CASE STUDIES ON ESTIMATING CRASH MODIFICATION FACTORS FOR TREATMENT COMBINATIONS WITH EMPIRICAL INVESTIGATION OF DUAL RUMBLE STRIP APPLICATION IN ONTARIO

by

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Bachelor of Engineering, Ryerson University, Toronto, Ontario, Canada, 2016

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Abstract

Crash modification factors (CMFs) are used to quantify the impact of safety treatments. These treatments are often used in combination and so the need for estimating CMFs for simultaneous applications arises. Applications of new heuristic methods in combining treatments showed mixed results, indicating a need for sound judgement in their usage. A case study for centreline and edgeline rumble strips on Ontario highways resulted in combined CMFs of 0.805, 0.79, 0.743, 0.799, and 0.689 for total, injury, PDO, single vehicle, and approach & sideswipe crash types, respectively. The estimates were comparable to the CMFs estimated in other research for actual dual rumble strip application. CMFs developed separately for tangent and curved segments showed that both rumble strip types are more effective on curved segments.

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Introduction

Vehicle collisions result in a large portion of injuries and fatalities in Canada. Although Figure 1 below demonstrates a general declining rate of injuries and fatalities in Canada, the social costs from vehicle collisions due to factors such as property damage, lost productivity, injury rehabilitation, and loss of life is measured in the tens of billions (Transport Canada, 2011). In 2013, roadway collisions accounted for roughly 17% of all Canadian deaths which were categorised as unintentional fatal injuries. In the same year, almost 165,000 Canadians were injured as a result of a vehicle collision (Transport, 2015). In Ontario alone, more than 500 persons were killed and over 39,000 were injured due to motor vehicle crashes (Road Safety Research Office - MTO, 2015). As vehicles will remain a main mode of transportation for the foreseeable future, steps must be taken to ensure the safety of drivers, passengers, and road users. The rationale behind continued research in road safety is thus made apparent.

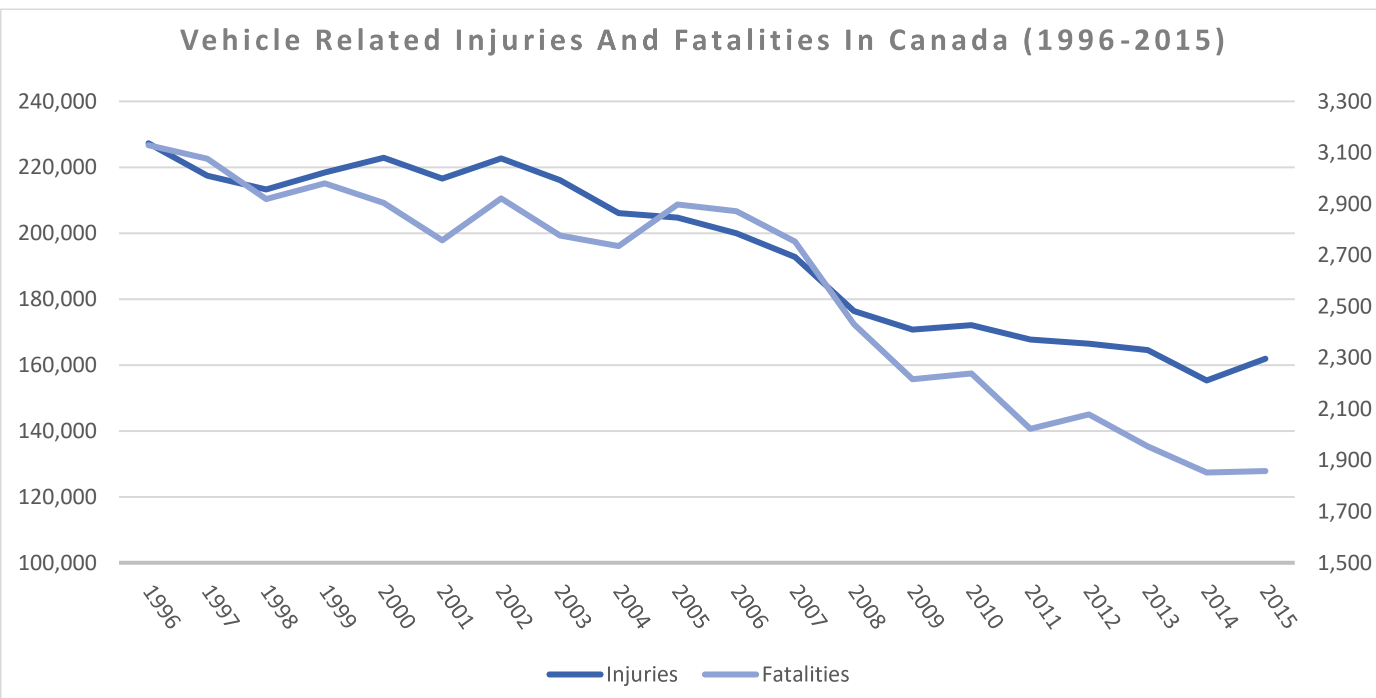


Figure 1: Canadian Injury and Fatality Figures (1996 - 2015)

Background

The Ministry of Transportation of Ontario is a leader in the progress and use of judicious methods for road safety management. Programs such as their Science of Highway Safety initiative have produced the likes of the *Safety Analyst* (MTO, 2009) software. Although it's extensive, there is a need for more research to be done for the *Safety Analyst* software to reach its full potential. This thesis aims to enhance the software by adding new Collision Modification Factor's (CMF's) to *Safety Analyst* to increase the size of its database. A CMF is a multiplicative factor which is used to estimate the effectiveness of a safety treatment. It works by enabling a user to estimate the expected number of crashes after the safety treatment has been applied to a site ("Crash Modification Factors (CMF)," n.d.). For example, a CMF of 0.75 would lead to the expectation that 75% of collisions will be expected after applying the safety treatment in comparison to if the safety treatment was not implemented. Similarly, a CMF of 0.3 would lead to the expectation that only 30% of collisions will be expected after the countermeasure has been applied. CMFs are important as they enable for an educated decision for the selection of countermeasures for diagnosed safety issues to be made. Having CMFs that are properly calibrated to Ontario highways is necessary in ensuring that safety decisions are made with accurate information.

Assessing Multiple Safety Treatments

While it is vital to know the crash modification factor of individual safety treatments to properly appraise the safety performance of a decision, in many cases more than one treatment is selected simultaneously at a site to resolve several safety concerns or to work in conjunction on one area of note. Ideally, a CMF has been established which encompasses the net safety effect of the decided upon safety treatments. In lieu of such an existing CMF, the National Cooperative Highway Research Program Project 17-63 has developed a draft report (Carter et al., 2017) which provides guidance on estimating combined treatment CMFs. While the methodologies explored in the report can theoretically be applied to more than two treatments, the accuracy of using the report for more than two treatments has not been properly assessed so the research for this thesis is focused on the application of two treatments.

Objectives

Dual Safety Treatment Study

In many instances, multiple safety treatments are applied to the same road segment. The question of how to combine CMFs together correctly arises from this situation. Historically, the main approach to calculating a combined CMF was to multiply the individual ones together as the Highway Safety Manual suggests (AASHTO, 2010). It is believed that this approach underestimates the CMF and therefore overestimates the safety benefit (Carter et al., 2017). While the ideal approach to determining the safety effect of multiple treatments is to undertake a comprehensive empirical study to determine its crash modification factor, this is not always feasible as finding enough sites with the same combination of safety treatments to perform a comprehensive study is difficult. Furthermore, the vast combinations of safety treatments which can be applied together suggests the laborious effort of finding a CMF for each one is too resource intensive to be achievable. To combat this dilemma of determining the net effect of multiple safety treatments, guidelines have been developed very recently to recommend the best estimate of a combined safety effect. NCHRP Project 17-63 (Carter et al., 2017) outlines the appropriate methods for combining CMFs depending on their scale of impact, spheres of overlap, and specificity in terms of crash type, crash severity, and suitable location for implementation. This thesis will address the following objectives related to combining CMFs:

1. Determine the safety performance of several dual treatments using the NCHRP Project 17-63 methodology.

2. Evaluate the accuracy of Report 17-63’s methodology by comparing the net effect of combining two, single CMFs found in the CMF Clearinghouse with dual treatment CMF’s found in the CMF Clearinghouse.
3. Evaluate the accuracy of Report 17-63’s methodology by comparing the net effect of combining two, single CMFs determined in an Ontario case study with dual treatment CMF’s found in the CMF Clearinghouse. The Ontario case study is further explored in the next section.

Ontario Centreline and Edgeline Rumble Strip CMF Case Study

In a related project undertaken by CIMA + (CIMA +, 2018), a Canadian civil engineering firm, a list was compiled of potentially useful CMFs for Ontario highways which the Ministry of Transportation of Ontario should look into developing further. This list was based on CMFs in the Highway Safety Manual and in the CMF Clearinghouse. In their report, Development of Collision Modification Factors for Countermeasures at Highway Mainline Segments and Highway Ramps (Izadpanah, Hoeun, Beattie, Masliah, & Hawash, 2016), CIMA identified high priority safety treatments for the MTO to develop into CMFs that are specific to Ontario highways. Two of the identified countermeasures to be developed are the installation of centreline rumble strips (CLRS) and edgeline rumble strips (ELRS).

Rumble strips refer to parallel milled grooves that span either the centreline or edgeline of a roadway. The intention of a rumble strip is to provide auditory feedback and vehicle vibration to the driver to communicate to them that they have started to depart from their lane. Thus, rumble strips are known to reduce lane departure relates crashes such as run-off road , head-on, and sideswipe-opposite direction crashes (Persaud et al., 2016).

As part of the MTO's Highway Infrastructure Innovation Funding Program, Ryerson University is tasked with developing CMFs for identified higher priority safety treatments and thus the motivation for this case study is made apparent.

Using Ontario highway data, the following objectives will be addressed:

1. Determine Ontario specific CMFs for ELRS and CLRS implementation.
2. Determine Ontario specific CMFs for ELRS and CLRS implementation at curve and tangent sections.

Thesis Structure

The remainder of this thesis is organised into the following chapters:

Chapter 2, Literature Review: Literature relating to appropriate methods in combining safety treatments will be explored as well as literature on the safety effects of rumble strips.

Chapter 3, Investigation into the NCHRP Project 17-63 Heuristic Method for Combining Crash Modification Factors: This chapter reviews current practices in combining CMFs.

Chapter 4, Ontario-Specific Empirical Case Study: Combined Application of Centre Line and Edge Line Rumble Strips: This chapter entails a case study to determine CMFs for CKRS and ELRS segments of Ontario highways. The resulting CMFs are combined using the estimation techniques and tested against known dual rumble strip CMFs.

Chapter 5, Summary and Conclusions: The study's findings are summarized and final comments on the findings are made.

Literature Review

Combining Safety Treatments

CMFs provide transportation engineers a quantitative method in determining the ramifications of a safety treatment. While CMFs are very useful by themselves, there are cases where a decision maker may want to apply multiple treatments to the same segment of road. An example of this is signalizing a stop controlled intersection and adding turn lanes. Ideally, a single CMF for both treatments exists and can be applied to determine the expected number of collisions (Carter et al., 2017). In lieu of such an existing CMF, the National Cooperative Highway Research Program Project 17-63 has developed a draft report that provides guidance on estimating combined treatment CMFs. The intention of this draft report is to combat the potential issue of overestimating the combined benefit that arises from the multiplicative procedure mentioned in the HSM (Carter et al., 2017). While the methodologies explored in the report can theoretically be applied to more than two treatments, the accuracy of using the report for more than two treatments has not been properly assessed (Carter et al., 2017). Details of these methodologies are provided later in applying them in this thesis.

Crash Modification Factors

A crash modification factor (CMF) is a multiplicative factor used to predict the expected number of crashes after a safety treatment is applied (Gross, Persaud, & Lyon, 2010). If the expected number of crashes at a site without the desired treatment is known, the crash modification factor can be multiplied to this expected number of collisions to determine the predicted number of collisions at the site if the treatment had been applied.

A safety treatment may affect different types of crashes and crash severities at a specified location disproportionately. For this reason, a CMF can be made specific to the roads characteristics, and for different crash severities and types.

Since a CMF is a factor, it can result in either an increase or decrease the expected number of collisions. A CMF with a value larger than 1.0 results in an increased expected number of collisions, while a CMF less than 1.0 results in a decreased number of collisions (Gross et al., 2010).

Rumble Strips

A rumble strip is a milled or rolled strip which is intended to give a driver both auditory and tactile feedback to correct their path of steering if they are veering out of their lane. The main purpose of a ELRS is to warn inattentive or sleepy drivers to counteract the issue of single-vehicle run-off road (SVROR) (Torbic et al., 2009). As a result of the high benefit to cost ratio of ELRS, transportation agencies commenced installing CLRS (Torbic et al., 2009). The intention of a CLRS is to reduce head-on and sideswipe collisions with opposing vehicles as well as SVROR (Torbic et al., 2009).

The safety impact of ELRS has been primarily evaluated on highways. While some studies have investigated the safety impact of ELRS on total collisions, most have focused on SVROR (Torbic et al., 2009). SVROR crashes were reduced by 10% to 80% after ELRS installation with an average reduction of 36%. The total crashes were reduced by 13% to 33% with an average reduction of 21%. NCHRP Report 617 assigned a medium-high level of predictive certainty to these estimates (Harkey, Council, & Gross, 2008). NCHRP Report 617 specifically states that the estimated safety effects are only applicable to freeways and not other types of roads (Harkey et al., 2008). Specific to 2-lane rural roads, a 26.1% reduction was observed for SVROR collisions in a study of British Columbia roads (Sayed, DeLeur, & Pump, 2010). In their report on rumble strip guidance, estimations of crash reduction rates of -14.4% (increase), -40.5% (increase), and 24.4% for the states of Minnesota, Montana, and Pennsylvania respectively with a combined increase rate of 5.9% for total crashes were determined (Torbic et al., 2009). The crash reduction values for injury crashes on 2-lane roads are -5.1% (increase), 19.24%, and 18% for Minnesota, Montana, and Pennsylvania respectively (Torbic et al., 2009).

Unlike ELRS, many of the CLRS safety evaluations were completed for 2-lane rural roads according to NCHRP Report 641 (Torbic et al., 2009). Most of the studies investigated head-on and sideswipe collision types, while few also investigated total crash reductions. Head-on collisions were reduced by between 34% and 95% with an average reduction of 65% (Torbic et al., 2009). NCHRP Report 617 assigned a medium-high level of predictive certainty to these estimates. The report specifically states that the estimated safety effects are only applicable to rural two-lane roads and not other types of roads (Harkey et al., 2008). The British Columbia study mentioned above observed a 29.3% reduction in SVROR and head on collisions with CLRS (Sayed et al., 2010). An IIHS study found that total crashes decrease by 14.1% and injury crashes decrease by 15.5%, while NCHRP Report 641 found a decrease in total crashes by 4.1% and injury crashes by 9.4% in their study (Persaud, Lyon, & Retting, 2003; Torbic et al., 2009). This NCHRP report also combines the two studies to find a combined decrease of total crashes by 8.7% and of injury crashes by 11.7% (Persaud et al., 2003; Torbic et al., 2009).

Specific to curved sections, A study performed on Minnesota, Pennsylvania, and Washington found total crash reductions of 17.1%, -16.0% (increase), and -2.7% (increase) respectively, with a combined crash increase rate of 3.5%. For injury crashes, Minnesota, Pennsylvania, and Washington found total crash reductions of -36.7 %, 9.8% (increase), and -20.7% respectively, with a combined crash reduction rate of 6.4%.

While much research has been done on the individual effects of both ELRS and CLRS, there is limited research on their combined effect due to a small sample size. (Persaud et al., 2016) The aforementioned British Columbia study indicates a 21.4% reduction in total run of road collisions and head-on collisions. (Sayed et al., 2010) A 2016 study looking at data from Kentucky, Missouri, and Pennsylvania calculated combined CMFs of 0.80 for total collisions, 0.771 for injury, 0.742 for run-off road, 0.632 for head-on collisions, and 0.767 for sideswipe-opposite-direction collisions (Persaud et al., 2016).

Investigation into the NCHRP Project 17-63 Heuristic Method for Combining Crash Modification Factors

The purpose of this chapter is to explore the heuristic methods developed in NCHRP Project 17-63 (Carter et al. 2017). The combination methods will then be used in several applications. The methodology selection process will follow the guidelines outlined in this NCHRP paper. The estimated CMFs from two of the applications will then be compared to combined CMFs from the CMF Clearinghouse (FHWA, 2018) to assess if the heuristic method gives an adequate approximation for combination CMFs. Observations and commentary on the effectiveness of the NCHRP Project 17-63 will be made throughout the chapter.

Selecting Appropriate CMFs

Put briefly, to determine a quality combined CMF, quality individual CMFs should be selected. When considering suitable CMFs for creating combined CMFs, the following considerations should be made:

Availability of CMFs

Reputable sources for CMFs are the CMF Clearinghouse (FHWA, 2018), AASHTO's Highway Safety Manual (AASHTO, 2010), and MTO's Safety Analyst software (MTO, 2009).

Applicability of CMFs

CMFs can be disaggregated by crash type, crash severity, or road conditions. It is important for CMFs of similar applicability to be combined. This ensures the combined CMF is an appropriate representation of the specific application the original CMFs were intended for. For two CMFs to be appropriate to combine, it is important that considerations are made for variables such as treatment type, road type, road geometry, and intersection control type.

Quality of CMFs

As some safety treatments have multiple CMFs in literature, the CMF with the highest quality should be used. Sources such as the CMF Clearinghouse provide star ratings, while individual CMF reports generally give an appraisal of their CMFs quality in the form of standard error values. In this study, CMFs of 4 stars or higher in the CMF Clearinghouse will be used unless otherwise stated.

Methodology

NCHRP Project 17-63 outlines a 4-step process to selecting the appropriate method for combining CMFs for two treatments. Figure 2, taken from the report for NCHRP Project 17-63 (Carter et al., 2017) outlines the 4 steps:

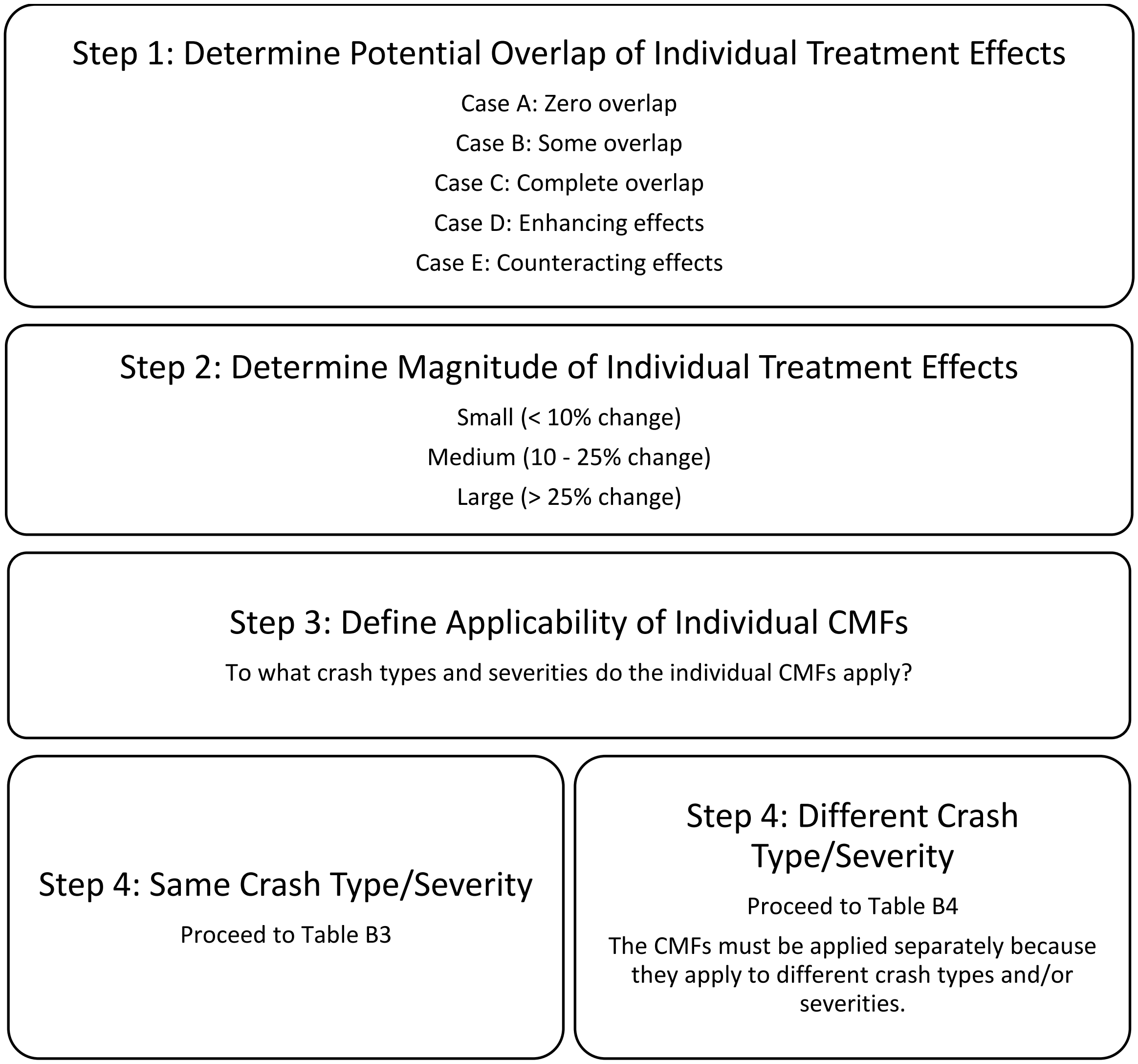


Figure 2: NCHRP Methodology for Combining Treatments (Carter et al., 2017)

Step 1: Determine Potential Overlap of Individual Treatment Effects

The purpose of step 1 is to determine how the safety treatments are related. Case A applies to safety treatments that are mutually exclusive. Case B is used when the two safety treatments have some overlapping benefit. Case C should be selected if the two treatments are non-independent, where the benefit of one treatment is fully enveloped by the other. Case D is for the scenario where the presence of both treatments enhances the predicted safety more than the sum of the individual treatments. Finally, Case E can be used if the combined safety of both treatments is less than the effect of the most effective treatment.

