Estimating crash modification factors for lane-departure countermeasures in Kansas

by

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B.Sc.Eng(Hons), University of Moratuwa, Sri Lanka, 2013
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

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Abstract

Lane-departure crashes are the most predominant crash type in Kansas which causes very high number of motor vehicle fatalities. Therefore, the Kansas Department of Transportation (KDOT) has implemented several different types of countermeasures to reduce the number of motor vehicle fatalities associated with lane-departure crashes. This research was conducted to estimate the safety effectiveness of commonly used lane-departure countermeasures in Kansas on all crashes and lane-departure crashes using Crash Modification Factors (CMFs). Paved shoulders, rumble strips, safety edge treatments and median cable barriers were identified as the commonly used lane-departure countermeasures on both tangent and curved road segments while chevrons and post-mounted delineators were identified as the most commonly used lane-departure countermeasures on curved road segments. This research proposes a state-of-art method of estimating CMFs using cross-sectional data for chevrons and post-mounted delineators. Furthermore, another state-of-art method is proposed in this research to estimate CMFs for safety edge treatments using before-and-after data.

Considering the difficulties of finding the exact date of implementation of each countermeasure, both cross-sectional and before-and-after studies were employed to estimate the CMFs. Cross-sectional and case-control methods, which are the two major methods in cross-sectional studies were employed to estimate CMFs for paved shoulders, rumble strips, and median cable barriers. The conventional cross-sectional and case-control methods were modified when estimating CMFs for chevrons and post-mounted delineators by incorporating environmental and human behaviors in addition to geometric and traffic-related explanatory variables. The proposed method is novel and has not been used in the previous cross-sectional models available in the

literature. Generalized linear regression models assuming negative binomial error structure were used to develop models for cross-sectional method to estimate CMFs while logistic regression models were used to estimate CMFs using case-control method. Results showed that incorporating environmental and human-related variables into cross-sectional models provide better model fit than in conventional cross-sectional models. To validate the developed models for cross-sectional method, mean of the residuals and the Root Mean Square Error (RMSE) were used. For the case-control method, Receiver Operational Characteristic (ROC) was used to evaluate the predictive power of models for a binary outcome using classification tables. However, it was seen that the case-control method is not suitable for estimating CMFs for all crashes since the range of the crash frequency is wide in each road segment.

A regression-based method of estimating CMFs using before-and-after data was proposed to estimate CMFs for safety edge treatments. This method allows researchers to identify the safety effectiveness of an individual CMFs on road segments where multiple treatments have been applied at the same time. Since this method uses road geometric and traffic-related characteristics in addition to countermeasure information as the explanatory variables, the model itself would be the Safety Performance Function (SPF). Therefore, developing new SPF is not necessary. Finally, the CMFs were estimated using before-and-after Empirical Bayes method to validate the results from the regression-based method.

The results of this study can be used as a decision-making tool when implementing lane-departure countermeasures on similar roadways in Kansas. Even though there are readily available CMFs from the national level studies, having more localized CMFs will be beneficial due to differences in traffic-related and geometric characteristics on different roadways.

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Considering the difficulties of finding the exact date of implementation of each countermeasure, both cross-sectional and before-and-after studies were employed to estimate the CMFs. Cross-sectional and case-control methods, which are the two major methods in cross-sectional studies were employed to estimate CMFs for paved shoulders, rumble strips, and median cable barriers. The conventional cross-sectional and case-control methods were modified when estimating CMFs for chevrons and post-mounted delineators by incorporating environmental and human behaviors in addition to geometric and traffic-related explanatory variables. The proposed method is novel and has not been used in the previous cross-sectional models available in the

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Table of Contents

List of Figures

List of Tables

Abbreviations

CANSYS-Control Section Analysis System (Kansas State Highway System Database)

