0.961	0.173
-5 to less than -2 mph	Injury (KABC)	29	27.97	1.033	0.201
-2 to less than 0 mph	Injury (KABC)	11	14.16	0.772	0.239
0 to less than 2 mph	Injury (KABC)	19	18.27	1.034	0.248
2 to less than 5 mph	Injury (KABC)	37	41.77	0.883	0.152
Greater than 5 mph	Injury (KABC)	64	57.04	1.120	0.147
Less than -5 mph	Injury (KAB)	23	23.58	0.972	0.211
-5 to less than -2 mph	Injury (KAB)	21	18.22	1.146	0.263
-2 to less than 0 mph	Injury (KAB)	7	10.11	0.686	0.265
0 to less than 2 mph	Injury (KAB)	11	12.74	0.856	0.267
2 to less than 5 mph	Injury (KAB)	20	29.69	0.671*	0.155
Greater than 5 mph	Injury (KAB)	44	42.05	1.044	0.166

** Statistically Significant at the 95-percent Confidence Level*
*** Statistically Significant at the 90-percent Confidence Level*

The speed delta results for both measures indicate that higher speed delta generally leads to an increase in injury (KABC and KAB) crashes. Total crashes show the opposite trend, with higher speed delta leading to reduction in total crashes. It is hard to make any overall conclusions here due to the limited sample of segments included in the speed delta analysis coupled with the fact that most of the CMFs are not statistically different from 1.0.