Step 2: Determine Magnitude of Individual Treatment Effects

The intention of step 2 is to find the magnitude of the safety effect of each safety treatment. In this step the individual effect of each CMF is considered and placed into 1 of 3 categories; small, medium, or large. As the individual effect of the CMF increases, the difference in method used in estimating the combined effect also increases. Thus, the choice of method becomes increasingly important to select an appropriate method as the CMFs increase. Table 1 below shows the three categories of treatment effectiveness.

Table 1: Classification of Treatment Magnitude

Individual Treatment Effect	**Magnitude of Treatment**
Less than 10% crash reduction rate	Small
10 – 25 % crash reduction rate	Medium
Over 25% crash reduction rate	Large

Step 3: Define Applicability of Individual CMFs

Different CMFs can only be applied in their context. To ensure the combined effect is an accurate representation of a situation where both safety treatments are applied, care must be taken to use CMFs with matching crash type and severity.

In the situation where CMFs are not available for the desired safety treatments and the crash type and severity match, the method used for determining the combined treatment CMF is adjusted accordingly.

Step 4: Application of Appropriate Method for Estimating Combined Treatment

Using the considerations is steps 1-3, apply the appropriate method as listed in the report. There are 5 methods which are to be used depending on the information gathered in steps 1-3.

Table 2 may be used as a guideline to selecting the correct methodology in the event that the CMFs are transferable (Carter et al., 2017):

Table 2: Method Selection for Same Crash Type and Severity (Carter et al., 2017)

Overlap	**Magnitude**	**Method**
Case A *Case D*	Not applicable	Additive effects with maximum reduction of 100% (i.e., CMF = 0)
Case B	Small-Small	Dominant effect
	Small-Medium	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
	Small-Large	Dominant effect
	Medium-Medium	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
	Medium-Large	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
	Large-Large	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
Case C	Not applicable	Dominant effect
Case E	Not applicable	Multiplicative

When the CMFs selected are deemed inapplicable as is, the following guidelines should be used for determining the correct methodology (Carter et al., 2017):

Table 3: Method Selection for Different Crash Type and Severity (Carter et al., 2017)

Overlap	Method
Case A *Case D*	*Additive Effects with Maximum Reduction of 100% (i.e., CMF = 0).* Assuming no overlap among treatment effects, one would expect the full benefit of each treatment. 1. Apply the CMF for the first treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest. 2. Apply the CMF for the second treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest. 3. Sum the estimated change in crashes to calculate the net effect. 4. Check that the estimated change does not exceed the potential bounds of the combined treatments. If so, the estimated change is equal to the respective bound.
Case B *Case E*	*Dominant Effect for Overlapping Crash Types* Assuming some overlap among the treatment effects, one would expect the full benefit of the most effective treatment and some additional benefit from the second treatment. 1. Apply the CMF for the most effective treatment (i.e., the lowest CMF) to the estimated crashes without treatment for the applicable crash type/severity at the location of interest. 2. Apply the CMF for the second treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest, excluding crashes associated with the most effective treatment. 3. Sum the estimated change in crashes to calculate the net effect. 4. Check that the estimated change does not exceed the potential bounds of the combined treatments. If so, the estimated change is equal to the respective bound.
Case C	*Dominant Effect* Assuming complete overlap among the treatment effects, one would expect the full benefit of only the most effective treatment. Note that this is a simplified version of Case B. 1. Apply the CMF for the most effective treatment (i.e., the lowest CMF) to the estimated crashes without treatment for the applicable crash type/severity at the location of interest.

These 5 methods are outlined below:

Dominant Effect Method:

The effect method is a conservative method that applies the most effective treatment's CMF as the overall CMF. While this method is both simple and conservative, it is useful in avoiding problems that may arise from determining the independence of the safety treatments. The main drawback of this method is that it likely underestimates the effect of both treatments as only one treatment is considered.

Additive Effects Method:

The additive effects method works under the assumption that the safety treatments are independent. As the name suggests, the CMFs effects are added together as the following formula demonstrates:

$$CMF_{combined} = 1 – [(1 - CMF_1) + (1 – CMF_2) + … + (1 – CMF_n)],$$

where

$CMF_{combined}$ is the CMF for the combined treatments

CMF_1 is the most effective CMF

CMF_2 is the second most effective CMF

CMF_n is the n^{th} most effective CMF

One main limitation of this treatment is that with small enough CMFs or with a sheer volume of CMFs, the combined CMF can equal 0. This method should only be used if the CMFs are truly independent.

Multiplicative Method:

The combined CMF is determined by multiplying the individual CMFs together as the following equation demonstrates:

$$CMF_{combined} = CMF_1 \times CMF_2 \times … \times CMF_n$$

The multiplicative method is the most commonly used method and the one which is listed in the Highway Safety Manual. Like the additive effects method, this method should be used for independent safety treatments. When applied as the general method of combining CMFs, it can overestimate or underestimate the safety effects if the treatments are dependent.

Dominant Common Residuals Method:

The dominant common residuals method is comparable to the multiplicative method, but differs in that it is targeted at dependent safety treatments. The CMFs are multiplied together and raised to the power of the most effective CMF as the following equation demonstrates:

$$CMF_{combined} = (CMF_1 \times CMF_2 \times \ldots \times CMF_n)\ \text{^}CMF_1$$

While there is no theoretical justification for this method, it does provide a more conservative estimate than the multiplicative method. As the dominant CMF is used as the power of the multiplication of the other CMFs, if it is greater than 1, the effect of the combined CMF is intensified, rather than dampened. As such, this method is not appropriate where the treatments have a CMF greater than 1.0.

Dominant Effect for Overlapping Crash Types:

This method applies the corresponding CMFs to their target crashes and the dominant CMF where there is overlap in the effects of the treatments. In the instance where the CMFs relate to different crash types with overlap, each CMF will be applied to its crash type while the overlapping area will only have the dominant CMF applied to it.

For example, if CMF_a applies to head-on and sideswipe collisions and CMF_b applies to sideswipe and rear end collisions, the combined treatment will apply to head-on, sideswipe, and rear end collisions where the CMF_a of head-on collisions and CMF_b applies to rear end collisions, and the CMF for sideswipe collisions will be determined by the dominant CMF between CMF_a and CMF_b.

While this method does account for overlap between the effects of treatments, it is not always easy to determine which crash category is influenced by which safety treatment.

Case Study Applications of NCHRP Project 17-63 Methodology for Developing CMFs for Combination Treatments

Application I – Combination CMF for Intersection Signalization and Addition of Left Turn Lanes

For this application, a study (Srinivasan, Lan, Carter, & Hill, 2014) performed by the University of North Carolina Highway Safety Research Center will be looked at. In this study both treatments of signalizing intersections and adding left turn lanes to intersections were examined and CMFs were determined. The overlapped CMFs that will be combined are for total, injury, and rear end crashes. Signalizing intersections yielded a total crashes CMF of 0.639, an injury crashes CMF of 0.642, and a rear end crashes CMF of 1.427. Adding left turn lanes yielded CMF values of 0.876, 0.744, and 0.494 for total crashes, injury crashes, and rear-end crashes respectively.

Step 1: Determine Overlap

It will be assumed that this combination of treatments will have some overlap (case B) for total crashes and injury crashes as it is expected that vehicles which would be turning left would benefit from both treatments, but not all other intersection mitigated collisions by a signal would have also been reduced by the installation of a left turn lane. For rear-end crashes, it is assumed that the treatments may have counteracting effects (case E) as it would be expected that the increased rear-end collisions because of a signalized intersection may reduce the effectiveness of the very successful left turn lane CMF for this crash type.

Step 2: Determine Magnitude

Table 4 displays the magnitude of each safety treatment.

Table 4: Magnitude of CMFs for Application I

	Lane Signalization	**Left Turn Lane**
Total Crashes	0.639 (large)	0.876 (medium)
Injury Crashes	0.642 (large)	0.744 (large)
Rear End Crashes	1.427 (small)	0.494 (large)

Step 3: Determine Applicability

Care was taken to select safety treatments which are applicable with each other. Both treatments were applied to the same crash types and in the same state. The treatments can therefore able to be combined as is.

Step 4: Applying the Correct Method

For total crashes and injury crashes, the dominant common residuals method has been selected according to the report's guidelines. For rear-end crashes, the multiplicative method has been selected according to the report's guidelines.

Total Crashes:

$$\text{CMF combined } = (0.642 \times 0.744)^{0.642} = 0.622$$

Injury Crashes:

$$\text{CMF combined } = (0.639 \times 0.876)^{0.639} = 0.690$$

Rear-End Crashes:

$$\text{CMF combined } = 0.494 \times 1.427 = 0.705$$

Combined CMF Summary:

Table 5 displays a summary of the combination CMFs

Table 5: Combined CMF Estimations for Application I

Crash Type	**Lane Signalization**	**Left Turn Lane**	**Combined CMF**
Total Crashes	0.639	0.876	0.622
Injury Crashes	0.642	0.744	0.690
Rear-End crashes	1.427	0.494	0.705

Observations:

While the combined CMF for injury crashes and rear-end crashes meet expectations, the combined CMF for total crashes seems conservative. It would be expected that the combined CMF would be more impactful than the maximum value of its individual parts as it is expected that there would be some overlap between the CMFs and they would also individually contribute into making intersections safer. The problem arises from the method used. Following the NCHRP Project 17-63 guidelines, the dominant common residuals method should be used. In this method, the product of the two CMFs is placed to the power of the most dominant CMF. If both CMFs are very effective, or the dominant CMF is very effective, the practice of using the dominant CMF as an exponent can be counterproductive as the result of a number less than 1 increases as the exponent decreases. While the exponent ensures the effectiveness of CMFs are not overestimated (compared to the multiplicative method), the exponent acts as too conservative of a number as the CMF decreases. For example, consider the two scenarios below where the dominant common residuals method for CMFs with some overlap is applied:

i) $CMF_1 = 0.35$, $CMF_2 = 0.65$, $CMF_{combined} = 0.600$

ii) $CMF_1 = 0.7$, $CMF_2 = 0.7$, $CMF_{combined} = 0.610$

The methodology would suggest the combined CMFs from both combinations are very close, but when looking at the individual CMFs, this looks unlikely. Table 6 illustrates this deficiency in the method further:

Table 6: Results of Dominant Common Residuals Method for Various CMF Values

CMF_1	CMF_2	$CMF_{combined}$
1	1	1.000
0.9	1	0.910
0.9	0.9	0.827
0.8	0.9	0.769
0.8	0.8	0.700
0.7	0.8	0.666
0.7	0.7	0.607
0.6	0.7	0.594
0.6	0.6	0.542
0.5	0.6	0.548
0.5	0.5	0.500
0.4	0.5	0.525
0.4	0.4	0.480
0.3	0.4	0.529
0.3	0.3	0.486
0.2	0.3	0.570
0.2	0.2	0.525
0.1	0.2	0.676
0.1	0.1	0.631

In practice, this issue in the dominant residuals method will not arise often as most CMFs are not effective enough to result in this mathematical dilemma when combining treatments.

Application II – Combination CMF for Transit Signal and Transit Lane Priority Implementation

For this application, CMFs from a study (Naznin, Currie, Sarvi, & Logan, 2011) exploring the effects of streetcar signal and lane prioritization in Melbourne, Australia were used to develop a combined CMF. In this study, safety effectiveness values of 13.9% and 19.4% were found for the signal treatment and the lane treatment respectively. This corresponds to CMF values of 0.861 and 0.806 respectively. It is of note that the transit priority lanes in question are exclusive bus and streetcar lanes (Naznin et al., 2011) as illustrated in Figure 3 below (Wong, 2015). It is also of note that the CMF of the signal treatment is not statistically different from 1.0 at a 2-standard deviation confidence interval.

Figure 3: Transit Only Lanes in Melbourne (Wong, 2015)

Step 1: Determine Overlap

It will be assumed that this combination of treatments will have complete overlap (Case C) in their safety effect. This assumption is made because the safety effects of the exclusive transit lane in Melbourne would encompass the safety effects of transit signal prioritization.

Step 2: Determine Magnitude

Table 7 displays the magnitude of each safety treatment.

Table 7: Magnitude of CMFs for Application II

	Transit Lane Prioritization	Transit Signal Prioritization
Total Crashes	0.806 (medium)	0.861 (medium)

Step 3: Determine Applicability

As both treatments were applied total crashes on urban arterials in Melbourne, Australia, they are highly relatable.

Step 4: Applying the Correct Method

The dominant effect method has been selected according to the report's guidelines. In this method, the dominant CMF is used, therefore:

$$\text{CMF combined} = 0.806$$

Combined CMF Summary:

Table 8 displays a summary of the combination CMFs

Table 8: Combined CMF Estimation for Application II

	Transit Lane Prioritization	Transit Signal Prioritization	Combined CMF
Total Crashes	0.806	0.861	0.806

Observations:

As the dominant treatment's safety effect would naturally encompass the crashes mitigated by the non-dominant safety treatment, the methodology used for this scenario intuitively makes sense.

Application III – Combination CMF for Lowered Speed Limit and Reducing Lane Width

For this application, a study (Islam & El-Basyouny, 2015) outlining crash reduction factors of lowering the speed limit from 50 km/h to 40 km/h in urban residential areas will be combined with a study (Wood, Gooch, & Donnell, 2015) which explored the safety effects of reducing lane widths. In the first study, crash reductions of 22.0%, and 49.9% were found for total crashes and injury crashes respectively. This corresponds to CMF values of 0.78 and 0.501 for the two crash severities respectively. It is of note that the crash reduction percentage for injury crashes only received a quality rating of 3 stars in the CMF Clearinghouse (FHWA, 2018). The second study produced CMFs for several different scenarios of lane width reductions. The two that will be explored for combination purposes are lane width reductions from 11 ft. (≈ 3.35 m) to 9 ft. (≈ 2.74 m) and from 11 ft. (≈ 3.35 m) to 10 ft. (≈ 3.05 m). For the first lane reduction, CMFs of 0.533 and 0.405 were found for total crashes and injury crashes respectively. For the second lane reduction, CMFs of 0.567 and 0.461 were found for total crashes and injury crashes respectively.

Step 1: Determine Overlap

It will be assumed that this combination of treatments will enhancing effects (case D) for total crashes and injury crashes as it is expected these safety measures will be complimentary of each other and further reduce the crash rate when combined.

Step 2: Determine Magnitude

Table 9 displays the magnitude of each safety treatment.

Table 9: Magnitude of CMFs for Application III

	Speed Reduction	Lane Reduction 1	Lane Reduction 2
Total Crashes	0.78 (medium)	0.533 (large)	0.567 (large)
Injury Crashes	0.501 (large)	0.405 (large)	0.461 (large)

Step 3: Determine Applicability

Although more CMFs are available for the concerning safety treatments, only those which were applicable to all treatments were applied. Some other considerations to be made are that the speed reduction study was performed in an urban residential environment in Edmonton, Alberta, Canada, while the lane width reduction study was performed in urban environments in Nebraska. Although the locations are different, the similarities between the two environments deem this exercise as appropriate.

Step 4: Applying the Correct Method

The dominant common residuals method has been selected according to the report's guidelines.

Total Crashes (w/ lane reduction 1):

$$\text{CMF combined } = (0.533 \ \times 0.78)^{0.533} = 0.626$$

Total Crashes (w/ lane reduction 2):

$$\text{CMF combined } = (0.567 \ \times 0.78)^{0.567} = 0.630$$

Injury Crashes (w/ lane reduction 1):

$$\text{CMF combined } = (0.405 \ \times 0.501)^{0.405} = 0.524$$

Injury Crashes (w/ lane reduction 2):

$$\text{CMF combined } = (0.461 \times 0.501)^{0.461} = 0.509$$

Combined CMF Summary:

Table 10 displays a summary of the combination CMFs

Table 10: Combined CMF Estimations for Application III

Crash Type	**Speed Reduction**	**Lane Reduction**	**Combined CMF**
Total Crashes (w/ lane reduction 1)	0.78	0.533	0.626
Total Crashes (w/ lane reduction 2)	0.78	0.567	0.630
Injury Crashes (w/ lane reduction 1)	0.501	0.405	0.524
Injury Crashes (w/ lane reduction 2)	0.501	0.461	0.509

Observations:

In all 4 instances above, the combined CMF is less effective than the dominant CMF. This shortcoming with the dominant residual method was explored further in the first application of the NCHRP Project 17-63 methodology.

Comparing Known Dual Treatment CMFs to Estimations of Dual Treatment CMFs

In the previous section, the estimations methodology of the report was demonstrated using multiple examples. In this section, two of the estimations explored above will be compared to CMFs developed specifically for those combined treatments.

Comparing the Estimated and Calculated CMFs for Application I

Table 11 shows the estimated CMFs found above and the CMFs for the combined treatments developed in extensive studies:

Table 11: Estimated and Actual CMF Comparison for Application I

Crash Type	**Estimated CMF**	**Actual CMF (SE)**	**CMF Lower Limit**	**CMF Upper Limit**
Total Crashes	0.690	0.561 (0.024)	0.513	0.609
Injury Crashes	0.622	0.480 (0.031)	0.418	0.542
Rear-End crashes	0.705	0.711 (0.052)	0.607	0.815

The total crashes and injury crashes CMFs are not within a 2-standard error confidence interval while the rear-end crashes CMF is. This suggests either the incorrect assumptions were made for Step 1 or the correct assumptions were made, but the methodology does not adequately predict CMFs. By working backwards and finding the overlap type which best fits the actual data, an overlap type that uses the multiplicative method must be used. Table 12 below shows the CMF estimations using the multiplicative method:

Table 12: Comparing Estimation Methods for Application I

Crash Type	**Multiplicative CMF Estimate**	**Actual CMF (SE)**	**CMF Lower Limit**	**CMF Upper Limit**
Total Crashes	0.560	0.561 (0.024)	0.513	0.609
Injury Crashes	0.478	0.480 (0.031)	0.418	0.542

To use this method, the overlap type must be altered to be Case E – Counteracting Effects. An issue arises from this selection and its methodology. The concern is that the intention of Case E is that the dominant CMF is reduced by the other safety treatment. For two CMF values less than 1, their product will always be less than the most dominant CMF and therefore the effect of the lesser CMF on the dominant one is that the combination is a safety enhancement. This suggests there should be a limitation built into the use of the multiplicative method into Case E, where it is only an applicable methodology if one (or both) CMFs are greater than 1.0.

As the two treatments likely mitigate some of the same crashes from occurring, it is believed that the correct case was used. The dominant common residuals method does not adequately estimate large CMFs as explored above.

Comparing the Estimated and Calculated CMFs for Application II

Table 13 shows the estimated CMFs found above and the CMFs for the combined treatments developed in extensive studies:

Table 13: Estimated and Actual CMF Comparison for Application II

	Estimated CMF	Actual CMF (SE)	CMF Lower Limit	CMF Upper Limit
Total Crashes	0.806	0.836 (0.061)	0.714	0.958

The CMF lies within the 2-standard deviation limits, but some observations can be made. The selection of complete overlap would suggest that the CMFs should be identical. This is hard to achieve in a practical sense and upon further inspection, the estimation is within half a standard deviation of the actual CMF, which suggests the method used provides an adequate estimation.

Ontario-Specific Empirical Case Study: Combined Application of Centre Line and Edge Line Rumble Strips

In this portion of the thesis, a rigorous empirical Bayes before-after study will be illustrated for centreline rumble strips (CLRS) and edgeline rumble strips (ELRS). The results from this study will then be applied to estimate a combined CMF for the dual treatment of rumble strips. The data used in this report uses 2-lane highways throughout the province of Ontario, Canada. Traffic, and crash data will also be combined with geospatial data to develop CMFs for tangent and curved sections of roads.

Ontario Case Study Methodology

This chapter details the methodology used in determining CMFs for this rumble strip study using Ontario data. The methodology used to estimate the safety effectiveness of the applied treatments in this study is consistent with current research practices (Persaud et al., 2016). An empirical Bayes (EB) methodology for before-after studies (BA) will be applied using crash prediction models (Hauer, 1997).

Empirical Bayes (EB) Before-After Study

Two main methods used in developing quality crash modification factors are an EB before-after study and a cross-sectional analysis (Gross et al., 2010). A before-after study involves a treatment at some period and comparing the safety performance of sites before and after the treatment. A cross-sectional analysis compares similar sites of which some have and some do not have a treatment at a single point in time. While both have their merits, the empirical Bayes before-after method was selected as it is a more rigorous method, that is designed to remove concerns of regression to the mean (Hauer, 2015).

In an EB study, the change in safety due to a treatment is given by the following equation:

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

Where,

λ = the expected number of collisions which would occur at the site given the treatment had not been implemented.

π = the observed number of collisions which occurred at the specified treatment site after the treatment had been implemented.

The λ value is estimated with the EB methodology using a specific safety performance function (SPF) to the collision type or severity being investigated.

Annual Factors

To account for temporal effects on safety such as yearly variations in weather, and reporting practices, the SPF is calibrated for each year of data using an annual SPF multiplier. The annual multiplier is determined by devising the observed collisions over the predicted collisions estimated by the SPF as demonstrated in the following equation:

$$Annual\ Factor = \frac{Observed\ Crashes}{SPF\ Predicted\ Crashes}$$

EB Crash Estimates

The first step in the EB procedure is to estimate the number of collisions in the before period using the predetermined SPF. The predictions for each year are summated per site. The resulting summed SPF predictions, (P), is then combined with the annual crash observations for each site (x) in the before period to determine an approximation of the number of crashes (m) using the following equation:

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

where *w* is calculated with the dispersion factor (k) and the before period SPF predictions (P) using the following equation:

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

The combination of using the observed data with the SPF before period prediction and SPF dispersion factor accounts for the effects of regression to the mean (RTM).