CG- Comparison Group

CMFs - Crash Modification Factors

EB - Empirical Bayes

FARS - Fatality Analysis Reporting System

FB- Full Bayesian

FHE-First harmful event

FHWA - Federal Highway Administration

High friction surface treatments (HFST)

KCARS -Kansas Crash and Analysis Reporting System

KDOT -Kansas Department of Transportation

MHE - Most harmful event

NHTSA - National Highway Traffic Safety Administration

SHSP - Strategic Highway Safety Plan

SPF - Safety performance function

VMT - Vehicle Mile Travelled

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Dedication

To my loving teacher S.A. Anurasinghe and son Dihen

Chapter 1 Introduction

1.1. Background

Motor vehicle injuries are one of the top-10 leading causes of death in the world, amounting to approximately 1.3 million fatalities every year (World Health Organization, 2015). Similarly, in the United States, motor vehicle injuries were the 11th-leading cause of death in 2014 (Dwyer-Lindgren L., Bertozzi-Villa A., et al., 2016). According to the Fatality Analysis Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA), more than 32,000 people died yearly, from 2009 to 2014, due to motor vehicle injuries in the United States. Figure 1.1 shows motor vehicle fatalities per 1,000 Vehicle Miles Traveled (VMT) and per 100,000 population in the United States, for 10 years from 2005 to 2014 (National Highway Traffic Safety Administration [NHTSA], 2016).

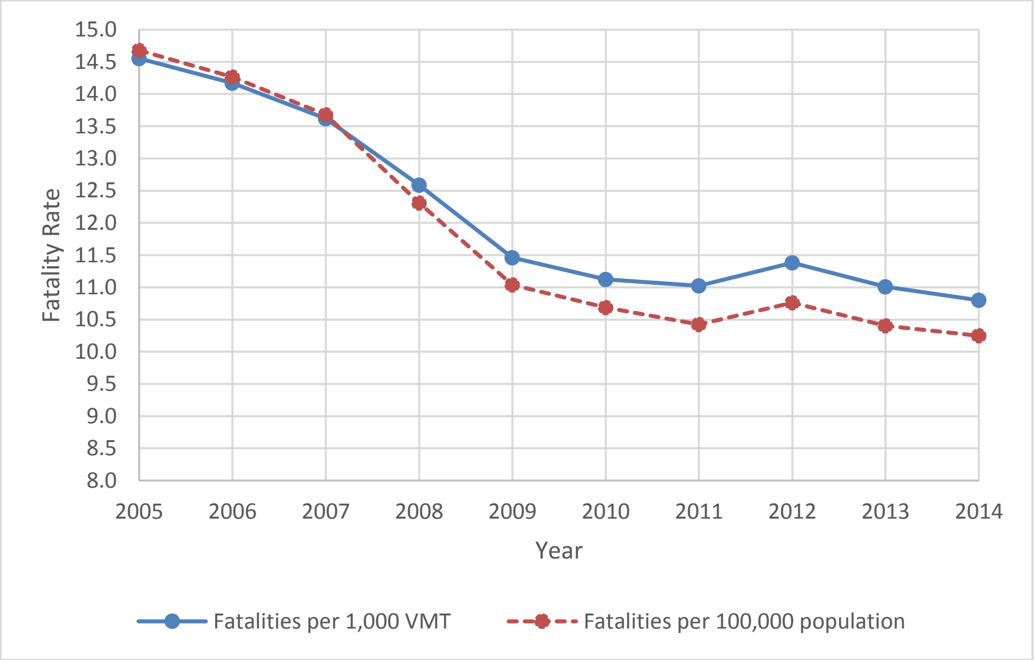


Figure 1.1 Trend in motor vehicle fatality rates in the United States from 2005 to 2014

Even though fatality rates are potentially decreasing due to advancements of vehicle technologies and engineering countermeasures, fatalities due to motor vehicle injuries still have a considerable effect on the society (Bonneson, Zimmerman, & Brewer, 2002; Insurance Institute for Highway Safety Highway Loss Data Institute, 2015; Retting, Ferguson, & McCartt, 2003).