To account for differences in traffic volumes and time periods, a factor (f) is the applied to *m* which is equal to the prediction of after period collisions over the before period predictions, *P.* The expected number of collisions at the site without a treatment, λ, is the calculated by multiplying the factor by the approximation of crashes, *m* as demonstrated by the following equations:

$$\lambda = f \times m$$

where,

$$f = \frac{predicted\ \#\ of\ crashes\ after\ safety\ treatment}{P}$$

Index of Effectiveness

To determine the efficacy of the safety treatment, the index of effectiveness (θ) is found using the following equation:

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

The index of effectiveness can be used to find the percent change in crashes caused by the safety treatment with the following equation:

$$percent\ change = 100\ \times (1 - \ \theta)$$

The index of effectiveness may be taken as the CMF for the specified crash type or crash severity.

The standard deviation of θ is determined using the following equation:

$$SD(\theta) = \sqrt{\frac{\theta^2 \left[\frac{Var\pi_{sum}}{\pi^2{}_{sum}} + \frac{Var\lambda_{sum}}{\lambda^2{}_{sum}}\right]}{\left[1 + \frac{Var\lambda_{sum}}{\lambda^2{}_{sum}}\right]^2}}$$

Development of Safety Performance Functions (SPFs)

Crash prediction models in the form of safety performance functions (SPFs) for untreated reference sites are used in an EB study for determining the expected number of collisions at a site for a specific year (Gross et al., 2010). The purpose of an SPF is to relate the crashes occurred at a site to its characteristics (Gross et al., 2010).

In instances where events are rare, generally Poisson or negative binomial models are used. For the case of crash prediction models, a Poisson distribution may be inappropriate as in a Poisson distribution the variance equals the mean. When looking at a sample of road segments, it is very common for each road to have some unique characteristics (such as posted speed or lane width) (Hauer, 2015). Generally, these differences cause the variance to be greater than the mean. The result of this is an over dispersion of the data. While it is also possible for the data to be under dispersed, it is less likely (Srinivasan & Bauer, 2013). To account for the tendency for Poisson models to over disperse in this scenario, a negative binomial regression model is used (Srinivasan & Bauer, 2013).

Generalized Linear Model (GLM)

As a crash prediction cannot be a negative number, the model used must be positive. To ensure positive predictions are made, a log linear model can be used. Another advantage of a log linear model is that the resulting equation leaves a simple linear combination on variables on the right-hand side, resulting in a generalized linear model (GLM). In a GLM the variables coefficients and significance are determined by estimating by the maximum likelihood method. (Srinivasan & Bauer, 2013).

The model now has the following form:

$$\lambda = e^{\beta \chi_i} e^{\varepsilon_i}$$

To create the generalized linear model using a negative binomial distribution, SAS software (SAS Institute, 2014) is used. This software will enable the parameters for the SPF in negative binomial form to be approximated.

Selection of SPF Variables

A vital component of developing accurate SPFs is the proper selection of independent variables. For this study the following SPF is used:

$$\text{Crashes/km/year} = e^{\alpha} AADT^{b} Length^{c}$$

Where,

AADT = annual average daily traffic

a, b, c = parameters estimated in the calibration of the SPF

The SPF is a simplified version of the SPF used in a 2016 study (Persaud et al., 2016) due to the limited variability in road characteristics in the study data. Characteristics such as posted speed, rural environment, shoulder width and lane width remained largely the same between sites and as such, length of road segment and AADT were left as the only statistically significant variables.

Goodness of Fit Measures

As predictive models are required to perform an empirical Bayes before-after study, it is important to test the goodness of fit of the crash prediction models used. Several goodness of fit measures will be used to evaluate the crash prediction models in this study. They are explored below.

Cumulative Residual Plots (CURE Plots)

A CURE plot shows the cumulative differences between the observed crash counts and the SPFs estimations for the crash counts plotted against each of the SPFs covariate's. In this study, this means the cumulative residuals will be plotted against the length of segments and the AADT of segments. A good SPF will not have large portions of upward or downward projecting residuals and will mostly remain within 2 standard deviation limits (Hauer, 2015). Figure 4 shows an example of a CURE Plot. In this example, the cumulative residuals surpass the 2-standard deviation upper limit between the AADT values of 6600 and 8000, which shows areas where the model inaccurately predicts crash values.

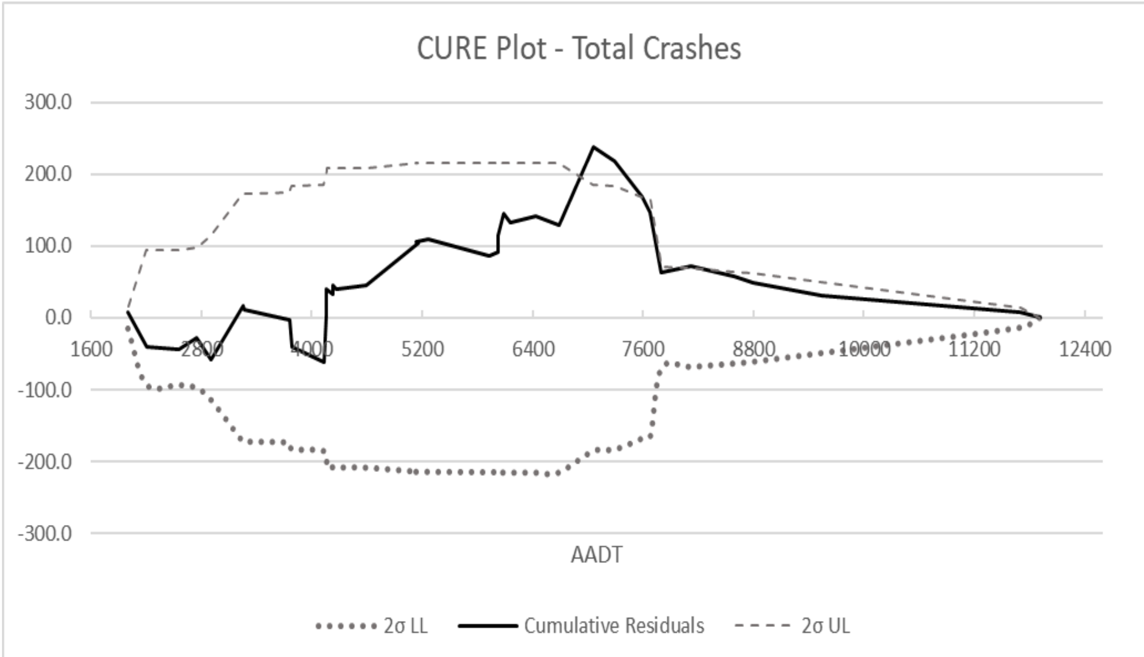


Figure 4: CURE Plot Example

Mean Prediction Bias (MPB)

The mean prediction bias is a means of understanding the tendency of the model to either overpredict or under predict crashes when compared to the observed crash data. The ideal MPB value is 0, while positive values indicate an overprediction by the SPF and negative values indicate an underprediction by the SPF. The MPB can be determined using the following equation:

$$MPB = \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)}{n}$$

Where,

n = sample size,

$\hat{Y}_i$ = SPF predicted values at site *i*,

Y_i = the observed values at site *i*

Mean Absolute Deviation (MAD)

The mean absolute bias resembles the MPB, but looks at the absolute difference between the predicted and observed crashes at each site. The MAD indicates the average variability in the model, regardless of whether the predicted value is larger or smaller than the observed crash value. A small MAD value is preferred over a large value as this indicates the crash prediction model resembles the observed values better. The MAD can be determined using the following equation:

$$MAD = \frac{\sum_{i=1}^{n} \left| \hat{Y}_i - Y_i \right|}{n}$$

Where,

n = sample size,

$\hat{Y}_i$ = SPF predicted values at site *i*,

Y_i = the observed values at site *i*

Mean Squared Prediction Error (MSE)

The mean squared error is used to measure the expected squared difference between the observed crashes and the estimated crashes. The MPSE can be determined using the following equation:

$$MPSE = \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{n}$$

n = sample size,

$\hat{Y}_i$ = SPF predicted values at site *i*,

Y_i = the observed values at site *i*

Over Dispersion Parameter (k)

An over dispersion parameter indicates if the variance is different than the mean assuming a Poisson distribution. The smaller the k value, the less dispersed the variance is from the mean (Hauer, 2015). The k value is found while estimating the model parameters in SAS.

Ontario Case Study Data Summary

The scope of this study includes highway segments in Ontario with centreline and edgeline rumble strip applications. Data for this study were provided by the Ministry of Transportation of Ontario (MTO) and will be explored more in detail in the upcoming sections. To determine the safety effectiveness of ELRS and CLRS for tangent and curve sections, the following information was needed:

- Location of ELRS, CLRS, and installation years
- Location of tangent and curved segments within ELRS and CLRS sites
- AADT for Ontario highways
- Crash related data for Ontario highways

Site Locations

Information on 2-lane undivided roads with centreline and edgeline rumble strips were made available by the MTO. The number of viable sites with either CLRS or ELRS in Ontario is quite small although the total length is sizeable. In total, 8 sites totalling 78.6 km were used for the CLRS portion of the study and 10 sites totalling 73.8 km were used for the ELRS study. In the case of an EB study, a reference group with similar characteristics, but without rumble strips is also needed. The compilation of reference sites was completed through several different ways. The MTO provided some reference sites directly, while some sites initially deemed as either CLRS or ELRS sites were also used as reference sites if the build year for the rumble strips was after 2013 (as no crash data is available for these years and thus the sites are ideal reference group candidates). Some sites were also found using MTO's iCorridor (MTO, n.d.) website. The

CLRS and ELRS sites were also used as reference groups for the years predating their rumble strip build year. In total, 20 unique sites totalling 279.1 km of road were used as reference sites, while in total 38 sites (including the mentioned overlap sites) totalling 431.5 km were used.

CLRS Location Information

Appendix: Table 1 in Appendix A summarizes the highway, location, build year, and length of the CLRS sites used in this study.

ELRS Location Information

Appendix: Table 2 in Appendix A summarizes the highway, location, build year, and length of the ELRS sites used in this study.

Reference Site Information

Appendix: Table 3 in Appendix A summarizes the highway, location, build year, and length of the reference sites used in this study. Note that for sites with rumble strip build years, only the years before the build year are used.

Tangent and Curve Sections

A portion of this study will explore the separate safety effect of applying CLRS and ELRS on tangent and curved segments of road. Although it is useful, currently no studies in the CMF Clearinghouse (FHWA, 2018) or HSM (AASHTO, 2010) provide this information. The differentiation between curved or tangent sections was made using information provided in the motor vehicle accident databases which will be discussed below and a shapefile provided by the

Systems Analysis and Forecasting Office of the MTO and analyzed on ArcGIS (ESRI, 2018). For each CLRS, ELRS, and reference site, the location of curved and tangent segments was tabulated as summarized in the following sections.

CLRS Tangent and Curved Sections

Of the 78.6 km of CLRS, 16.4 km are identified as tangent sections and the remaining 62.2 km are identified as curved sections. Appendix: Table 4 in Appendix A summarizes the length of the CLRS tangent and curved sites used in this study in order of location within each referred to site.

ELRS Tangent and Curved Sections

Of the 73.8 km of ELRS, 46 km are identified as tangent sections and the remaining 27.8 km are identified as curved sections. Appendix: Table 5 in Appendix A summarizes the length of the ELRS tangent and curved sites used in this study within each referred to site.

Reference Tangent and Curved Sections

Of the 279.1 km of reference sites, 79 km are identified as tangent sections and the remaining 200.1 km are identified as curved sections.

Appendix: Table 6 in Appendix A summarizes the length of the reference tangent and curved sites used in this study within each referred to site. A note that this table does not include previously mentioned ELRS and CLRS, tangent and curved sections.

Traffic Volumes and Collision Counts

AADT is a necessary variable in crash prediction model. Appendix: Table 7 and Appendix: Table 8 in Appendix A shows the AADT for the years 2000-2014 for each highway segment of this study.

Collision Counts

The MTO has provided queries from their motor vehicle accident database in the form of Excel (Microsoft, n.d.) spreadsheets. The database stores information regarding the characteristics and conditions of the infrastructure, environment, and affected users relating to every motor vehicle collision on MTO governed roads (MTO, 2004). For this study, columns relating to location (LHRS and Offset), location type (i.e. Intersection or segment), road configuration, crash severity classification, and initial impact type were used to sort the crash data. This study will be looking at the following collision severities and types:

- Total Collisions (Total)
- Fatal + Injury Severity Collisions (Injury)
- Property Damage Only Severity Collisions (PDO)
- Approach and Sideswipe Crashes (App + SS)
- Single Vehicle Collisions (SVeh)

The following sections detail the collision data used in this study.

Reference Site Collisions

Appendix: Table 9 in Appendix A summarizes the reference site collisions between 2000 and 2013.

CLRS Site Collisions

Appendix: Table 9 and Appendix: Table 10 in Appendix A summarize the CLRS site collisions before and after the safety treatment was applied.

ELRS Site Collisions

Appendix: Table 9 and Table Appendix: Table 11 in Appendix A summarize the ELRS site collisions before and after the safety treatment was applied.

Reference Site Collisions for Tangent and Curve Segments

Appendix: Table 12 in Appendix A summarizes the reference site collisions between 2000 and 2013 for the tangent and curve segments.

CLRS Site Collisions for Tangent and Curve Segments

Appendix: Table 13 in Appendix A summarize the CLRS site collisions before and after the safety treatment was applied for the tangent and curve segments.

ELRS Site Collisions for Tangent and Curve Segments

Appendix: Table 14 and Appendix: Table 15 in Appendix A summarize the ELRS site collisions before and after the safety treatment was applied for the tangent and curve segments.

Summary of Rumble Strip Data

A summary of the rumble strip crash and site data is available in Table 14 below.

Table 14: Rumble Strip Data Summary

	Reference			CLRS			ELRS		
	Total	**Tan.**	**Cur.**	**Total**	**Tan.**	**Cur.**	**Total**	**Tan.**	**Cur.**
# of km	432	262	169	79	29	50	74	46	28
# of years	14	14	14	3	3	3	8	8	5
km years before	5544	3448	2095	1008	307	701	760	473	287
km years after	-	-	-	171	63	108	198	124	74
Crashes / km before	1.008	1.003	1.016	0.663	0.645	0.674	1.285	1.167	1.480
Crashes / km after	-	-	-	0.701	0.679	0.714	1.035	1.018	1.065
Inj. crashes / km before	0.224	0.218	0.234	0.223	-	-	0.309	-	-
Inj. crashes / km after	-	-	-	0.197	-	-	0.212	-	-
PDO crashes / km before	0.785	0.786	0.782	0.469	0.446	0.482	0.976	0.882	1.132
PDO crashes / km after	-	-	-	0.532	0.474	0.565	0.823	0.808	0.849
Apr+SS / km before	0.112	0.109	0.118	0.080	-	-	0.174	-	-
Apr+SS / km after	-	-	-	0.075	-	-	0.116	-	-
SMV / km before	0.800	0.791	0.814	0.563	0.544	0.574	0.988	0.892	1.146
SMV / km after	-	-	-	0.561	0.553	0.565	0.778	0.784	0.768
Average AADT before	5511	5428	5814	4276	4567	4276	8293	8239	8454
Max AADT before	12700	12600	12700	7750	7700	7750	12700	12600	12700
Min AADT before	1700	1700	1700	1700	1700	1700	5000	5000	5700
Average AADT after	-	-	-	4677	4923	4743	9309	9368	10807
Max AADT after	-	-	-	8300	8100	8100	13800	13500	13500
Min AADT after	-	-	-	1700	1800	2000	4550	4700	6600

Ontario Case Study Safety Performance Functions

This chapter will explore the resulting SPFs which come about from the empirical Bayes study of the safety effectiveness of centreline and edgeline rumble strips on 2 lane undivided highways in Ontario. Models will also be developed separately for segments of road which are either curved or straight to further explore if rumble strips provide an effective safety benefit and if so, which types of rumble strips and road segments lead to an effective safety benefit.

Centreline and Edgeline Empirical Bayes Before-After Study

Selection of Crash Types

In a comprehensive rumble strip study evaluating Kentucky, Missouri, and Pennsylvania (Persaud et al., 2016), the crash types which were evaluated included:

- Total Crashes
- Injury Crashes
- Run-off-road crashes
- Head-on crashes
- Sideswipe-opposite-direction crashes

While each jurisdiction codes its collisions differently into their respective motor vehicle collision databases, these crash types were mimicked as closely as possible. In the MTO collision database total, and injury collisions can be determined directly. To evaluate head-on and sideswipe opposite direction crashes, the impact types of “Approach” and “Sideswipe” were combined. One consideration to be made is that the MTO coding of "sideswipe" is not limited to opposite direction crashes only, but in the event of a sideswipe collision on a 2-lane segment of road, it is unlikely that sideswipe collisions would not be between vehicles traversing in opposite directions. In a similar fashion, "Approach" collisions are used to mimic head-on collisions. As the data is limited, approach and sideswipe crashes were combined. Following this thought process, Single Vehicle collisions are used as a surrogate for run-off-road crashes, as single vehicle collisions would encapsulate run-off-road collisions. Property damage only collisions will also be modelled as they are the most common severity of crash type. Therefore, the following crash types will be used to develop the crash prediction models:

- Total Crashes
- Injury Crashes
- Property Damage Only Crashes
- Single Vehicle Crashes
- Approach + Sideswipe Crashes

For the case of tangent and curved CLRS and ELRS sections, a reduced number of crash types will be explored. The crash types that will be investigated are listed below:

- Total Crashes
- PDO Crashes
- Single Vehicle Crashes

The criteria for selecting which of the crash types used previously for this section was based upon data restrictions. As the other crash types did not have enough collisions for the subgroupings, they were omitted.

Safety Performance Functions

The safety performance functions (SPFs) have been developed in the form of generalized linear models (GLM) using a negative binomial (NB) distribution. The general form of the SPFs is shown in the equation below:

$$\text{Crashes/year} = e^{\alpha} AADT^{b} Length^{c}$$

Table 15 summarizes the SPF parameters and over dispersion value (k):

Table 15: SPF Parameter Estimates

Crash Type	*a*	*b*	*c*	k
Total	-5.4619	0.6469	0.9677	0.0345
Injury	-6.1696	0.5878	0.8633	0.0694
PDO	-5.9628	0.6606	1.0174	0.0366
Single Vehicle	-4.943	0.5652	0.9527	0.0429
Approach + Sideswipe	-10.1432	0.9203	1.0218	0.0705
	Curved Segments			
Total	-6.1609	0.736	0.9052	0.1427
PDO	-6.6589	0.7623	0.9006	0.119
Single Vehicle	-5.663	0.6488	0.9272	0.1147
	Tangent Segments			
Total	-4.801	0.5675	0.9646	0.1198
PDO	-4.909	0.5436	1.0019	0.1044
Single Vehicle	-3.9975	0.4491	0.951	0.1188

Goodness of Fit (GOF) Measures

CLRS and ELRS GOF Measures

Table 16 shows the GOF measures for the CLRS and ELRS SPFs for each crash type.

Table 16: GOF Measures for Crash Models

GOF Measures	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
$MPB = \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)}{n}$	0.000	0.000	0.000	0.000	0.000
$MAD = \frac{\sum_{i=1}^{n}\lvert\hat{Y}_i - Y_i\rvert}{n}$	24.73	9.25	19.31	19.85	5.04
$MPSE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}$	1192.62	165.00	652.23	725.85	73.40
k	0.0345	0.0694	0.0366	0.0429	0.0705

It is expected that the mean prediction bias will be very close to zero for the SPFs used because crash type specific annual factors have been applied to the SPFs. This ensures the cumulative residuals will equal zero when all reference sites are considered. The mean absolute deviation and mean squared prediction error demonstrate the variation of predictions and actual crash values at sites. Both the MAD and MPSE values are generally high across the board. To give context, outlines the MAD value and the average crash values aggregated over every site per crash type. Table 17 would suggest that the MAD value is relatively high for the injury and approach + sideswipe crash types, which suggests that the lower the observed crashes, the higher variability per site predicted in the SPF. The variability seems to stabilize at higher crash counts as illustrated by the relatively similar rates for total, PDO, and single vehicle collisions.

Table 17: Comparing MAD and Crashes Per Site

Performance Measure	Total	Injury	PDO	Single Vehicle	Approach + Sideswipe
$average\ crashes\ per\ site$	147.1	32.7	114.4	116.7	16.4
$MAD = \frac{\sum_{i=1}^{n} \lvert \hat{Y}_i - Y_i \rvert}{n}$	24.73	9.25	19.31	19.85	5.04
MAD / average crashes per site	0.17	0.28	0.17	0.17	0.31

CLRS and ELRS SPF CURE Plots

In this section, the cumulative residual plots will be shown for the total crash type for both variables: AADT and length. The remaining CURE Plots can be viewed in Appendix B: CURE Plots. In Figure 5 the cumulative residuals surpass the lower bound of the 2- standard deviation limit for several points between 12 and 25 km. As the limits roughly indicate the 95% confidence interval, it is expected that the cumulative residuals will only pass the limits on rare occasions (Hauer, 2015). As such, one limitation of the model used is for its propensity to overpredict crashes for length values between 12 and 25 km. The AADT CURE plot shown in Figure 6 demonstrates a better fitting CURE plot. In similar fashion, the models for PDO and single vehicle collisions shown Appendix: Figure 14 and Appendix: Figure 16 in respectively have the same limitation.

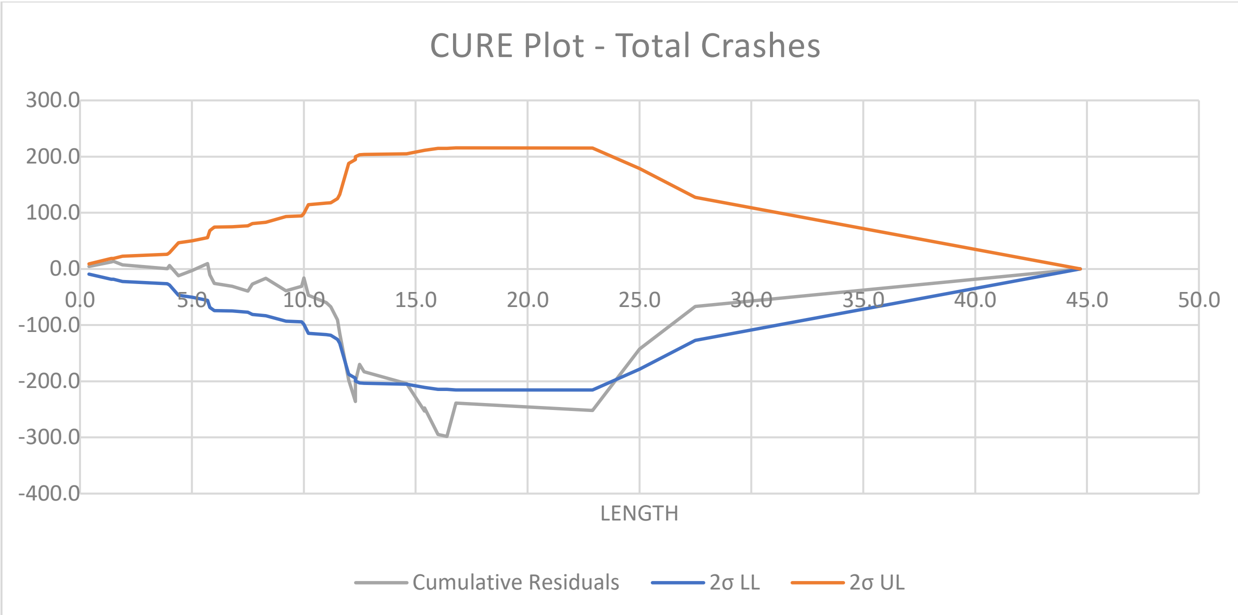


Figure 5: CURE Plot of Total Crashes Against Length Variable

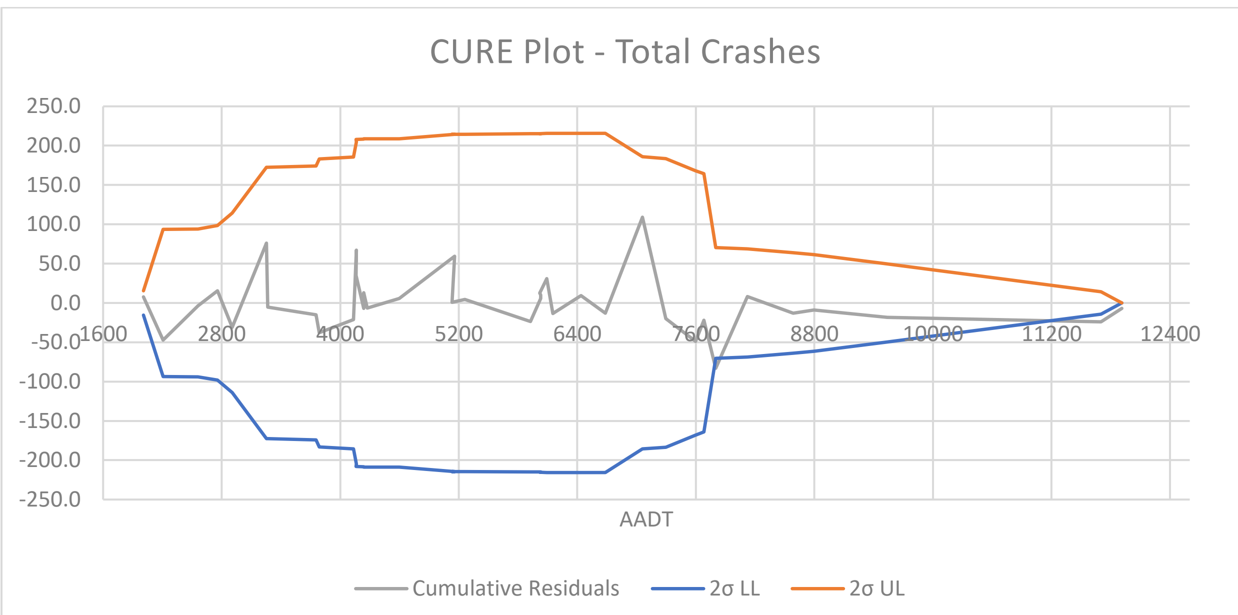


Figure 6: CURE Plot of Total Crashes Against AADT Variable

Tangent and Curved Segment GOF Measures

Table 18 and Table 19 shows the GOF measures for each crash type of the curved segment SPFs.

Table 18: GOF Measures for Curved Section Crash Models

GOF Measure	**Total**	**PDO**	**Single Vehicle**
$MPB = \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)}{n}$	0.000	0.000	0.000
$MAD = \frac{\sum_{i=1}^{n}\lvert\hat{Y}_i - Y_i\rvert}{n}$	8.264	7.072	7.079
$MPSE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}$	132.35	128.62	105.84
k	0.1427	0.1190	0.1147

Table 19: GOF Measures for Tangent Section Crash Models

GOF Measure	**Total**	**PDO**	**Single Vehicle**
$MPB = \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)/n}{n}$	0.000	0.000	0.000
$MAD = \frac{\sum_{i=1}^{n}\lvert\hat{Y}_i - Y_i\rvert}{n}$	11.56	8.546	9.638
$MPSE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}$	304.65	171.97	232.08
k	0.1198	0.1044	0.1188

As expected, the MAD and MPSE values are highest for the total crash predictions as there are higher crash counts for this data (over the same number of sites), which lends the safety performance functions to estimate predictions with higher variability. The same holds true for the tangent models when compared to the curved models; as there are more km-years and crashes in the tangent sections, it was expected that these models would yield higher MAD and MPSE values. As crash type specific annual factors were assigned to each section, MPB values of virtually 0 were expected.

In this section, the cumulative residual plots will be shown for the total crash type for both variables of the curved and tangent models: AADT and length. The remaining CURE Plots can be viewed in Appendix B: CURE Plots.

The cumulative residuals of the curved segment CURE plots shown in Figure 7 and Figure 8 lie within the acceptable confidence interval range. The AADT tangent segment CURE plot shown in Figure 9 shows a clear propensity for the model to underpredict crashes from the

AADT range of 6000 to 7600. Although this issue may go away with more data points, as the model stands this is a limitation which should be noted. In similar fashion, the models for PDO and single vehicle collisions shown in Appendix: Figure 9 and Appendix: Figure 11 respectively have the same limitation.

Curved Segments:

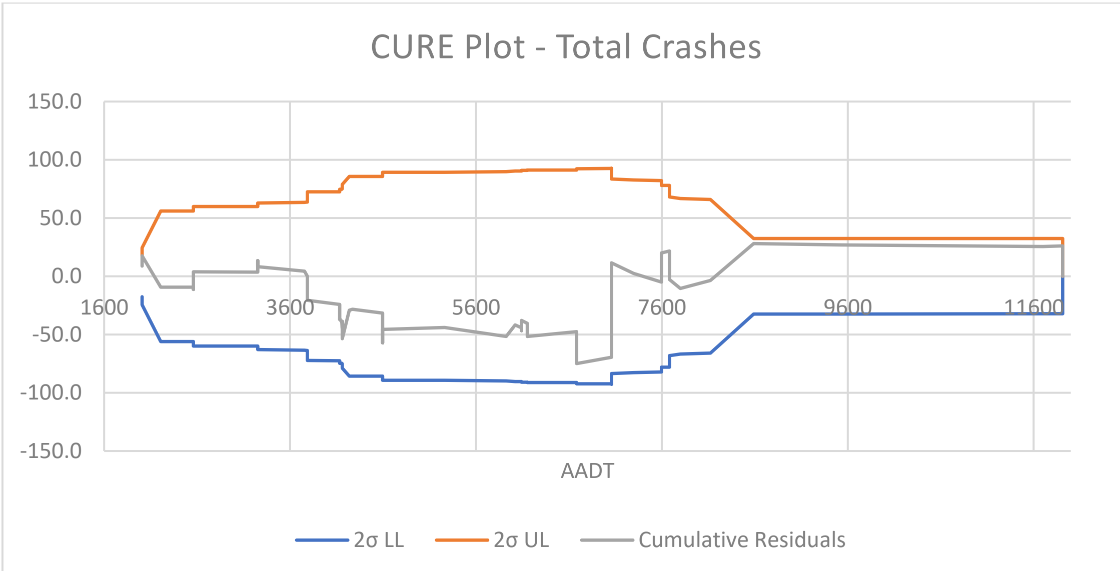


Figure 7: CURE Plot of Total Crashes Against AADT Variable (Curved Sections)

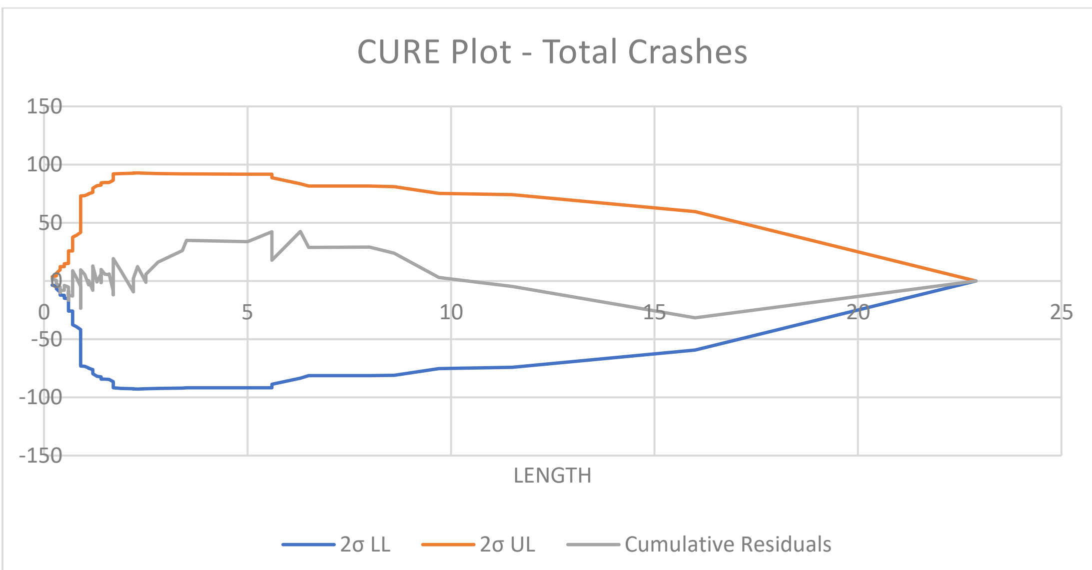


Figure 8: CURE Plot of Total Crashes Against Length Variable (Curved Sections)

Tangent Segments:

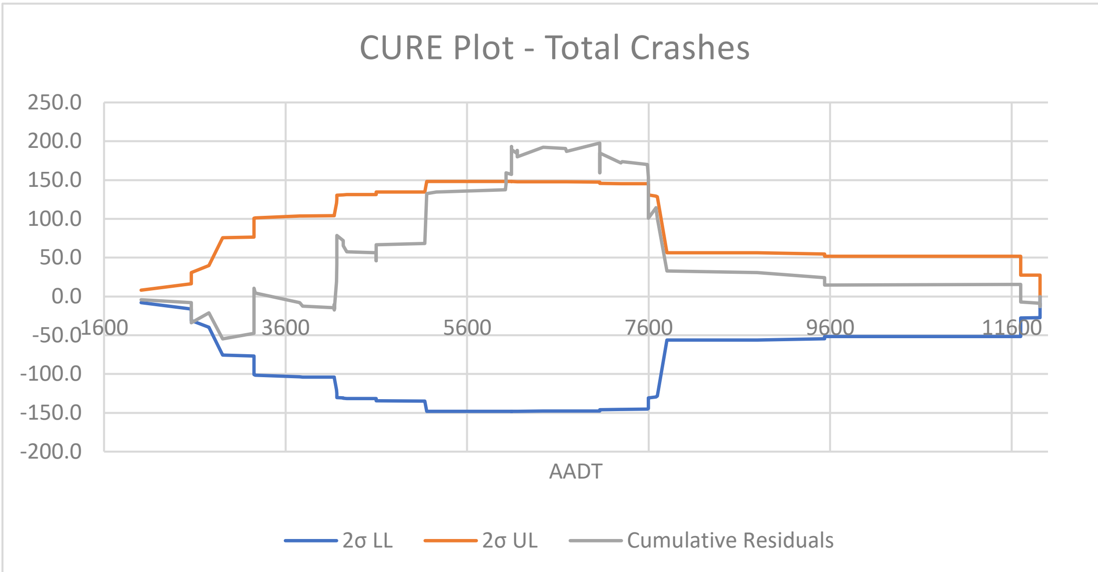


Figure 9: CURE Plot of Total Crashes Against AADT Variable (Tangent Sections)

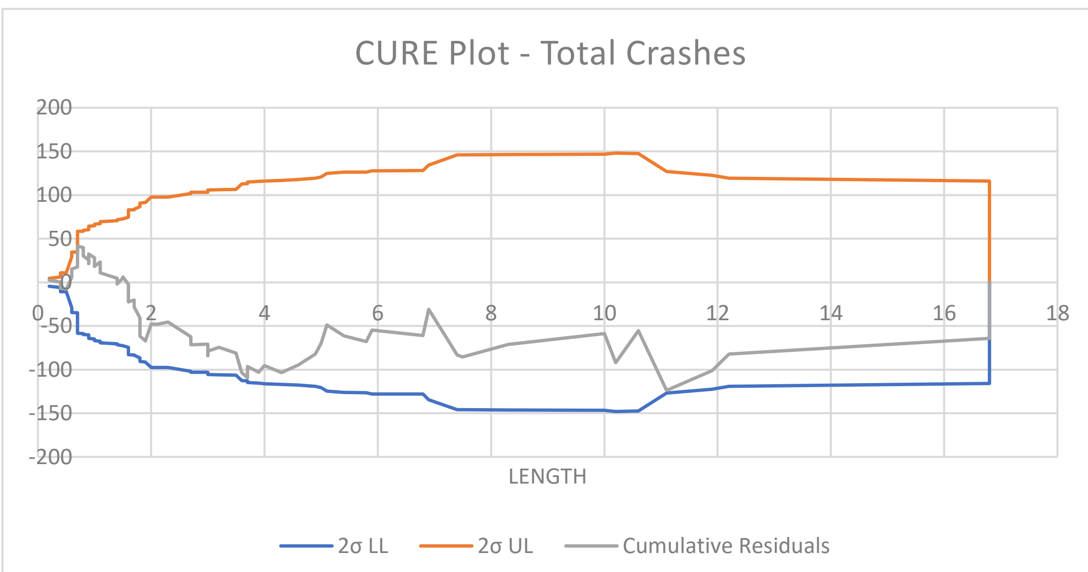


Figure 10: CURE Plot of Total Crashes Against Length Variable (Tangent Sections)

Ontario Case Study Results

Table 20 and Table 21 provide the estimates of the expected number of crashes without a safety treatment in the after period, the observed number of crashes in the after period and the computed CMF for CLRS and ELRS applications respectively.

CMF Results for Centreline Rumble Strip

The results for the CLRS study are shown below in Table 20. Before regarding the statistical significance of the results, it is observed that there was virtually no difference for implementing CLRS for total, injury, PDO, and single vehicle crashes. The same holds true for the crashes resulting in fatalities and injuries. While the PDO, single vehicle, and approach + sideswipe collisions show reductions after the safety treatment, none are significant to the 95-percent confidence level. As these results are not statistically significant, concrete conclusions should not be drawn from the data, but several observations can be made. Intuitively, centreline rumble strips should decrease the approach and sideswipe collisions as their intention is to notify drivers when they encroach into the oncoming lane, so the value of 0.863 can be understood. As there were only 11 collisions observed, more km-years of data are needed. It would be expected that a CLRS would decrease the injury rate in similar fashion to the approach and sideswipe rate, but with such a large standard deviation of results, more km-years of data may be needed to see a potential drop from a CMF value of 1.085. Similar decreases in single vehicle and property damage only collisions are expected as it would be expected that most collisions involving one vehicle would not result in serious injuries. It is also intuitive that this safety treatment would not drastically affect their crash rates as a CLRS does not primarily focus on areas where many single vehicle or PDO crashes occur, so CMF values of

0.988 and 0.982 for PDO and single vehicle crashes respectively seem high, yet within reason. In general, the lack of effectiveness of this treatment is surprising, but may be a result of the low km-years of data available.

Table 20: CMF Estimates for CLRS

Crash Type	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
Observed "After" Crashes	120	29	91	96	11
Expected "After" Crashes	127.73	24.42	102.40	98.69	12.49
CMF	0.996	1.085	0.988	0.982	0.942
SE	0.0927	0.207	0.107	0.103	0.295
CMF 95% Upper Limit	1.18	1.50	1.20	1.19	1.53

CMF Results for Edgeline Rumble Strip

The results for the ELRS study are shown below in Table 21. The results from this study show that apart from injury collisions, all results are significant. The results indicate that edgeline rumble strips seem to be a more effective safety measure to a 2-standard deviation level. The EB study suggests that the total collisions in the ELRS sites were reduced by roughly 25%. This is to be expected as on a two-lane highway the expected common crash type would be run-off-road crashes, which ELRS aims to rectify directly. The CMF for injury collisions is slightly higher than the total crashes CMF, which is to be expected as it would be expected that ELRS has a larger effect on non-injury crashes. Mysteriously, the crash types most affected by this treatment are approach and sideswipe crashes. It is expected that the effect of ELRS on this crash type would be smaller than that of other crash types. The small sample size could be skewing the results, so this CMF should be understood within the context of limited data.

Table 21: CMF Estimates for ELRS

Crash Type	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
Observed "After" Crashes	205	42	163	154	23
Expected "After" Crashes	299.14	57.91	237.44	220.60	35.15
CMF	**0.753**	0.79	**0.743**	**0.757**	**0.689**
SE	0.054	0.13	0.0606	0.0632	0.151
CMF 95% Upper Limit	0.86	1.04	0.86	0.88	0.99

CMF Results for CLRS, Curved and Tangent Sections using Disaggregated SPFs

The results for the CLRS study on curved sections and tangent sections are shown below in Table 22. No results are significant to the 95% confidence level, so conclusions will be kept to observations of the CMFs at face value. The CMFs for the curved sections are smaller than those on the tangent sections, which suggests this treatment option is more effective on curves. The CMF may be effective in preventing crashes on curves and not tangent segments of road because it aids drivers by ensuring they do not encroach into the opposite lane curves, whereas on turns this isn’t as large of an issue. The most affected crash type was PDO crashes on curved roads. The CLRS may be reducing this crash type because the rumble strips keep drivers alert and prevent them from run-off road collisions. Curiously, the total and single vehicle crashes on tangent sections seem to be negatively affected by the CLRS. It is possible that the vibrations from the rumble strips are detrimental because they are an added form of stress to the driver. The PDO crashes on tangent segments seem to be largely unaffected by the rumble strips.

Table 22: CMF Estimates for Curved and Tangent CLRS Sections

Crash Type	**Total**	**PDO**	**Single Vehicle**
Curved Segments			
Observed "After" Crashes	77	61	61
Expected "After" Crashes	104.74	87.54	78.20
CMF	0.913	0.888	0.923
SE	0.106	0.117	0.121
CMF 95% Upper Limit	1.13	1.12	1.16
Tangent Segments			
Observed "After" Crashes	43	30	35
Expected "After" Crashes	39.13	29.50	30.17
CMF	1.057	1.009	1.079
SE	0.168	0.194	0.191
CMF 95% Upper Limit	1.39	1.40	1.46

CMF Results for ELRS, Curved and Tangent Sections using Disaggregated SPFs

The results for the ELRS study on curved sections and tangent sections are shown in Table 23. Unlike the CLRS segments, the ELRS results are significant at a 95% confidence interval. This mirrors the results found in the original ELRS study. Looking at the curved sections, it appears that the same phenomena observed in the CLRS section is occurring; the safety treatment is better suited for reducing crashes on curved segments when compared to the tangent segments. The curved segment CMF's are all quite large, with crash reductions of roughly 28%, 33%, and 31% for total crashes, PDO crashes and single vehicle crashes respectively. These results match expectations as edgeline rumble strips would aid in preventing run-off-road collisions, which may be a main source of collisions on curved segments of 2-lane highways. As the reduction in total collisions is less than the property damage only collisions, it can be inferred that this safety treatment, while still effective in reducing injury collisions, is proportionally more effective in reducing non-injury collisions. The similar values of PDO and single vehicle collisions matches expectations as there is a substantial overlap between the two crashes. While not as effective as on curved sections, ELRS on tangent sections of road are still effective at the 95% confidence interval level. The CMFs for total crashes and PDO crashes are virtually the same. An inference that injury collisions would also be reduced by the same amount can be made. Although slightly less effective with a crash reduction of roughly 20% compared to the 22% of total crashes and 21% of PDO crashes, ELRS are still quite useful in reducing single vehicle crashes on tangent segments of 2-lane highways.