1.2. Motor vehicle crashes in Kansas

Most motor vehicle crashes do not occur due to a single cause. Different crash types such as single-vehicle, head-on, side-swipe same direction, side-swipe opposite direction, and rear-end collision contribute differently to motor vehicle fatalities. Out of the many crash types, lane-departure crashes are the most predominant for motor vehicle fatalities in the United States, which are defined as a “non-intersection event that occurs after a vehicle crosses an edge line or center line, or otherwise leaves the traveled way” (Federal Highway Administration [FHWA], 2013). Most of the lane-departure crashes are single vehicle crashes, although a vehicle traveling off a road and hitting a parked vehicle is considred a multi-vehicle lane-departure crash (Neuman, 2013). Furthermore, it was found that lane-departure crashes account for approximately 54% of total motor vehicle fatalities in the United States (NHTSA, 2016). Similar to the national level statistics, motor vehicle fatalities in Kansas have a higher number of lane-departure fatalities compared to fatalities associated with other crash types, which accounts for approximately 60%. Furthermore, lane-departure crashes are the source of 47% of disabling crashes in Kansas (Kansas Department of Transportation, 2015). Figure 1.2 summarizes all motor vehicle fatalities and lane-departure crash fatalities in Kansas from 2009 to 2014.

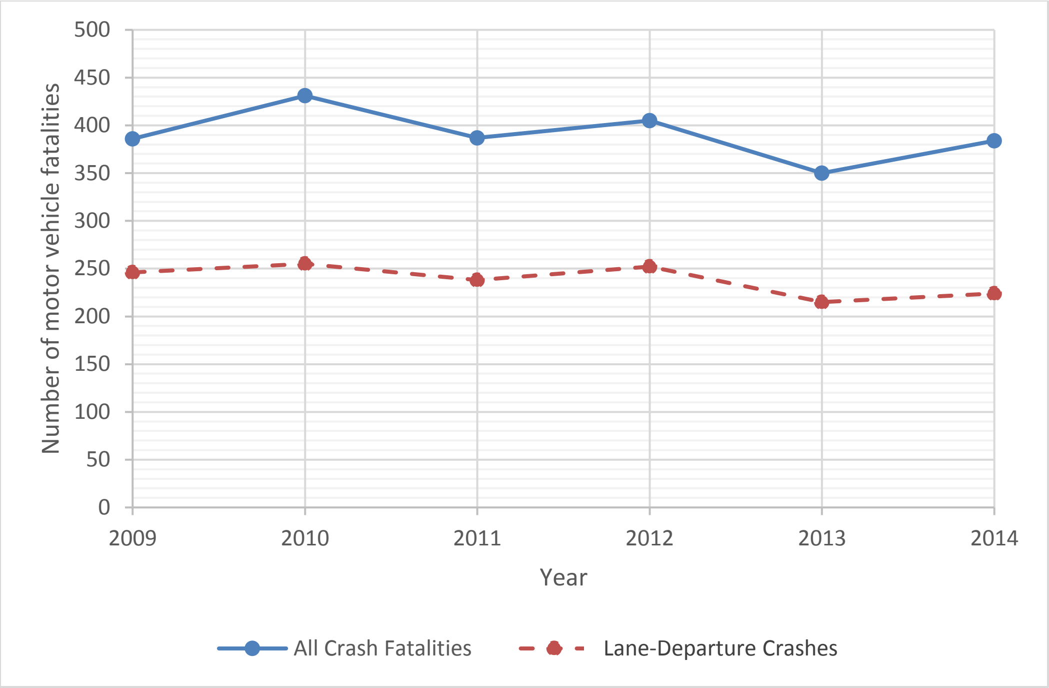


Figure 1.2. Trends in motor vehicle fatalities in Kansas from 2009 to 2014

Since lane-departure crashes have a high impact on motor vehicle fatalities, Kansas Department of Transportation (KDOT) has identified those as one of the six emphasis areas in the Strategic Highway Safety Plan (SHSP) (Kansas Department of Transportation, 2015). Furthermore, it can be seen that lane-departure crashes in Kansas have different crash attributes such as light conditions, road surface conditions, first harmful events, and most harmful events. Table 1.1 shows environmental conditions at the time of crashes on Kansas road network using combined crash data from 2009 to 2014. According to the Table 1.1, most of these crashes occurred in daylight on dry road surface conditions, leading researchers to believe the respective crashes can be avoided by improving road geometry, signage, and road surface. Furthermore, it is also evident that many crashes occurred in dark without street lights. Therefore, consideration should be given to improving signage which is visible in the dark with no street lights.