Table 23: CMF Estimates for Curved and Tangent ELRS Sections

Crash Types	**Total**	**PDO**	**Single Vehicle**
Curved Segments			
Observed "After" Crashes	79	63	57
Expected "After" Crashes	124.05	104.60	88.91
CMF	**0.716**	**0.665**	**0.693**
SE	0.082	0.087	0.095
CMF 95% Upper Limit	0.88	0.84	0.88
Tangent Segments			
Observed "After" Crashes	126	100	97
Expected "After" Crashes	179.64	137.57	128.91
CMF	**0.776**	**0.788**	**0.803**
SE	0.079	0.083	0.085
CMF 95% Upper Limit	0.93	0.95	0.97

CMF Results for Curved and Tangent Sections using Aggregated CLRS and ELRS SPFs

The results for the CMFs of curved and tangent sections using the aggregated CLRS SPFs are displayed in Table 24. At first glance, it can be observed that no CLRS CMFs are statistically different to 1.0 at the 95% confidence level. This matches the findings found in the CLRS CMF estimates table. Another general observation that can be made is that the curved segments, have generally lower CMF values when compared to the tangent segments. The CMF estimates for the total and single vehicle collisions is virtually the same for both curved and tangent sections, whole the PDO collisions CMF is higher than the other two for curved segments and lower than the other two for tangent sections. These results vary from the CMF results above. This may be due to the generalization of the SPFs used. Using an aggregated SPF for disaggregated CMFs may lend itself to increased variability as it is intended for a more generalized purpose as evidenced by the results below.

Table 24: CMF Estimates for Curved and Tangent CLRS Sections Using Aggregated CMF

Crash Type	**Total**	**PDO**	**Single Vehicle**
	Curved Segments		
Observed "After" Crashes	77	61	61
Expected "After" Crashes	111.56	85.46	86.07
CMF	0.873	0.915	0.867
SE	0.104	0.122	0.116
CMF 95% Upper Limit	1.08	1.16	1.10
	Tangent Segments		
Observed "After" Crashes	43	30	35
Expected "After" Crashes	40.75	29.35	32.08
CMF	0.978	0.911	0.989
SE	0.166	0.184	0.185
CMF 95% Upper Limit	1.31	1.28	1.36

The results for the CMFs of curved and tangent sections using the aggregated ELRS SPFs are displayed in Table 25. Like the ELRS results, all CMFs for both curved and tangent sections are statistically below 1.0 at the 2-confidence interval level. One general difference between these results and the ELRS results found using the disaggregated tangent and curved sections is that the curved segments here have larger CMFs than the tangent segments while the other results show the opposite. In general, the results displayed in have lower CMF estimates when compared to the disaggregated ELRS curved and tangent sections. This indicates that the aggregated SPFs are overestimating the treatment effect.

Table 25: CMF Estimates for Curved and Tangent ELRS Sections Using Aggregated CMF

Crash Type	**Total**	**PDO**	**Single Vehicle**
Curved Segments			
Observed "After" Crashes	79	63	57
Expected "After" Crashes	119.08	88.97	89.17
CMF	**0.721**	**0.704**	**0.698**
SE	0.091	0.100	0.103
CMF 95% Upper Limit	0.90	0.90	0.90
Tangent Segments			
Observed "After" Crashes	126	100	97
Expected "After" Crashes	222.44	166.75	168.05
CMF	**0.625**	**0.623**	**0.641**
SE	0.065	0.074	0.077
CMF 95% Upper Limit	0.76	0.77	0.79

CMF Results for CLRS and ELRS Using Disaggregated Curved + Disaggregated Tangent SPFs

As all the same data were used for both the CLRS/ELRS study and the disaggregated curved and tangent segments study, the results from both studies should produce similar results when the latter study is aggregated. The results for combining the curved and tangent sections for both the CLRS and ELRS sections are displayed in Table 26. As expected, the results indicate that regardless of crash type, ELRS are a more effective treatment than CLRS for 2-lane highways in

Ontario. The CMFs for the aggregation of the curved and tangent segment study match the disaggregated results in that all the CLRS results are not statistically different than a CMF of 1.0 at the 2-standard deviation level, while all the ELRS results are statistically different than 1.0 at the 2-standard deviation level. While all the results for the CLRS CMFs lie within the range of 0.92 to 0.98, which indicates that CLRS have a similar effect on total, PDO and single vehicle crashes when curved and tangent sections are looked at together. The same observation can be made about ELRS segments, as all the results for the ELRS CMFs lie between 0.74 and 0.76. Following along the lines of similar observations, for both CLRS and SLRS segments, this safety treatment seems to effect PDO crashes the most, followed by total crashes and single vehicle crashes the least, although the caveat that all the CMFs are within 4.9% and 2.3% for CLRS and ELRS should be made. The small discrepancy between the CMFs indicates that the similar order of effectiveness may be coincidence.

Table 26: CMF Summary for Combined Curved and Tangent Sections

Crash Types	**Total**	**PDO**	**Single Vehicle**
	CLRS		
Observed "After" Crashes	120	91	96
Expected "After" Crashes	143.88	117.03	108.37
CMF	0.961	0.926	0.975
SD	0.090	0.101	0.103
CMF 95% Upper Limit	1.14	1.13	1.18
	ELRS		
Observed "After" Crashes	205	163	154
Expected "After" Crashes	303.69	242.17	217.82
CMF	**0.751**	**0.736**	**0.759**
SE	0.057	0.060	0.064
CMF 95% Upper Limit	0.87	0.86	0.89

The results are difficult to judge on their own accord, so the differences between the two study methods are displayed in Table 27. The numbers show the aggregation of tangent and curved sections minus the original CLRS and ELRS data. Therefore, a positive number indicates the aggregation of tangent and curved sections are higher than their original CLRS and ELRS counterparts. Apart from the ELRS Single Vehicle results, the SPFs for all crash types for both sets of rumble strips expects less crashes in the original SPFs. This observation matches the results for the CMFs as apart from the ELRS single vehicle CMF, the original CMFs are larger. This means that the aggregation of tangent and curved sections estimates less conservative (more effective) CMFs.

Table 27: CMF Differences Between Case Study Methods

Crash Types	**Total**	**PDO**	**Single Vehicle**
CLRS			
Observed "After" Crashes	0	0	0
Expected "After" Crashes	16.15	14.63	9.68
CMF	-0.035	-0.062	-0.007
SE	-0.0027	-0.006	0
CMF 95% Upper Limit	-0.04	-0.07	-0.01
ELRS			
Observed "After" Crashes	0	0	0
Expected "After" Crashes	4.55	4.73	-2.78
CMF	-0.002	-0.007	0.002
SE	0.003	-0.0006	0.0008
CMF 95% Upper Limit	0.01	0	0.01

When determining which set of values of CMFs should be used, it is beneficial to see which models behave the closest to the input data. For this exercise, the GOF measures will be analyzed to see which SPFs perform best. The MPB values are roughly 0 across the board as the SPFs are all adjusted with annual factors. The MAD results are a good indication for comparing SPFs as it is a cumulative measure. The individual and combined MAD values for the aggregated tangent and curved sections SPFs are less than the MAD values for the original data. Along these lines, the CURE plots show less cumulative residuals over the 2-standard deviation boundary for the aggregated curved and tangent sections results (although the CURE plots for the tangent sections do also have cumulative residuals over the allowed amount).

CMF Results for CLRS and ELRS by Grouping AADT Values

The purpose of this section is to investigate the effect that centreline and edgeline rumble strips have when the sites are grouped according to AADT values. Table 28 shows the CMF values for the CLRS sections grouped by AADT. The groups used were for AADTs under and over 4000 vehicles per day. This value was used as roughly half of the total length of site locations had AADT values under and over 4000 vehicles per day. The results indicate that no CLRS values are statistically different than a CMF of 1.0 at the 95% confidence interval level regardless of the AADT grouping. When inspecting the CMF values there is a large discrepancy between the two groupings. The statistical insignificance of this difference may be attributed to the large standard error values, which would naturally decrease as more site locations are used. While no concrete statements can be made due to the limited sample size, the discrepancy in the results can be explored further. At lower AADT values, there are naturally less opposing vehicles, which may result in drivers driving more aggressively as visually the road seems less dangerous. The result is that the effect of a centreline rumble strip may be amplified at lower AADTs as there are less visual cues to tell drivers when they are encroaching into the opposite lane and this the auditory cues and rumbling from the CLRS is then relied upon more.

Table 28: CLRS CMFs Grouped by AADT

Crash Type	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
	AADT Under 4000				
Observed "After" Crashes	21	4	17	19	2
Expected "After" Crashes	35.390	7.020	28.160	28.380	2.840
CMF	0.767	0.635	0.800	0.878	0.668
SE	0.17	0.32	0.20	0.21	0.47
CMF 95% Upper Limit	1.105	1.275	1.196	1.288	1.612
	AADT Over 4000				
Observed "After" Crashes	99	25	74	77	9
Expected "After" Crashes	92.340	17.410	74.240	70.310	9.650
CMF	1.063	1.222	1.044	1.011	1.027
SE	0.11	0.25	0.13	0.12	0.36
CMF 95% Upper Limit	1.281	1.726	1.294	1.247	1.741

Table 29 shows the CMF values for the ELRS sections grouped by AADT. The groups used were for AADTs under and over 8000 vehicles per day. This value was used as roughly half of the total length of site locations had AADT values under and over 8000 vehicles per day. The results from the table indicate less of an obvious pattern when compared to the CLRS results. While all ELRS CMF values were statistically different than 1.0 this is not the case when the CMFs are grouped as both groups have CMF values over 1.0 at the 95% confidence interval level for varying crash types. Once again, the larger standard error values because of the smaller data set is a large reason for the statistically insignificant data. When just looking at the CMF values, some observations can be made. While the total collisions and approach & sideswipe collisions between the two groups are similar, the CMF for the injury crashes is noticeably smaller for the lower AADT group. The number of observed crashes for injury collisions is very small at 9 observed crashes, so this discrepancy will be ignored. The CMF values for property damage and single vehicle collisions are each smaller by more than 10% for the larger AADT group. It is logical that these two crash types follow the same trend as they are dependent on each other. One reason for why their CMF values have decreased at larger AADT values is because the increased traffic may be aiding the edgeline rumble strips with ensuring drivers are less distracted and do not get into typical single vehicle and property damage collisions such as run-off road collisions.

Table 29: ELRS CMFs Grouped by AADT

Crash Type	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
	AADT Under 8000				
Observed "After" Crashes	52	9	43	43	5
Expected "After" Crashes	75.248	15.206	58.940	56.382	35.148
CMF	**0.772**	0.592	0.833	0.869	0.665
SE	0.11	0.21	0.13	0.14	0.31
CMF 95% Upper Limit	0.998	1.002	1.101	1.149	1.277
	AADT Over 8000				
Observed "After" Crashes	153	33	120	111	18
Expected "After" Crashes	223.894	42.706	178.495	164.221	27.515
CMF	**0.747**	0.863	**0.715**	**0.721**	**0.692**
SE	0.06	0.16	0.07	0.07	0.17
CMF 95% Upper Limit	0.871	1.177	0.851	0.861	1.036

Application of the NCHRP Project 17-63 Methodology to Estimate a CMF for ELRS and CLRS Combination Treatment

Table 30 indicates the CMF values determined in the EB study above.

Table 30: Summary of Rumble Strip CMFs

Crash Type	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
CLRS	0.996	1.085	0.988	0.982	0.942
ELRS	0.753	0.79	0.743	0.757	0.689

Step 1: Determine Overlap

It will be assumed that this combination of treatments will have some overlap (Case B) in their safety effect. This assumption is made because although the rumble strips are placed in different locations and target different collisions in specific (CLRS targets opposing vehicle collisions and ELRS targets run-off road collisions), there is some overlap in targeting inattentive or distracted drivers who may veer to either side of the road.

Step 2: Determine Magnitude

Table 31 displays the magnitude of each safety treatment.

Table 31: Magnitude of CMFs for CLRS and ELRS

Crash Type	**Total**	**Injury**	**PDO**	**Single Vehicle**	**Approach + Sideswipe**
CLRS	small	Small (>1)	small	Small	small
ELRS	medium	medium	large	Medium	large

Step 3: Determine Applicability

The road characteristics throughout the study were kept consistent for both safety treatments and thus the two treatments can be combined.

Step 4: Applying the Correct Method

For the conditions of the total crashes and single vehicle CMFs, the guidelines state to use the dominant common residuals method. For the conditions of the injury crashes, PDO crashes, and Approach + Sideswipe crashes, the guidelines state to use the dominant effect method.

Total Crashes:

$$\text{CMF combined } = (0.753 \times 0.996)^{0.753} = 0.805$$

Single Vehicle Crashes:

$$\text{CMF combined } = (0.757 \times 0.982)^{0.757} = 0.799$$

Injury Crashes:

$$\text{CMF combined} = 0.79$$

PDO Crashes:

$$\text{CMF combined} = 0.743$$

Approach + Sideswipe Crashes:

$$\text{CMF combined} = 0.689$$

Combined CMF Summary

Table 32 displays a summary of the combination CMFs

Table 32: Combined Rumble Strip CMF Estimations

Crash Type	**CLRS CMF**	**ELRS CMF**	**Combined CMF**
Total	**0.996**	**0.753**	**0.805**
Injury	1.085	**0.79**	**0.79**
PDO	**0.988**	**0.743**	**0.743**
Single Vehicle	**0.982**	**0.757**	**0.799**
Approach + Sideswipe	**0.942**	**0.689**	**0.689**

Observations:

The combined total crashes estimated CMF has increased slightly from the total crashes ELRS CMF. The same is true for single vehicle crashes. It is unlikely that combining CLRS and ELRS would increase the collisions when compared to ELRS by itself. As no CLRS are statistically different than 1.0 at the 2-standard deviation confidence level, it would also be reasonable to use the dominant effect method for all crash types. This would in effect disregard the CLRS values.

Comparing Study Results to Dual Rumble Strip CMFs

A suitable study to compare this one is the FHWA's study on the safety evaluation of dual rumble strips in Kentucky, Missouri, and Pennsylvania (Persaud et al., 2016). As the MTO and the various state DoT's have different methods for coding accidents into their databases, the crash types are not perfectly aligned. It is expected that the run-off-road CMF of the study used would represent the Single Vehicle crashes of this Ontario study as intuitively, the main crash type for single vehicle collisions are run-off-road crashes. This generalisation may result in some variations of the results as there are other notable causes of single vehicle crashes on rural highways such as collisions related to wildlife. Similarly, while the verbiage is different, approach + sideswipe crashes should give a good representation of sideswipe-opposite-direction crashes. The study in question does not have a CMF value for PDO crashes, so these crashes are omitted. Table 33 shows the estimated CMFs found above and the CMFs for the combined treatments developed in extensive studies:

Table 33: Comparison of Estimated and Actual Dual Rumble Strip CMFs

Crash Type	**Estimated Ontario CMF**	**CMF (SE) from Persaud et al.**	**CMF Lower Limit**	**CMF Upper Limit**
Total	0.805	0.800 (0.025)	0.75	0.85
Injury	0.79	0.771 (0.034)	0.703	0.839
Single Vehicle (Run-Off Road)	0.799	0.742 (0.041)	0.660	0.824
Approach + Sideswipe (Sideswipe Opposite Direction)	0.689	0.767 (0.097)	0.573	0.961

All the CMFs lie within the 2-standard deviation limits. Furthermore, the total crashes CMF, injury crashes CMF, and Approach + Sideswipe CMFs are within 1-standard deviation of the FHWA's calculated CMFs. While the total and injury crash types estimated CMFs are only different by up to 1.3% of the actual CMF values, the single vehicle and approach + sideswipe are within 8% of their respected CMFs values. The higher deviations of the latter two estimations may be because they are not exact comparisons as there are differences in how the jurisdictions classify crashes as explored above. As such, the expected deviation from actual values is slightly higher for the approximations of single vehicle and approach + sideswipe crashes. These observations indicate that the estimation methods proposed by the NCHRP Project 17-63 do perform adequately in this scenario.

Along with the variations in the crash and collision types between the two studies, the context that both studies were performed in is also different and should be considered. The states of Kentucky, Pennsylvania, and Missouri are substantially south of Ontario. The differences in climate should be considered as a rumble strip is naturally less effective when it is under snow. One expectation would be that these studies have lower CMF values than the Ontario study. The differences in the average AADT values between the studies can largely be ignored as they are all relatively close. It should be noted that the range of AADT values is higher in the FHWA study however. Unlike the Ontario study, the FHWA study used lane and shoulder widths in their SPF determination. Since there was little variation in the values, the lack of inclusion of these variables in the Ontario study should still result in comparable models.

Summary and Conclusions

The objective if this study was to observe current methods on estimating dual treatment CMFs. This study uses the methodology outlined NCHRP Project 17-63 to estimate CMFs for different applications including: the combination of installing left turn lanes and converting stop control intersections into signalized intersections, the combination of Transit Signal Implementation and Transit Lane Prioritization, and the combination of lowering the posted speed limit and reducing lane width. The estimated CMFS of the first two studies were compared to known dual treatment CMFs and the results were mixed. One main area of concern was with the issue of underestimating the CMF when the dominant CMF was too effective; the closer it was to 0, the less effectual it made the combined CMF. Another issue with the methodology arose with the use of the multiplicative method for CMFs with counteracting effects. While the multiplication of two CMFs < 1.0 will result in a more effective CMF (as CMFs are more effective as they approach 0), the counteracting effects method should be definition be aiming for the opposite effect; it aims to reduce the effectiveness of the dominant CMF (by increasing its overall value). The two methodology issues can be resolved by limiting their scope to certain CMF values.

In this study, CMFs for CLRS and ELRS were developed using Ontario highway data. The CMFs were then combined using the appropriate estimation methodology and compared to known CMF values. The estimated combined CMFs were all comparable the calculated combined CMFs within the allowable range indicating that the methodology listed in NCHRP Project 17-63 can be used to estimate high quality dual treatment CMFs.

To complement the CLRS and ELRS CMFs developed, CMFs were also formulated for tangent and curved segments for both safety treatment applications. For both locations of rumble strips, the corresponding CMFs for the curved segments were observed to be more effective when compared to the tangent segments. This observation demonstrates the ability of a rumble strips to alert distracted drivers of changes in road geometry and mitigate crossing over into opposing lanes or running of the road.

The results suggest that rumble strips become more effective as the length and AADT of a segment increases. As the length of an undisturbed segment increases, it is expected that drivers will be more prone to distraction and fatigue. This may result in encroaching into the opposite lane or shoulder. In a similar fashion, as the AADT increases on a segment, the opportunities for dangerous multi-vehicle collisions also increase. Rumble strips can mitigate these issues by keeping drivers alert and in their lanes. Given the CMF results above, it would be worthwhile to formulate a CMFunction based upon the expected number of crashes per km-year in the before treatment. With additional years of data it is suggested that a CMFunction is explored.

Appendix A: Tables

Appendix: Table 1 CLRS Locations

		From		To			
Ref	Highway	LHRS	Offset	LHRS	Offset	Build Year	Length (km)
CLRS 1	11	17285	4.9	17285	19.5	2010	14.6
CLRS 2	17	20990	7.5	20990	7.9	2012	0.4
CLRS 3	17	21000	0	21010	2	2010	12.5
CLRS 4	17	21036	0.08	21036	11	2012	11
CLRS 5	17	21210	1.6	21210	3.5	2011	1.9
CLRS 6	17	21210	8.9	21220	4.2	2011	12.3
CLRS 7	17	21410	4.9	21410	20.9	2012	16
CLRS 8	17	21410	29.95	21420	9.87	2012	9.9

Appendix: Table 2 ELRS Locations

		From		To			
Ref	Highway	LHRS	Offset	LHRS	Offset	Build Year	Length (km)
ELRS 1	17	20682	0	20688	0	2008	11.2
ELRS 2	17	20688	0	20701	1.2	2009	11.6
ELRS 3	17	20703	2.7	20708	0	2008	4.4
ELRS 4	17	20708	0	20722	0	2011	9.2
ELRS 5	17	20722	0	20722	1.4	2011	1.4
ELRS 6	17	20722	1.4	20722	8.9	2011	7.5
ELRS 7	17	20730	1.3	20746	0	2012	15.5
ELRS 8	17	20746	0	20751	0	2012	5.7
ELRS 9	17	20761	1.4	20771	0	2012	5.8
ELRS 10	15	20030	4.9	20030	6.4	2006	1.5

Appendix: Table 3 Reference Site Locations

		From		To			
Ref	Highway	LHRS	Offset	LHRS	Offset	Build Year	Length (km)
CLRS 1	11	17285	4.9	17285	19.5	2010	14.6
CLRS 2	17	20990	7.5	20990	7.9	2012	0.4
CLRS 3	17	21000	0	21010	2	2010	12.5
CLRS 4	17	21036	0.08	21036	11	2012	11
CLRS 5	17	21210	1.6	21210	3.5	2011	1.9
CLRS 6	17	21210	8.9	21220	4.2	2011	12.3
CLRS 7	17	21410	4.9	21410	20.9	2012	16
CLRS 8	17	21410	29.95	21420	9.87	2012	9.9
ELRS 1	17	20682	0	20688	0	2008	11.2
ELRS 2	17	20688	0	20701	1.2	2009	11.6

ELRS 3	17	20703	2.7	20708	0	2008	4.4
ELRS 4	17	20708	0	20722	0	2011	9.2
ELRS 5	17	20722	0	20722	1.4	2011	1.4
ELRS 6	17	20722	1.4	20722	8.9	2011	7.5
ELRS 7	17	20730	1.3	20746	0	2012	15.5
ELRS 8	17	20746	0	20751	0	2012	5.7
ELRS 9	17	20761	1.4	20771	0	2012	5.8
ELRS 10	15	20030	4.9	20030	6.4	2006	1.5
REF 1	11	17280	0	17283	13.7	2015	27.5
REF 2	11	17285	1	17285	4.9	2015	3.9
REF 3	11	17285	20.6	17285	28.3	2015	7.7
REF 4	11	17293	2.3	17310	0	2015	15.4
REF 5	17	20751	0.1	20761	1.6	2014	12.7
REF 6	17	21041	0.92	21041	12.37	2015	11.5
REF 7	41	29710	4.1	29710	10.1	2015	6
REF 8	138	45430	0	45450	0	2015	16.8
REF 9	89	16550	0	16550	4	N/A	10
REF 10	17	16557	0	16557	8.3	N/A	16.4
REF 11	10	16570	1	16570	6	N/A	4
REF 12	89	20840	1	20840	17.4	N/A	10.2
REF 13	21	24120	0	24160	0	N/A	44.7
REF 14	21	24170	6	24190	0	N/A	12.3
REF 15	23	24590	1.3	24600	0	N/A	12
REF 16	23	25620	0	25640	0	N/A	25
REF 17	26	25665	0	29690	0	N/A	22.9
REF 18	10	38670	3.2	38670	10	N/A	8.3
REF 19	10	38685	0	38685	10	N/A	5
REF 20	89	38690	1	38690	11.2	N/A	6.8

Appendix: Table 4 Curved and Tangent CLRS Locations

REF	Type	Length (km)	REF	Type	Length (km)
CLRS 1	cur	8	CLRS 3	cur	0.7
CLRS 1	tan	1.1	CLRS 3	tan	0.6
CLRS 1	cur	0.7	CLRS 3	cur	0.6
CLRS 1	tan	0.4	CLRS 3	tan	0.7
CLRS 1	cur	0.6	CLRS 4	cur	0.5
CLRS 1	tan	0.4	CLRS 4	tan	1
CLRS 1	cur	0.4	CLRS 4	cur	1.3
CLRS 1	tan	1.1	CLRS 4	tan	1.7
CLRS 1	cur	1.9	CLRS 4	cur	6.5
CLRS 2	cur	0.2	CLRS 5	cur	0.9

CLRS 2	tan	0.2	CLRS 5	tan	1
CLRS 3	cur	2.5	CLRS 6	cur	0.9
CLRS 3	tan	1.6	CLRS 6	tan	1.7
CLRS 3	cur	0.6	CLRS 6	cur	9.7
CLRS 3	tan	0.7	CLRS 7	cur	16
CLRS 3	cur	0.3	CLRS 8	cur	3.5
CLRS 3	tan	0.4	CLRS 8	tan	0.8
CLRS 3	cur	0.8	CLRS 8	cur	5.6
CLRS 3	tan	3			

Appendix: Table 5 Curved and Tangent ELRS Locations

REF	Type	Length (km)	REF	Type	Length (km)
ELRS 1	cur	0.5	ELRS 4	cur	0.4
ELRS 1	tan	1	ELRS 4	tan	0.8
ELRS 1	cur	1.5	ELRS 5	cur	1.4
ELRS 1	tan	3.7	ELRS 6	tan	7.5
ELRS 1	cur	2.5	ELRS 7	tan	0.4
ELRS 1	tan	0.8	ELRS 7	cur	1.2
ELRS 1	cur	1.2	ELRS 7	tan	2.7
ELRS 2	tan	3	ELRS 7	cur	0.9
ELRS 2	cur	5	ELRS 7	tan	7.4
ELRS 2	tan	3.6	ELRS 7	cur	2.8
ELRS 3	tan	2.7	ELRS 8	cur	3.4
ELRS 3	cur	0.3	ELRS 8	tan	2.3
ELRS 3	tan	1.4	ELRS 9	tan	1.7
ELRS 4	tan	0.6	ELRS 9	cur	1.1
ELRS 4	cur	5.6	ELRS 9	tan	3
ELRS 4	tan	1.9	ELRS 10	tan	1.5

Appendix: Table 6 Curved and Tangent Reference Site Locations

REF	Type	Length (km)	REF	Type	Length (km)
REF 1	tan	6.9	REF 10	cur	0.5
REF 1	cur	1.6	REF 10	tan	0.8
REF 1	tan	2	REF 10	cur	1.4
REF 1	cur	2.3	REF 10	tan	3.5
REF 1	tan	4.6	REF 10	cur	1.1
REF 1	cur	8.6	REF 10	tan	1.8
REF 1	tan	1.5	REF 11	tan	4
REF 2	tan	3.9	REF 12	tan	10.2

REF 3	tan	1.4	REF 13	tan	16.8
REF 3	cur	6.3	REF 13	cur	0.9
REF 5	cur	1.4	REF 13	tan	11.9
REF 4	tan	2.1	REF 13	cur	1.7
REF 4	cur	0.6	REF 13	tan	12.2
REF 4	tan	0.5	REF 13	cur	1.2
REF 4	cur	0.4	REF 14	tan	10.6
REF 4	tan	0.9	REF 14	cur	1.7
REF 4	cur	0.4	REF 15	tan	11.1
REF 4	tan	5.1	REF 15	cur	0.9
REF 4	cur	2.2	REF 16	cur	0.6
REF 4	tan	1.1	REF 16	tan	3.7
REF 4	cur	2.2	REF 16	cur	1.7
REF 5	tan	4.3	REF 16	tan	1.6
REF 5	cur	0.9	REF 16	cur	1.6
REF 5	tan	3.2	REF 16	tan	1.8
REF 5	cur	1	REF 16	cur	0.9
REF 5	tan	1.9	REF 16	tan	5.9
REF 6	cur	11.5	REF 16	cur	0.7
REF 7	tan	5.4	REF 16	tan	0.9
REF 7	cur	0.6	REF 16	cur	0.7
REF 8	tan	16.8	REF 16	tan	4.9
REF 9	tan	10	REF 17	cur	22.9
REF 10	tan	5.8	REF 18	tan	8.3
REF 10	cur	0.6	REF 19	tan	5
REF 10	tan	0.9	REF 20	tan	6.8

Appendix: Table 7 Site AADTs (2000-2007)

REF	2000	2001	2002	2003	2004	2005	2006	2007
CLRS 1	3950	4000	4000	4050	4100	4100	4200	4300
CLRS 2	4950	4950	5050	5100	5150	5250	5250	5350
CLRS 3	5800	5800	5950	6000	6050	6150	6200	6250
CLRS 4	5600	5800	6000	6200	6300	6600	6800	6850
CLRS 5	3800	4450	4450	4450	4350	4350	4300	4300
CLRS 6	3800	3850	3850	3850	3800	3800	3800	3750
CLRS 7	4050	4050	4100	4100	4150	4200	4200	4250
CLRS 8	2250	2250	2300	2200	2300	2450	2200	2200
ELRS 1	2050	2050	2050	2100	2050	2150	2000	2000
ELRS 2	11200	11400	11600	11800	12000	12200	12400	12700
ELRS 3	10500	10800	11100	11600	11700	12000	12300	12600
ELRS 4	8500	8850	9150	9450	9750	10000	10400	10200
ELRS 5	7000	7000	7200	7350	7500	7650	7850	8000

ELRS 6	7600	7750	7850	7700	8050	8150	8250	8350
ELRS 7	8550	8600	8600	8650	8700	8800	8750	8900
ELRS 8	5700	5700	5800	5850	5900	6000	6050	6100
ELRS 9	6600	6650	6800	6650	7100	7250	7550	7500
ELRS 10	5250	5150	5200	5000	5200	5000	5050	5050
REF 1	3150	3150	3150	3150	3200	3200	3200	3200
REF 2	3950	4000	4000	4050	4100	4100	4200	4300
REF 3	3950	4000	4000	4050	4100	4100	4200	4300
REF 4	7000	7100	7200	7300	7400	7550	7650	7750
REF 5	3650	3800	4200	4150	4600	4400	4400	4600
REF 6	5700	5700	5800	5850	5900	6000	6050	6100
REF 7	4350	4650	4800	5000	5250	5450	5800	5900
REF 8	3650	3700	3750	3750	3850	3750	3950	3850
REF 9	4600	4650	4700	4600	4800	5000	5200	5350
REF 10	2500	2550	2700	3300	2700	2800	2850	2900
REF 11	2250	2250	2300	2300	2350	2350	2500	2400
REF 12	5650	5750	6300	5900	5800	5950	5900	6100
REF 13	2750	2800	2800	2800	2850	2900	2950	3000
REF 14	4000	4100	4050	4100	4050	4100	4150	4150
REF 15	7300	7400	7500	7700	7700	7800	7900	8000
REF 16	6200	6350	6500	6650	6800	6950	7300	7150
REF 17	7950	8100	8450	8650	8550	8550	8550	8750
REF 18	5650	5750	6300	5900	5800	5950	5900	6100
REF 19	5900	6050	6300	6650	6600	6650	6600	6700
REF 20	3100	3200	3500	3600	3500	3500	3500	3500

Appendix: Table 8 Site AADTs (2008 - 2014)

REF	2008	2009	2010	2011	2012	2013	2014
CLRS 1	4200	4450	4550	4300	4450	4400	4500
CLRS 2	5400	5600	5500	5600	5650	5700	5750
CLRS 3	6300	6400	6450	6500	6600	6650	6700
CLRS 4	7050	7700	7550	7750	7900	8100	8300
CLRS 5	4150	4200	4200	4150	4150	4100	4100
CLRS 6	3750	3700	3700	3700	3650	3650	3600
CLRS 7	4250	4300	4300	4350	4000	4000	4100
CLRS 8	2150	2200	1800	2200	1950	2150	1850
ELRS 1	1950	2000	1700	2000	1800	2000	1700
ELRS 2	12900	13100	13300	13500	12500	12300	10000
ELRS 3	12700	13200	12500	13500	12500	12300	13800
ELRS 4	10200	10200	11000	11300	10900	11100	11800
ELRS 5	8150	8300	8500	8650	7900	8800	8950
ELRS 6	8450	8550	8650	8750	8200	8650	8850
ELRS 7	8950	9200	9050	9100	9800	10000	9500

ELRS 8	6200	6250	6300	6400	6800	6600	6650
ELRS 9	7650	7800	7950	8050	8200	8350	8500
ELRS 10	5050	5050	4800	5050	4800	4700	4550
REF 1	3200	3200	3200	3200	3850	3350	3400
REF 2	4200	4450	4550	4300	4450	4400	4500
REF 3	4200	4450	4550	4300	4450	4400	4500
REF 4	7900	8000	8100	8200	8100	8450	8500
REF 5	4750	5200	5000	4100	5250	5350	5500
REF 6	6200	6250	6300	6400	6800	6600	6650
REF 7	6150	6350	6600	6800	7050	7250	7500
REF 8	3900	3600	3950	4000	3400	3400	3850
REF 9	5100	5150	5200	5250	6000	6100	5650
REF 10	2850	3000	2750	2750	2600	2600	2500
REF 11	2450	3500	2750	2800	2500	2850	2850
REF 12	5900	6250	6300	6300	6000	6000	6350
REF 13	3050	3050	3100	3150	2750	2750	2900
REF 14	4100	4200	4250	4250	4300	4300	4350
REF 15	8100	8200	8150	8150	7700	7700	7700
REF 16	7300	7400	7250	7700	6750	7750	7850
REF 17	8550	8950	8900	8900	8300	9150	8500
REF 18	5900	6250	6300	6300	6000	6000	6350
REF 19	6950	6950	6300	6300	6200	6200	6200
REF 20	3500	3600	3100	3100	2800	2800	2700

Appendix: Table 9 Crashes per Site in Before Period

REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
CLRS 1	29	83	112	13	98
CLRS 2	4	6	10	1	8
CLRS 3	50	128	178	14	161
CLRS 4	50	93	143	7	112
CLRS 5	4	10	14	2	12
CLRS 6	23	54	77	14	61
CLRS 7	15	48	63	4	57
CLRS 8	20	53	73	9	60
ELRS 1	5	6	11	0	7
ELRS 2	55	132	187	35	122
ELRS 3	32	126	157	21	120
ELRS 4	38	126	164	21	133
ELRS 5	11	28	39	7	28
ELRS 6	25	90	115	11	96
ELRS 7	7	24	31	4	26
ELRS 8	21	93	114	17	88

ELRS 9	21	69	90	5	78
ELRS 10	20	49	69	11	53
REF 1	5	6	11	0	7
REF 2	91	263	354	36	290
REF 3	13	30	43	3	38
REF 4	24	85	109	11	97
REF 5	55	132	187	35	122
REF 6	37	166	203	34	156
REF 7	27	158	185	20	148
REF 8	48	102	150	27	111
REF 9	12	43	55	6	43
REF 10	60	231	291	26	242
REF 11	18	92	110	7	97
REF 12	39	101	140	7	124
REF 13	20	50	70	5	55
REF 14	12	56	68	6	54
REF 15	118	471	589	51	449
REF 16	17	120	137	16	101
REF 17	120	406	526	87	353
REF 18	58	367	425	29	354
REF 19	34	106	140	11	118
REF 20	24	69	93	16	66
REF 20	10	58	68	7	59

Appendix: Table 10 CLRS Crashes per Site in After Period

REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
CLRS 1	29	83	112	13	98
CLRS 2	4	6	10	7	8
CLRS 3	50	128	178	14	161
CLRS 4	50	93	143	7	112
CLRS 5	4	10	14	2	12
CLRS 6	23	54	77	14	61
CLRS 7	15	48	63	4	57
CLRS 8	20	53	73	9	60

Appendix: Table 11 ELRS Crashes per Site in After Period

REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
ELRS 1	5	6	11	0	7
ELRS 2	55	132	187	35	122
ELRS 3	32	125	157	21	120
ELRS 4	38	126	164	21	133
ELRS 5	11	28	39	7	28

ELRS 6	25	90	115	11	96
ELRS 7	7	24	31	4	26
ELRS 8	21	93	114	17	88
ELRS 9	21	69	90	5	78
ELRS 10	20	49	69	11	53

Appendix: Table 12 Crashes per Tangent or Curved Site in Before Period

REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle	Type
1	20	50	70	5	55	tan
2	34	106	140	11	118	tan
3	24	69	93	16	66	tan
4	22	82	104	9	89	tan
5	2	15	17	3	13	cur
6	11	31	42	2	38	tan
7	10	24	34	6	25	cur
8	20	39	59	6	51	tan
9	22	52	74	9	52	cur
10	4	20	24	1	22	tan
11	13	30	43	3	38	tan
12	20	47	67	7	59	cur
13	4	12	16	2	14	tan
14	1	6	7	2	5	cur
15	0	2	2	0	2	tan
16	1	4	5	1	4	cur
17	0	3	3	0	3	tan
18	0	1	1	1	0	cur
19	1	3	4	0	4	tan
20	2	5	7	0	7	cur
21	1	11	12	0	12	tan
22	23	74	97	11	85	cur
23	5	23	28	6	19	tan
24	0	2	2	0	2	cur
25	0	6	6	0	6	tan
26	1	2	3	0	3	cur
27	3	5	8	2	5	tan
28	1	4	5	1	3	cur
29	19	69	88	18	65	tan
30	1	11	12	3	9	cur
31	1	9	10	0	9	tan
32	6	35	41	4	35	cur
33	5	6	11	0	7	tan
34	2	9	11	3	6	cur

35	2	8	10	1	6	tan
36	5	17	22	6	12	cur
37	13	51	64	6	53	tan
38	5	23	28	2	25	cur
39	3	7	10	2	8	tan
40	2	11	13	1	11	cur
41	11	36	47	5	40	tan
42	20	64	84	11	68	cur
43	7	26	33	5	25	tan
44	7	17	24	6	15	tan
45	1	3	4	0	3	cur
46	3	8	11	1	10	tan
47	5	18	23	3	18	tan
48	11	46	57	4	50	cur
49	3	12	15	2	12	tan
50	5	4	9	1	8	cur
51	1	10	11	1	8	tan
52	7	24	31	4	26	cur
53	21	93	114	17	88	tan
54	1	2	3	0	2	tan
55	7	29	36	7	21	cur
56	11	14	25	6	13	tan
57	4	5	9	0	7	cur
58	14	44	58	11	43	tan
59	18	38	56	11	36	cur
60	12	44	56	2	49	cur
61	9	25	34	3	29	tan
62	3	14	17	0	15	cur
63	7	52	59	8	44	tan
64	1	13	14	0	12	cur
65	10	45	55	5	45	tan
66	5	9	14	3	11	cur
67	1	24	25	4	20	tan
68	9	19	28	5	23	tan
69	1	9	10	2	8	cur
70	10	22	32	4	23	tan
71	10	38	48	2	42	tan
72	1	3	4	2	2	cur
73	1	4	5	1	4	tan
74	2	3	5	0	5	cur
75	1	3	4	0	4	tan

76	8	16	24	2	21	cur
77	9	18	27	0	25	tan
78	5	9	14	0	13	cur
79	2	7	9	0	8	tan
80	2	3	5	0	4	cur
81	2	3	5	1	4	tan
82	11	27	38	3	34	cur
83	6	5	11	0	10	tan
84	2	4	6	1	5	cur
85	4	7	11	1	10	tan
86	0	2	2	0	2	cur
87	0	3	3	0	3	tan
88	1	4	5	0	5	cur
89	7	34	41	2	39	tan
90	3	12	15	0	15	cur
91	6	11	17	4	13	tan
92	4	7	11	2	9	cur
93	10	23	33	2	23	tan
94	4	9	13	3	9	cur
95	4	9	13	0	11	tan
96	3	4	7	1	5	cur
97	10	11	21	1	19	tan
98	26	49	75	8	61	cur
99	47	102	149	27	111	cur
100	4	7	11	2	9	cur
101	0	3	3	0	3	tan
102	0	5	5	0	5	cur
103	6	7	13	4	8	tan
104	17	42	59	10	48	cur
105	15	48	63	3	57	cur
106	6	24	30	6	24	cur
107	1	1	2	1	1	tan
108	13	28	41	4	35	cur
109	36	183	219	18	174	tan
110	0	7	7	1	5	cur
111	35	132	167	15	126	tan
112	2	5	7	0	6	cur
113	41	126	167	16	120	tan
114	4	18	22	1	18	cur
115	26	140	166	10	143	tan
116	3	16	19	3	15	cur

117	15	110	125	13	92	tan
118	2	10	12	3	9	cur
119	3	15	18	1	11	cur
120	7	50	57	9	40	tan
121	20	43	63	5	53	cur
122	2	6	8	0	6	tan
123	3	28	31	5	21	cur
124	5	14	19	3	14	tan
125	13	38	51	10	30	cur
126	30	82	112	20	77	tan
127	6	21	27	5	19	cur
128	8	19	27	5	21	tan
129	3	15	18	4	13	cur
130	20	75	95	20	48	tan
131	58	367	425	29	354	cur
132	12	39	51	5	40	tan
133	0	4	4	1	3	cur
135	10	58	68	7	59	tan
136	18	92	110	7	97	tan
137	12	56	68	6	54	tan
138	60	231	291	26	242	tan

Appendix: Table 13 Crashes per Tangent or Curved Site for CLRS in Before Period

Type	REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
cur	12	20	47	67	7	59
tan	13	4	12	16	2	14
cur	14	1	6	7	2	5
tan	15	0	2	2	0	2
cur	16	1	4	5	1	4
tan	17	0	3	3	0	3
cur	18	0	1	1	1	0
tan	19	1	3	4	0	4
cur	20	2	5	7	0	7
cur	80	2	3	5	0	4
tan	81	2	3	5	1	4
cur	82	11	27	38	3	34
tan	83	6	5	11	0	10
cur	84	2	4	6	1	5
tan	85	4	7	11	1	10
cur	86	0	2	2	0	2
tan	87	0	3	3	0	3

cur	88	1	4	5	0	5
tan	89	7	34	41	2	39
cur	90	3	12	15	0	15
tan	91	6	11	17	4	13
cur	92	4	7	11	2	9
tan	93	10	23	33	2	23
cur	94	4	9	13	3	9
tan	95	4	9	13	0	11
cur	96	3	4	7	1	5
tan	97	10	11	21	1	19
cur	98	25	49	74	8	61
cur	100	4	7	11	2	9
tan	101	0	3	3	0	3
cur	102	0	5	5	0	5
tan	103	6	7	13	4	8
cur	104	17	42	59	10	48
cur	105	15	48	63	3	57
cur	106	6	24	30	6	24
tan	107	1	1	2	1	1
cur	108	13	28	41	4	35

Appendix: Table 14 Crashes per Tangent or Curved Site for CLRS in After Period

Type	REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
cur	12	3	13	16	4	11
tan	13	0	2	2	0	2
cur	14	0	3	3	0	3
tan	15	0	2	2	0	2
cur	16	1	2	3	0	3
tan	17	1	1	2	0	2
cur	18	0	0	0	0	0
tan	19	0	1	1	0	1
cur	20	2	4	6	2	4
cur	80	0	1	1	0	1
tan	81	0	2	2	0	2
cur	82	3	6	9	0	8
tan	83	2	1	3	1	2
cur	84	0	1	1	0	1
tan	85	0	1	1	0	1
cur	86	0	1	1	0	1
tan	87	1	1	2	0	2
cur	88	0	1	1	0	1

tan	89	5	8	13	0	8
cur	90	0	5	5	0	4
tan	91	0	0	0	0	0
cur	92	1	1	2	0	2
tan	93	4	6	10	1	9
cur	94	1	1	2	0	0
tan	95	0	0	0	0	0
cur	96	0	0	0	0	0
tan	97	0	3	3	0	2
cur	98	1	6	7	1	4
cur	100	0	0	0	0	0
tan	101	0	1	1	0	1
cur	102	1	0	1	0	1
tan	103	0	1	1	0	1
cur	104	3	6	9	1	8
cur	105	0	4	4	1	3
cur	106	0	5	5	0	5
tan	107	0	0	0	0	0
cur	108	0	1	1	0	1

Appendix: Table 15 Crashes per Tangent or Curved Site for ELRS in Before Period

REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
33	5	6	11	0	7
34	2	8	10	3	5
35	2	8	10	1	6
36	5	17	22	6	12
37	13	51	64	6	53
38	5	23	28	2	25
39	3	7	10	2	8
40	2	11	13	1	11
41	11	36	47	5	40
42	20	64	84	11	68
43	7	26	33	5	25
44	7	17	24	6	15
45	1	3	4	0	3
46	3	8	11	1	10
47	5	18	23	3	18
48	11	46	57	4	50
49	3	12	15	2	12
50	5	4	9	1	8
51	1	10	11	1	8