Table 1.1 Crash environment when lane-departure crashes occur on Kansas roadways during the time period of 2009 to 2014

Crash attributes	Description	Crash severity					Total crashes
		Fatal	Disable	NIC	Possible injury	PDO	
Light Condition	Dark (No Street Lights)	431	802	3,136	2,130	10,591	17,090
	Dark (Street Lights On)	148	518	2,155	1,667	11,648	16,136
	Dawn	26	106	316	274	1,685	2,407
	Day Light	628	2,027	7,366	6,025	29,334	45,380
	Dusk	35	88	323	232	1,246	1,924
	Unknown	12	10	30	17	827	896
On Road Surface Condition	Debris	1	1	18	9	26	55
	Dry	1,109	2,975	10,342	7,573	34,219	56,218
	Ice	38	142	795	740	5,656	7,371
	Mud Dirt and Sand	13	31	180	124	635	983
	Other	12	12	60	38	621	743
	Slush	6	21	61	85	707	880
	Snow	13	81	456	566	5,445	6,561
	Standing/Moving Water	1	1	26	29	139	196
	Wet	87	287	1,388	1,181	7,883	10,826

Note-:- NIC- Non incapacitating, PDO – Property damage only crashes

Table 1.2 shows attributes of lane-departure crashes occurring on Kansas road network using combined crash data from 2009 to 2014. Since a majority of the first harmful event (FHE) and most harmful event (MHE) of lane-departure crashes are due to hitting fixed objects and overturning or rolling over on dry pavements in daylight conditions, geometric and signage improvements can be implemented as remedial measures.

Table 1.2. Lane-departure crash attributes with crash severity on Kansas road network from 2009 to 2014

Crash Attributes	Description	Crash Severity					Total crashes
		Fatal	Disable	NIC	Possible injury	PDO	
Accident Class First Harmful Event (FHE)	Animal	0	1	4	5	284	294
	Fixed Object	639	2,022	8,183	6,635	43,336	60,815
	Legally Parked Vehicle	0	3	20	16	329	368
	Motor Vehicle in Transportation	299	440	1,393	1,355	6,228	9,715
	Other Non-Collision	0	4	6	2	35	48
	Other Object	0	2	1	2	26	31
	Overturned Rollover	341	1,077	3,703	2,312	5,085	12,518
	Pedal Cyclist	0	0	7	5	1	13
	Pedestrian	0	2	8	10	2	22
	Railway Train	0	0	0	0	1	1
	Unknown	0	0	1	3	4	8
Accident Class Most Harmful Event (MHE)	Animal	0	0	5	6	293	304
	Fixed Object	319	1,275	5,426	4,874	36,079	47,973
	Legally Parked Vehicle	6	19	72	77	639	813
	Motor Vehicle in Transportation	270	414	1,339	1,343	5,918	9,284
	Other Non-Collision	4	12	30	19	126	191
	Other Object	1	6	14	18	125	164
	Overturned Rollover	512	1,356	4,548	2,924	6,104	15,444
	Pedal Cyclist	0	0	8	6	2	16
	Pedestrian	5	8	11	14	3	41
	Railway Train	0	1	2		7	10
	Unknown	163	460	1,871	1,064	6,035	9,593