52	7	24	31	4	26
53	21	93	114	17	88
54	1	2	3	0	2
55	7	29	36	7	21
56	11	14	25	6	13
57	4	5	9	0	7
58	14	44	58	11	43
59	18	38	56	11	36
60	12	44	56	2	49
61	9	25	34	3	29
68	9	18	27	5	22
69	1	9	10	2	8
70	10	22	32	4	23

Appendix: Table 16 Crashes per Tangent or Curved Site for ELRS in After Period

REF	Injury	PDO	Total	Approach + Sideswipe	Single Vehicle
33	1	6	7	1	5
34	2	6	8	1	5
35	0	0	0	0	0
36	5	4	9	3	2
37	5	14	19	0	15
38	2	4	6	1	3
39	0	0	0	0	0
40	0	2	2	0	2
41	1	17	18	0	17
42	2	22	24	3	20
43	4	8	12	4	5
44	6	18	24	2	17
45	0	2	2	0	2
46	1	5	6	0	6
47	0	3	3	0	3
48	2	3	5	0	4
49	0	4	4	0	4
50	1	2	3	1	2
51	2	2	4	0	4
52	0	7	7	1	5
53	5	11	16	3	12
54	0	0	0	0	0
55	0	3	3	0	3
56	0	2	2	0	2
57	0	0	0	0	0

58	1	3	4	1	2
59	1	5	6	0	6
60	1	2	3	1	2
61	0	1	1	0	1
68	0	2	2	0	2
69	0	1	1	0	1
70	0	4	4	1	2

Appendix: Table 17 SPF Parameter Estimates for Total Crashes

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-5.4619	0.7207	-6.8744	-4.0495	57.44	<.0001
avg ln aadt	1	0.6469	0.0811	0.4879	0.8058	63.62	<.0001
avg ln length	1	0.9677	0.0495	0.8708	1.0647	382.57	<.0001
Dispersion	1	0.0345	0.0104	0.0191	0.0624		

Appendix: Table 18 SPF Parameter Estimates for Injury Crashes

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-6.1696	1.1417	-8.4074	-3.9318	29.20	<.0001
avg ln aadt	1	0.5878	0.1278	0.3372	0.8383	21.14	<.0001
avg ln length	1	0.8633	0.0793	0.7080	1.0187	118.63	<.0001
Dispersion	1	0.0694	0.0239	0.0353	0.1365		

Appendix: Table 19 SPF Parameter Estimates for PDO Crashes

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-5.9628	0.7586	-7.4496	-4.4759	61.78	<.0001
avg ln aadt	1	0.6606	0.0853	0.4935	0.8277	60.02	<.0001
avg ln length	1	1.0174	0.0538	0.9118	1.1229	357.15	<.0001
Dispersion	1	0.0366	0.0115	0.0198	0.0679		

Appendix: Table 20 SPF Parameter Estimates for Single Vehicle Crashes

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-4.9430	0.7992	-6.5095	-3.3765	38.25	<.0001
avg ln aadt	1	0.5652	0.0900	0.3888	0.7415	39.46	<.0001
avg ln length	1	0.9527	0.0549	0.8451	1.0602	301.52	<.0001
Dispersion	1	0.0429	0.0128	0.0239	0.0769		

Appendix: Table 21 SPF Parameter Estimates for Approach + Sideswipe Crashes

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-10.1432	1.3646	-12.8178	-7.4686	55.25	<.0001
avg ln aadt	1	0.9203	0.1516	0.6233	1.2173	36.88	<.0001
avg ln length	1	1.0218	0.1013	0.8232	1.2203	101.73	<.0001
Dispersion	1	0.0705	0.0296	0.0310	0.1606		

Appendix: Table 22 SPF Parameter Estimates for Total Crashes on Curved Segments

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-6.1609	1.0747	-8.2673	-4.0545	32.86	<.0001
ln addt	1	0.7360	0.1241	0.4928	0.9792	35.19	<.0001
ln length	1	0.9052	0.0555	0.7965	1.0139	266.38	<.0001
Dispersion	1	0.1427	0.0362	0.0868	0.2347		

Appendix: Table 23 SPF Parameter Estimates for Total Crashes on Tangent Segments

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-4.8010	1.0242	-6.8084	-2.7935	21.97	<.0001
ln addt	1	0.5675	0.1177	0.3368	0.7983	23.24	<.0001
ln length	1	0.9646	0.0492	0.8682	1.0610	384.74	<.0001
Dispersion	1	0.1198	0.0303	0.0730	0.1967		

Appendix: Table 24 SPF Parameter Estimates for PDO Crashes on Curved Segments

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-6.6589	1.0495	-8.7160	-4.6019	40.25	<.0001
ln addt	1	0.7623	0.1211	0.5251	0.9996	39.66	<.0001
ln length	1	0.9006	0.0535	0.7957	1.0055	283.04	<.0001
Dispersion	1	0.1190	0.0343	0.0676	0.2093		

Appendix: Table 25 SPF Parameter Estimates for PDO Crashes on Tangent Segments

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-4.9090	1.0051	-6.8788	-2.9391	23.86	<.0001
ln addt	1	0.5436	0.1154	0.3174	0.7698	22.19	<.0001
ln length	1	1.0019	0.0496	0.9047	1.0992	407.62	<.0001
Dispersion	1	0.1044	0.0296	0.0599	0.1822		

Appendix: Table 26 SPF Parameter Estimates for Single Vehicle Crashes on Curved Segments

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-5.6630	1.0282	-7.6782	-3.6478	30.34	<.0001
ln addt	1	0.6488	0.1187	0.4161	0.8815	29.86	<.0001
ln length	1	0.9272	0.0527	0.8240	1.0304	309.99	<.0001
Dispersion	1	0.1147	0.0336	0.0647	0.2036		

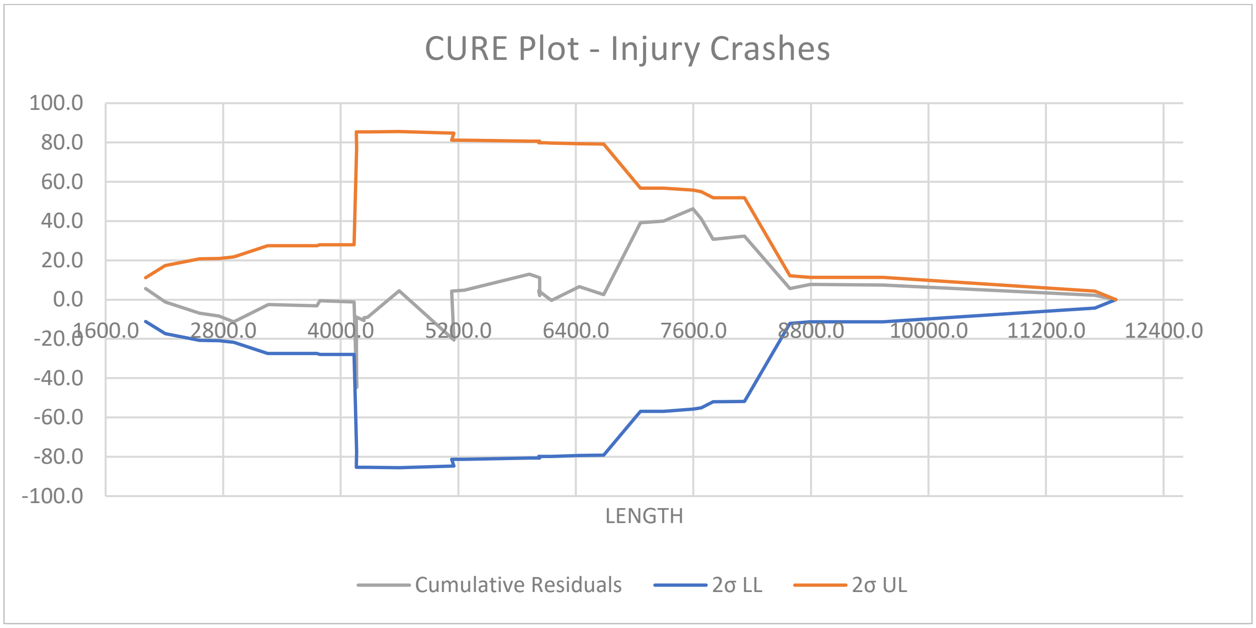
Appendix: Table 27 SPF Parameter Estimates for Single Vehicle Crashes on Tangent Segments

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-3.9975	1.0349	-6.0259	-1.9691	14.92	0.0001
ln addt	1	0.4491	0.1190	0.2159	0.6823	14.24	0.0002
ln length	1	0.9510	0.0507	0.8515	1.0504	351.23	<.0001
Dispersion	1	0.1188	0.0310	0.0713	0.1981		

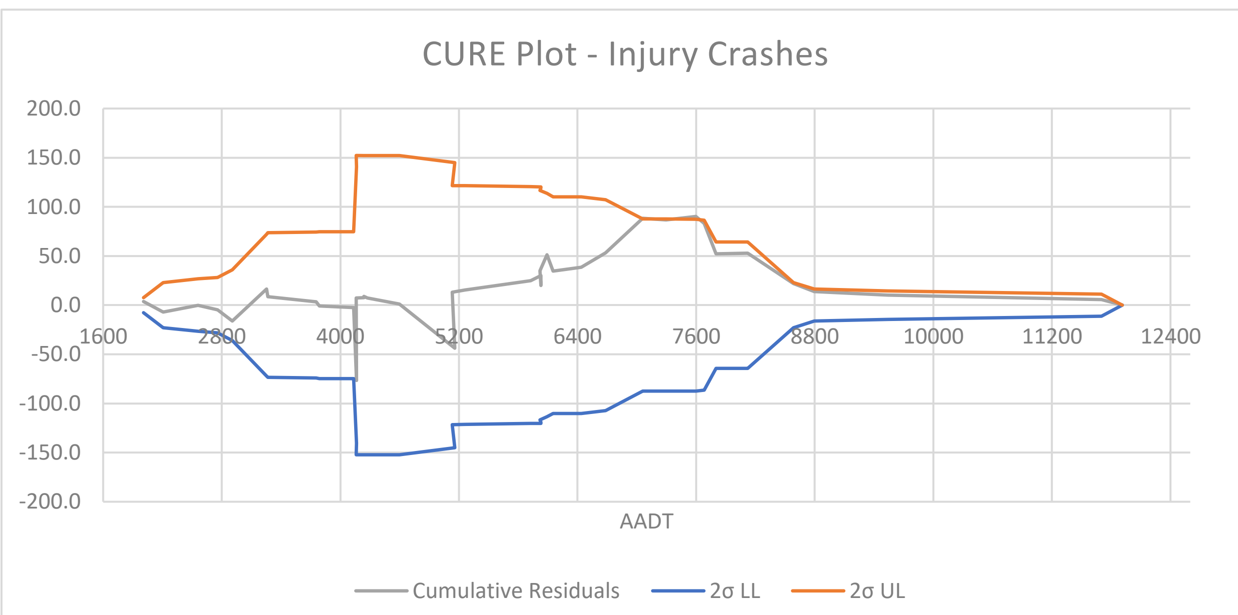
Appendix B: CURE Plots

CLRS and ELRS Cure Plots

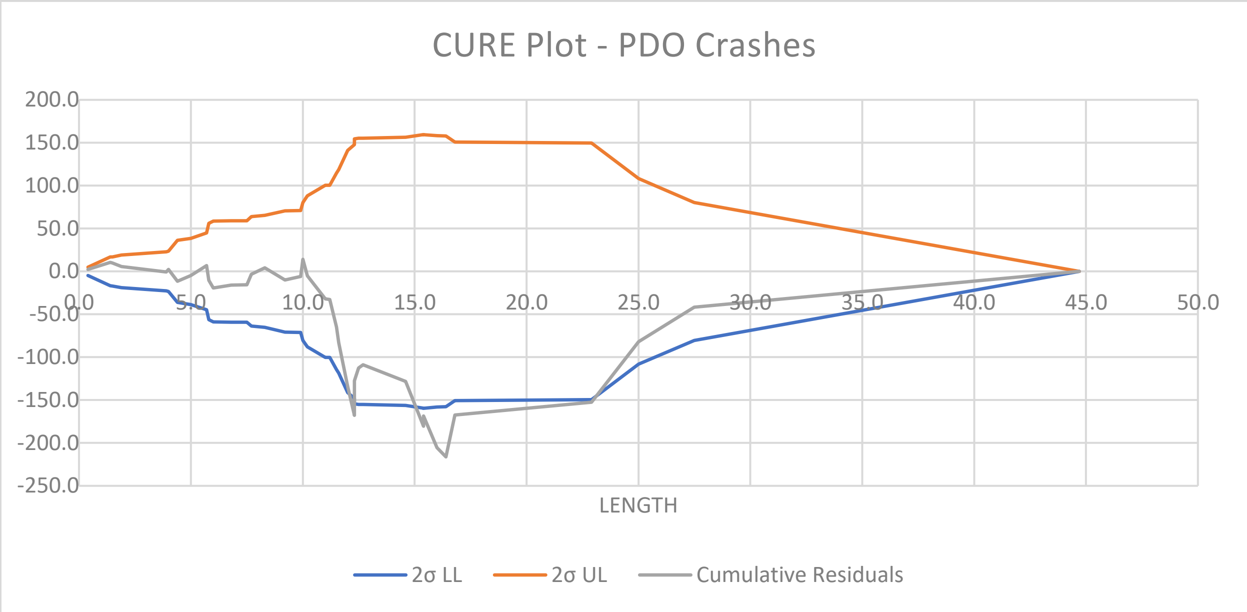
Appendix: Figure 1 CURE Plot of Injury Crashes Against Length Variable



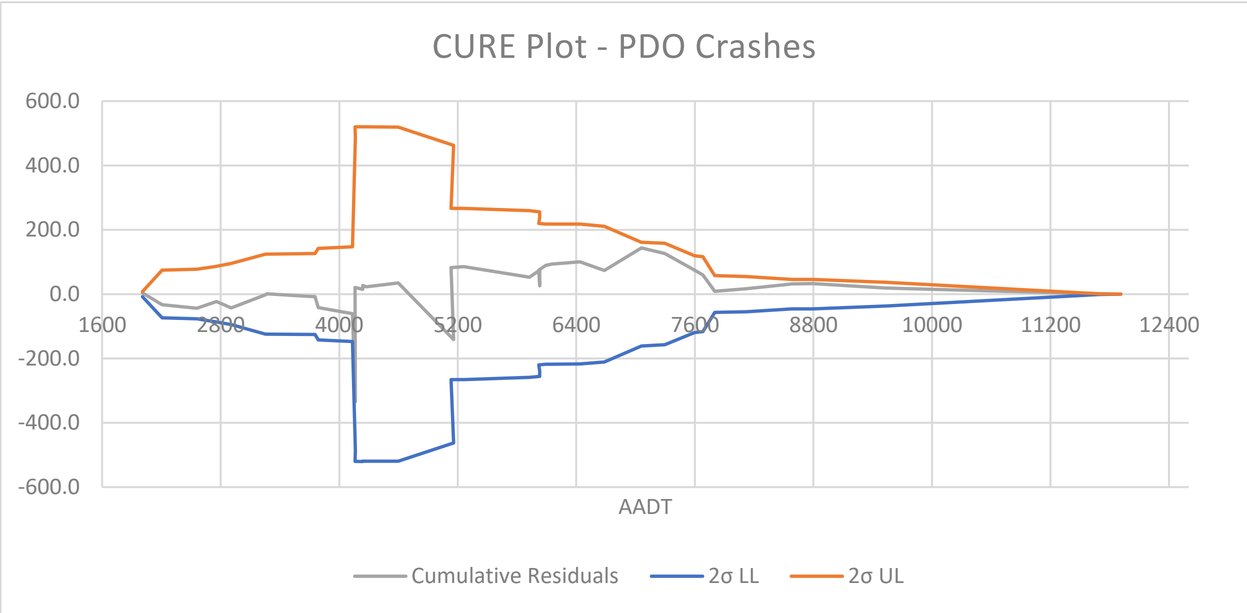
Appendix: Figure 2 CURE Plot of Injury Crashes Against AADT Variable



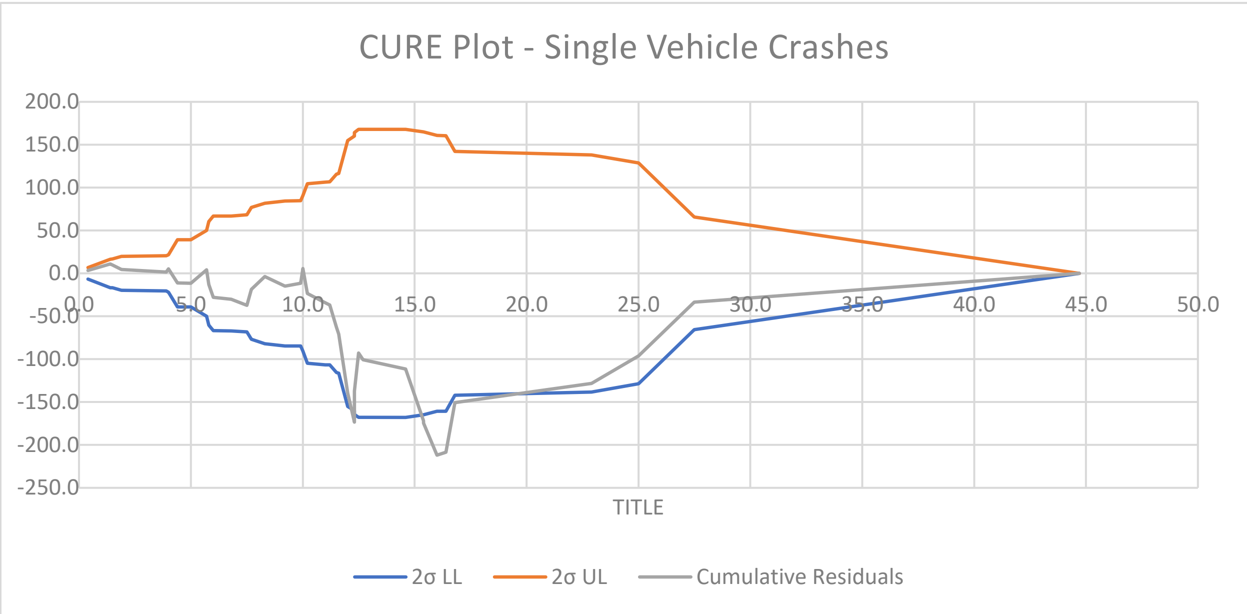
Appendix: Figure 3 CURE Plot of PDO Crashes Against Length Variable



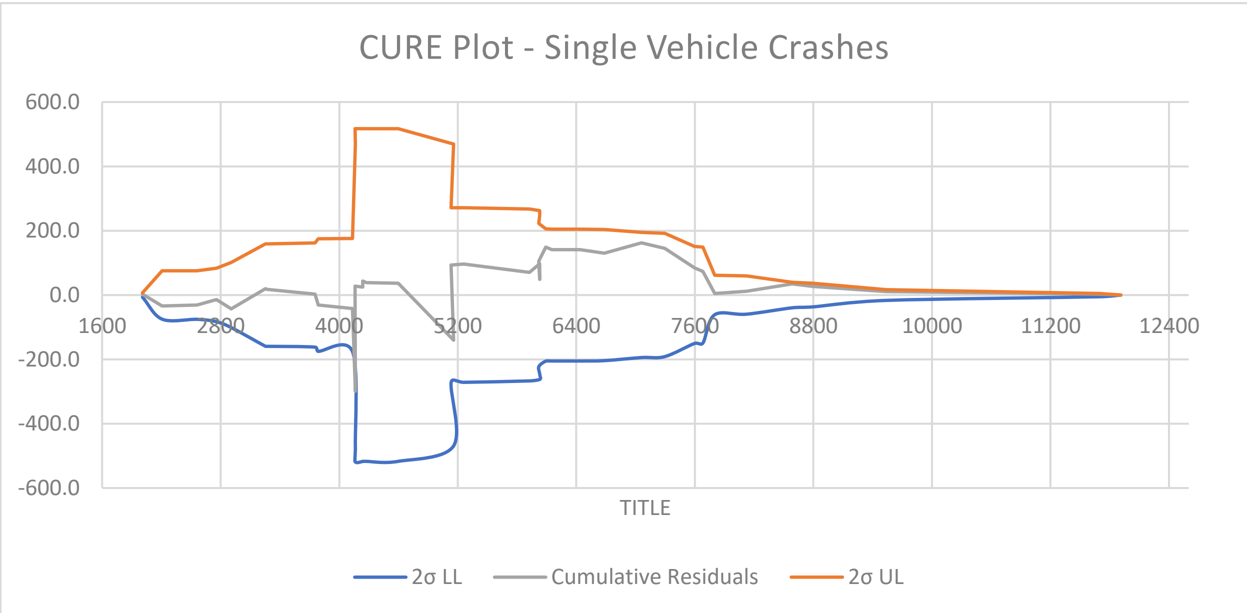
Appendix: Figure 4 CURE Plot of PDO Crashes Against AADT Variable