Note-:- NIC- Non incapacitating, PDO – Property damage only crashes

Pavement surface improvements can be employed in curved-road segments to improve safety. KDOT has implemented several countermeasures such as rumble strips, paved shoulders, median cable barriers, safety edges, high-friction surface treatments, oversized chevrons, optical speed bars, and pavement legends in many road segments as strategies of reducing lane -departure crashes. Many agencies and researchers have used different methods to evaluate the safety effectiveness of these implemented countermeasures such as statistical parametric and non-parametric analysis, crash rates, and crash modification factors (CMFs) (Highway Safety Manual, 2010; Council et al., 1980). However, with the introduction of HSM, CMF is the widely used method in the recent past due to its ease of understanding. Another advantage of CMF is that it is relatively easy to develop regression models for estimating regression coefficients, which are then used to estimate CMFs of the considered countermeasures.

1.1. Problem statement

Since lane-departure crashes have a high impact on motor vehicle fatalities in Kansas, KDOT has put emphasis on implementing countermeasures to reduce lane-departure crashes. However, it is important to know which countermeasures are more effective, because implementing and evaluating safety effectiveness of those countermeasures are costly as well as time consuming.

Current methods of estimating CMFs using cross-sectional and before-and-after methods have some limitations. The cross-sectional models only incorporate road geometric and traffic characteristics into the model development. This method is effective when developing models using the cross-sectional data for each and every road segment in the region. However, if the cross-sectional data are to be acquired manually based on few selected locations in a region where they are located apart from each other, road geometric and traffic-related explanatory variables might not accurately predict crashes, hence the CMFs based on such models might be flawed. In before-and-after studies such as empirical Bayes models, if multiple treatments have been applied on a road segment at the same time, CMFs can only be estimated for the combined treatment. Separating the effect of each treatment is not possible without employing additional methods.

Safety effectiveness of countermeasures could vary from country to country, or state to state, due to factors such as traffic, environmental, and demographic characteristics; human behavior; road culture, and geometric characteristics of the area. It may not always be accurate to assume a countermeasure which succeeded in reducing crashes in a specific location in one region may reduce a similar type of crashes in a different region. Therefore, having more localized safety effectiveness measures in hand will be an advantage in addressing lane-departure crashes. The results can be used by transportation agencies and authorities in Kansas to decide on appropriate countermeasures before implementation. Although several studies have been conducted in Kansas to estimate the safety effectiveness of some countermeasures using CMFs such as composite shoulders, unpaved shoulders, wide shoulders, and bypass lanes in work zones, those that are specific to lane-departure crashes have not been fully developed (Fitzsimmons, Schrock, Lindheimer, 2012; Dissanayake & Esfandabadi, 2015).

1.2. Countermeasures selected for further study

Even though many countermeasures have been implemented in Kansas, records on those including the location and date of implementation, are difficult to accurately track. Also, some countermeasures have only been implemented recently and do not have enough crash data for analysis, considering the shorter after-time period. Therefore, after discussions with KDOT, six lane-departure countermeasures were selected to carry out further analysis in this study:

- Centerline and shoulder rumble strips
- Paved shoulders

- Median cable barriers
- Chevrons
- Post-mounted delineators
- Safety edges

Furthermore, only two-lane undivided-road segments and four-lane divided-road segments were considered for the analysis, since those two facility types contribute toward a higher proportion of the total road network in Kansas, and a majority of lane-departure crashes occurred on those facility types.

1.3. Study objectives

Four main objectives were identified in this research to estimate CMFs for lane-departure countermeasures, which are as follows.

i. Identify suitable methods of developing CMFs for selected lane-departure countermeasures based on available data.
ii. Modify the existing cross-sectional methods to estimate representative CMFs where the commonly used explanatory variables are not adequate.
iii. Identify a method of estimating CMFs for individual countermeasures where multiple treatments have been implemented at the same time using. Alternative method for before-and-after empirical Bayes method
iv. Estimate the safety effectiveness of each lane-departure countermeasure on all crashes and lane-departure crashes in Kansas using CMFs and provide recommendations for implementing lane-departure countermeasures in future projects.

1.4. Organization of the dissertation

This dissertation contains five chapters. Chapter 1 provides background on lane-departure crashes in Kansas and the importance of having localized safety-effectiveness measures. Chapter 2 provides an in-depth literature review on CMFs for lane-departure countermeasures and commonly used methods of developing CMFs. Chapter 3 explains the two methods commonly used in this research to develop CMFs and the requirements of implementing those methods with their limitations. Chapter 4 and Chapter 5 consist of results and model validation, discussion, and conclusions, respectively.

Chapter 2 Literature Review

A road safety measure is a technical device or program implemented to reduce specific crash type or types on a particular road segment (Elvik, Vaa, Erke, & Sorensen, 2009). Therefore, evaluating effectiveness of road safety measures is one of the important steps of road safety studies. Out of many methods available such as statistical parametric and non-parametric analysis, crash rates, and CMFs (Highway Safety Manual, 2010; Council et al., 1980), nearly 80 % of transportation agencies in the United States use CMFs for safety evaluations of design alternatives, design expectations, and design consistency evaluations (Bonneson & Lord, 2005). A CMF is defined as the expected number of crashes with a countermeasure, divided by the expected number of crashes had the countermeasure not been implemented (Gross & Jovanis, 2007). According to data availability, methods of developing CMFs are varied. Commonly used methods of developing CMFs in the recent past are listed below.

- Before-and-after with comparison group studies (Gross & Jovanis, 2007; Zeng, Schrock, & Mulinazzi, 2013)

- Empirical Bayes before-and-after studies (Gross & Jovanis, 2007; Khan, Abdel-Rahim, & Williams, 2015; Nambisan & Hallmark, 2011; Sun, Das, Zhang, Wang, & Leboeuf, 2014; Zeng et al., 2013)

- Full Bayes studies (Gross & Jovanis, 2007; S. L. Hallmark, Qiu, Hawkins, & Smadi, 2015; Lan, Persaud, Lyon, & Bhim, 2009; Yanmaz-Tuzel & Ozbay, 2010; Zeng et al., 2013)

- Cross-sectional studies (Dissanayake & Esfandabadi, 2015; Gross & Jovanis, 2007; Gross & Donnell, 2011; Zeng et al., 2013)

- Case-control studies (Gross & Jovanis, 2007; Gross, Persaud, & Lyon, 2010; Gross & Donnell, 2011; Jovanis & Gross, 2007; Zeng et al., 2013) Cohort studies (Gross et al., 2010; Jovanis & Gross, 2007).

Using different methods available for developing CMFs, safety effectiveness of various countermeasures have been identified in the previous literature.

2.1. Lane-departure countermeasures

Different countermeasures have been identified in the literature to reduce crashes on tangent and curved-road segments. Table 2.1 summarizes the commonly used lane-departure countermeasures in the United States on both tangent and/or curved road segments, and are proven to be effective in many states.