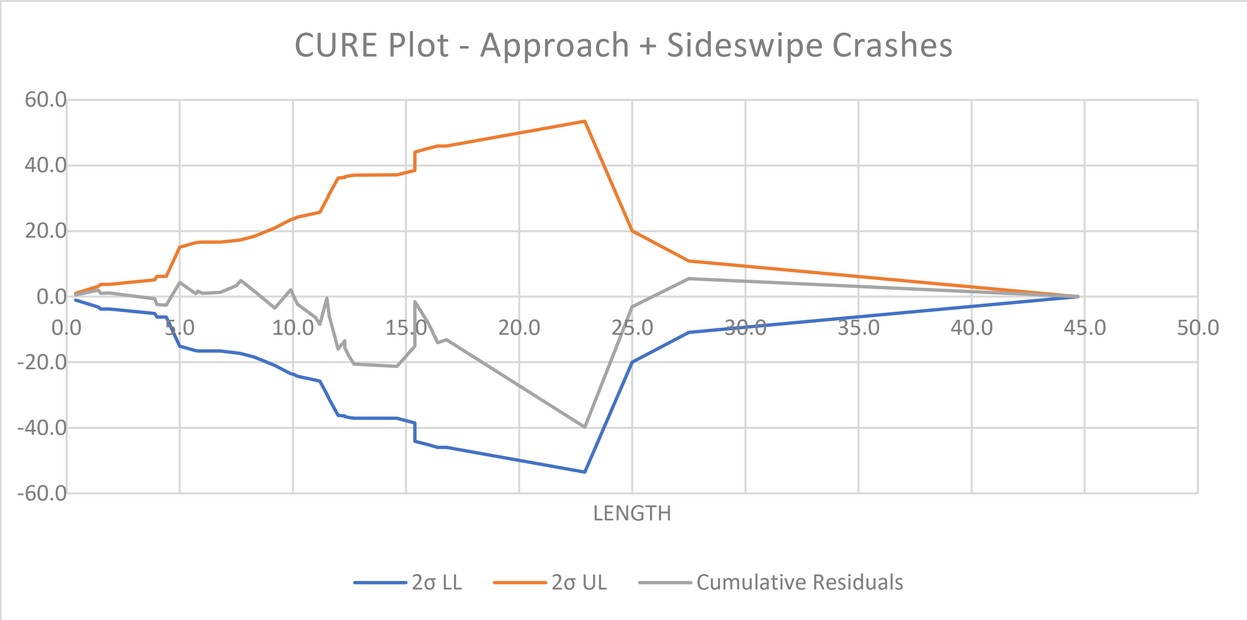
Appendix: Figure 5 CURE Plot of Single Vehicle Crashes Against Length Variable



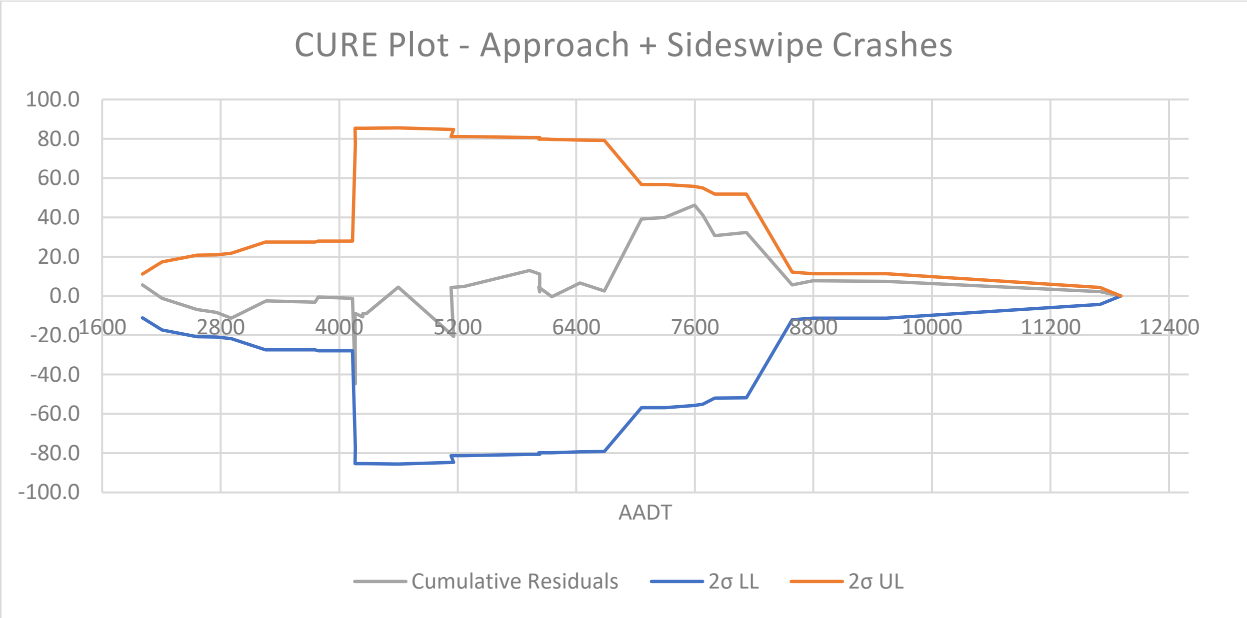
Appendix: Figure 6 CURE Plot of Single Vehicle Crashes Against AADT Variable



Appendix: Figure 7 CURE Plot of Approach + Sideswipe Crashes Against Length Variable

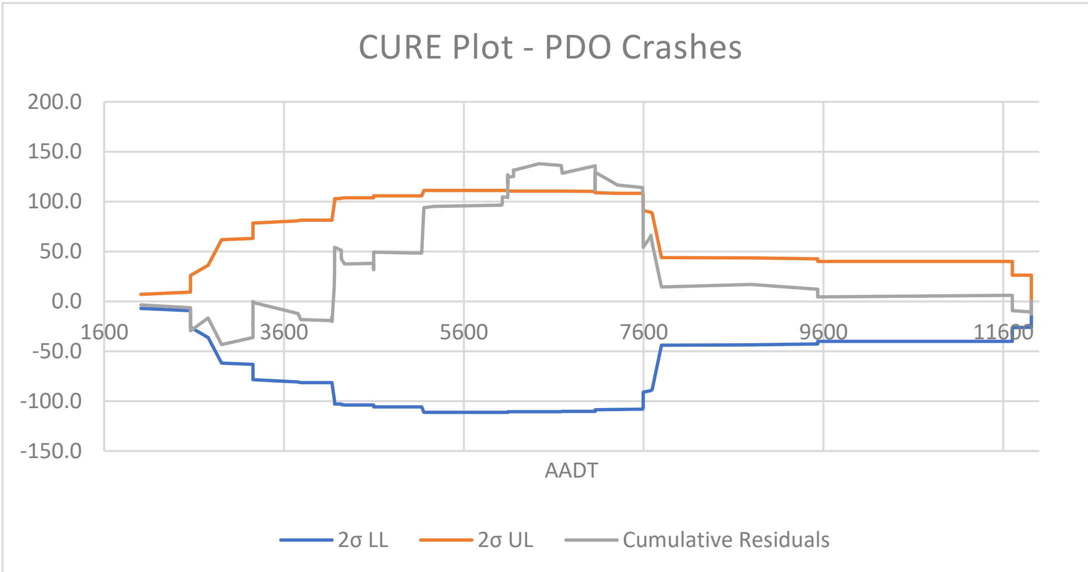


Appendix: Figure 8 CURE Plot of Approach + Sideswipe Crashes Against AADT Variable

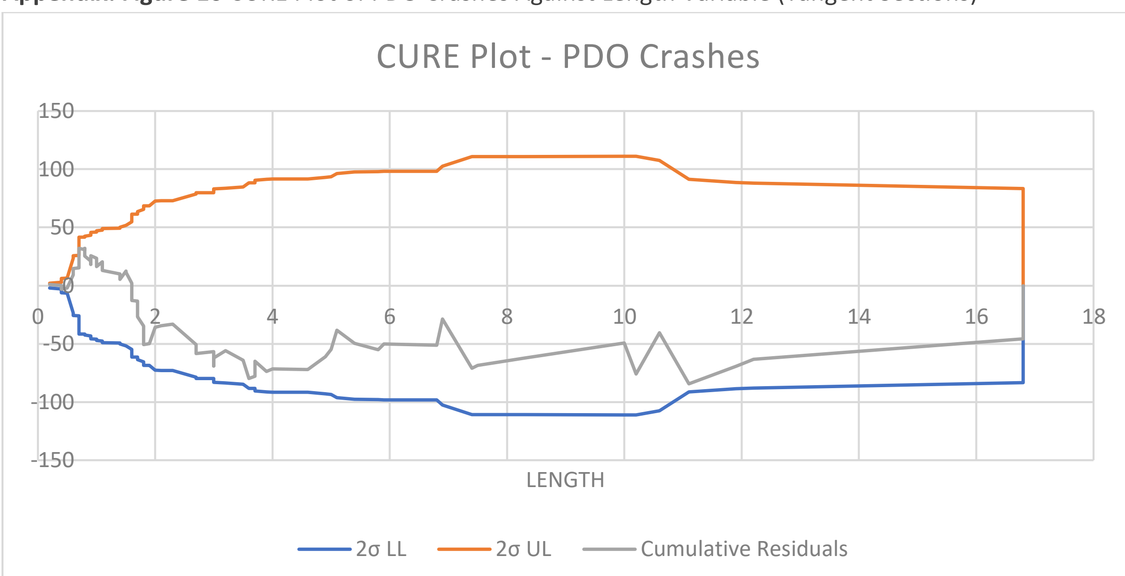


Tangent and Curved Section CURE Plots

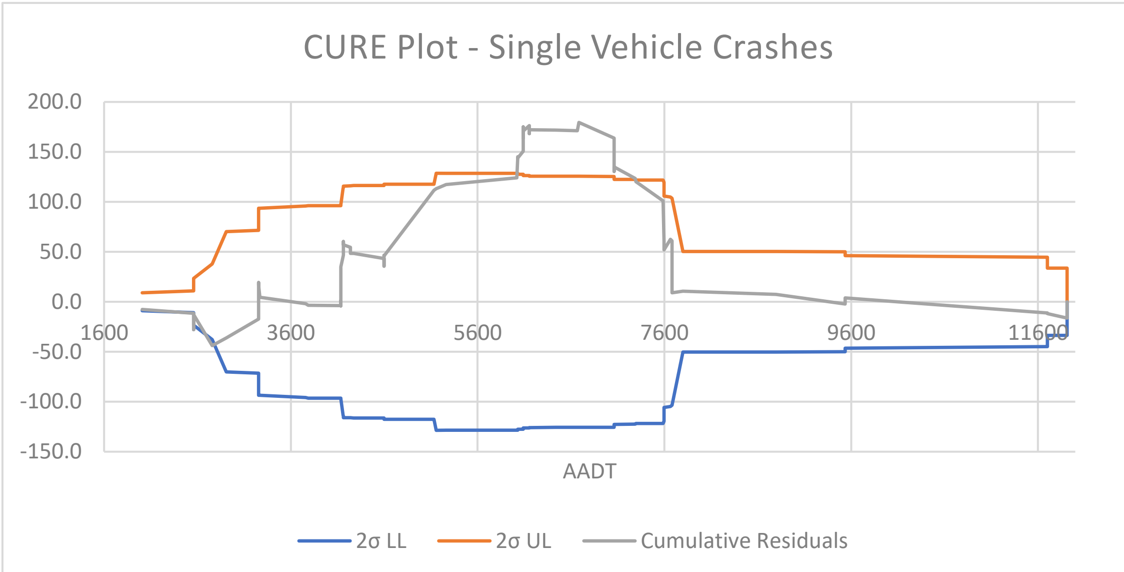
Appendix: Figure 9 CURE Plot of PDO Crashes Against AADT Variable (Tangent Sections)



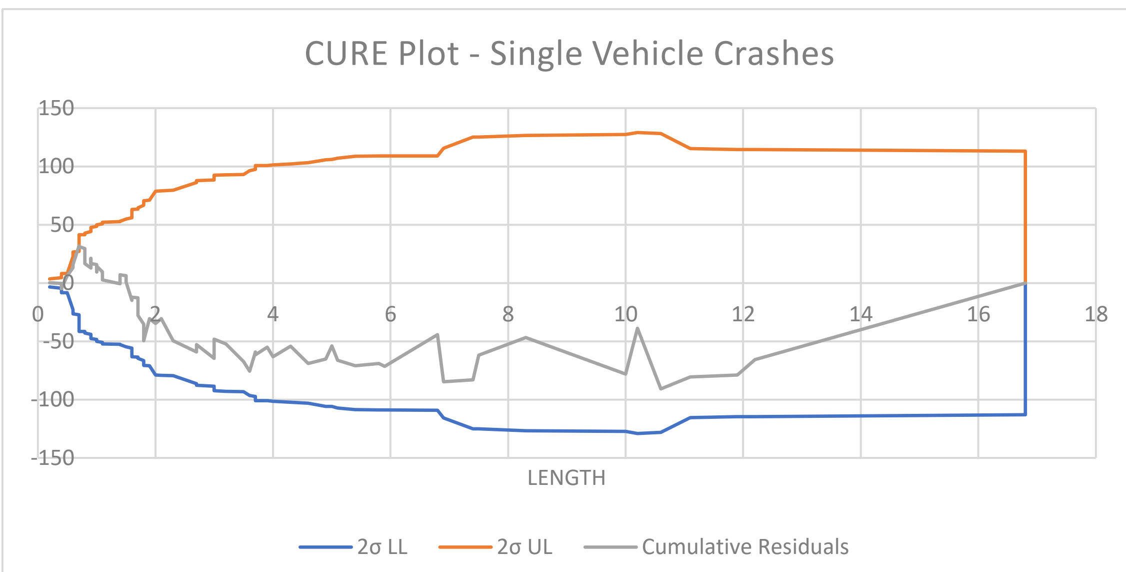
Appendix: Figure 10 CURE Plot of PDO Crashes Against Length Variable (Tangent Sections)



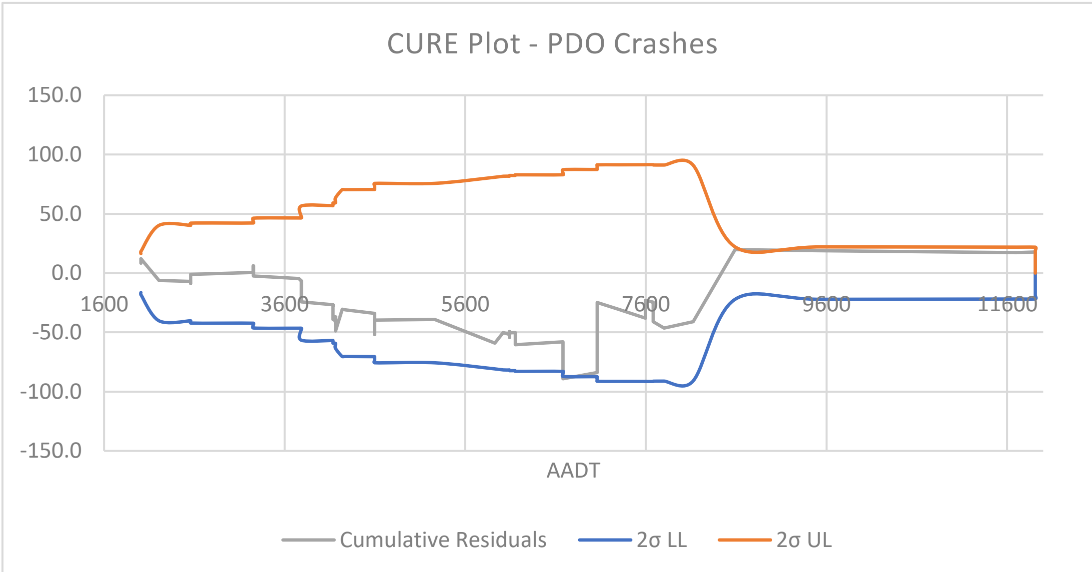
Appendix: Figure 11 CURE Plot of Single Vehicle Crashes Against AADT Variable (Tangent Sections)



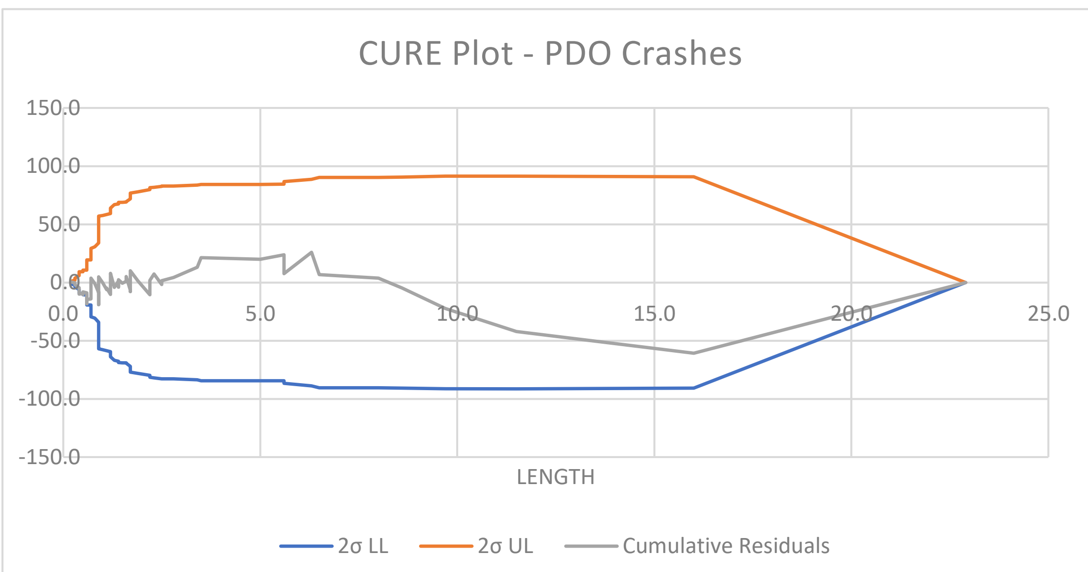
Appendix: Figure 12 CURE Plot of Single Vehicle Crashes Against Length Variable (Tangent Sections)



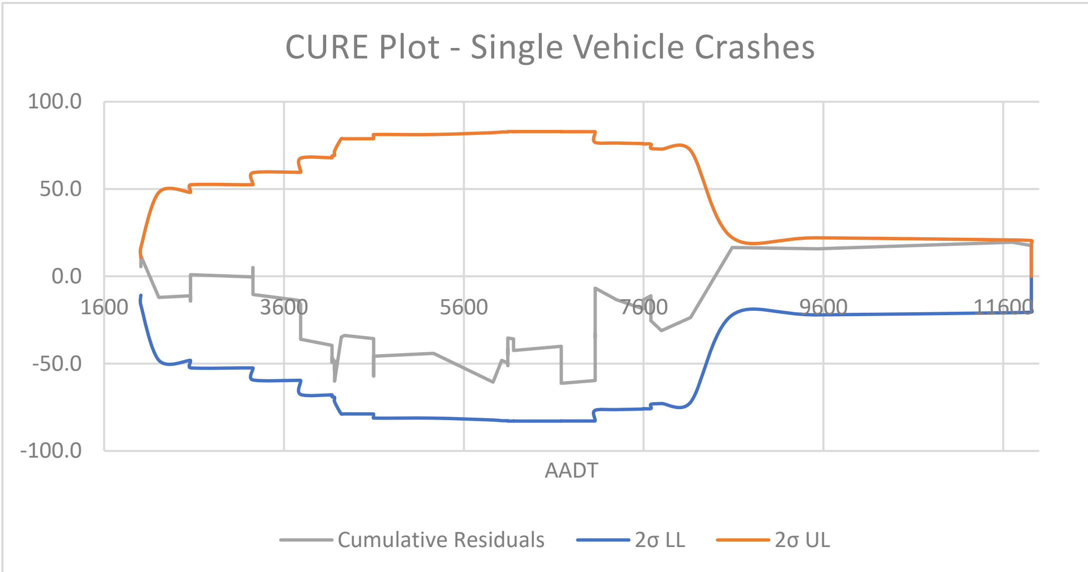
Appendix: Figure 13 CURE Plot of PDO Crashes Against AADT Variable (Curved Sections)



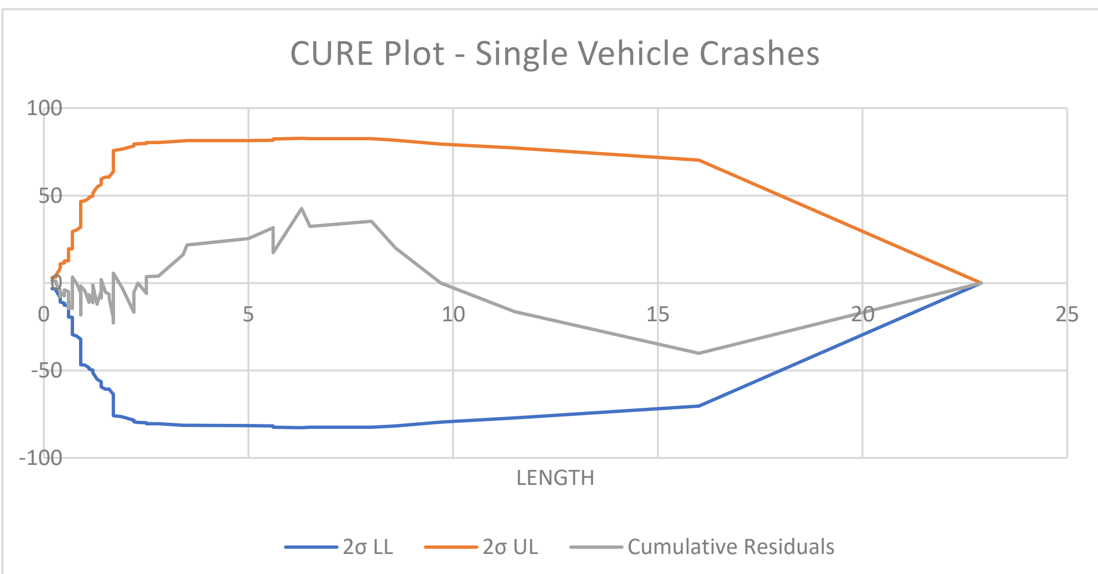
Appendix: Figure 14 CURE Plot of PDO Crashes Against Length Variable (Curved Sections)



Appendix: Figure 15 CURE Plot of Single Vehicle Crashes Against AADT Variable (Curved Sections)



Appendix: Figure 16 CURE Plot of Single Vehicle Crashes Against Length Variable (Curved Sections)



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Appendix