Table 2.1. Commonly used lane-departure countermeasures in the United States

Countermeasures	Reference
Advance curve warning and advisory speed signing	Hallmark, Hawkins, & Smadi, 2013
Chevrons and oversized chevrons	Hallmark et al., 2013; S. L. Hallmark & Hawkins, 2014; Nambisan & Hallmark, 2011
Widening/adding paved shoulders	Hallmark, Boyle, & Qiu, 2012; Hallmark et al., 2013; Khan et al., 2015; Nambisan & Hallmark, 2011
Reflective barrier delineation	Hallmark et al., 2013
Rumble strips	Hallmark, McDonald, & Sperry, 2009; Hallmark et al., 2013; Khan et al., 2015; Nambisan & Hallmark, 2011
Safety edge treatments	Gross & Jovanis, 2007; Hallmark et al., 2006; Hallmark, Goswamy, & Pawlovich, 2016; Hallmark, McDonald, Sperry, & Vencil, 2011; Nambisan & Hallmark, 2011
High-tension median cable barriers	Nambisan & Hallmark, 2011
Roadside post-mounted delineators	Nambisan & Hallmark, 2011
Vertical delineation	Hallmark et al., 2012
Dynamic curve warning systems/dynamic speed feedback	Hallmark et al., 2012; Hallmark et al., 2015; Nambisan & Hallmark, 2011
Raised pavement marking	Hallmark et al., 2013; Nambisan & Hallmark, 2011
High-friction surface treatment	Hallmark et al., 2013; Nambisan & Hallmark, 2011
Edge lines	Hallmark, Hawkins, & Smadi, 2015
Wider edge lines	Hallmark et al., 2013; Nambisan & Hallmark, 2011

Table 2.2 (continued). Commonly used lane-departure countermeasures in the United States

Countermeasures	**Reference**
Transverse pavement marking bars	Hallmark et al., 2013; Hallmark, Knickerbocker, & Hawkins, 2013; Nambisan & Hallmark, 2011
Pavement legends	Nambisan & Hallmark, 2011
On-pavement curve signs	Hallmark, Hawkins, & Smadi, 2012; Hallmark et al., 2013
Pavement insert lights	Hallmark et al., 2013
Profile thermoplastic markings	Lord, Brewer, Fitzpatrick, Geedipally, & Peng, 2011
Clear zones	Lord et al., 2011

Relevant literature related to commonly used countermeasures in Kansas, namely paved shoulders, rumble strips, chevrons and post-mounted delineators, median cable barriers, and safety edge treatments has been summarized in this section.

2.1.1. Paved shoulders

Paved shoulders have proven to be effective in reducing crash types — head-on, run-off-road, and side-swipe crashes. Figure 2.1 shows a paved shoulder on rural two-lane undivided highway.

Figure 2.1 Paved shoulders on rural two-lane undivided highway

A study conducted in Kansas for rural two-lane highways found that upgrading narrow unpaved shoulders to three-feet composite shoulders reduced shoulder-related crashes up to 61%, and reduced fatal and injury crashes up to 31% (Zeng & Schrock, 2012; Zeng et al., 2013). A study conducted using data from seven U.S. states concluded that increasing paved shoulders by two feet for shoulder widths between zero and 12 feet could reduce shoulder-related crashes by 16 % (Zegeer, Reinfurt, Hummer, Herf, & Hunter, 1988); and another study conducted in Texas showed that increasing paved shoulder width from two feet to 10 feet has reduced run-off-road and single-vehicle fatal, serious, and minor injury crashes by 71% to 87 % on rural two-lane undivided-road segments (Peng, Geedipally, & Lord, 2012). However, some literature showed contradictory results, which indicated that widening paved shoulders might increase fixed-object, head-on, run-off-road, and side -swipe crashes on urban interstate, multilane, and two-lane highways (Z. Li et al., 2013).

2.1.2. Rumble strips

Shoulder rumble strips and centerline rumble strips are the major types of rumble strips seen on roadways. Each type reduces a specific type of lane-departure crashes such as centerline rumble strips mainly focusing on reducing head-on crashes, while shoulder rumble strips are focused on single-vehicle crashes. In some road segments, especially on curved road segments, both shoulder and centerline rumble strips have been implemented to prevent crashes. Figure 2.2(a) and Figure 2.2 (b) show shoulder rumble strips and centerline rumble strips on rural two-lane highway respectively.

Figure2.2 (a)Copyright 2008 by Mugu-shisai. Licensed under a Creative Commons Attribution-ShareAlike 3.0 Unported License (CC BY-SA 3.0). Figure 2.2(b) Copyright 2006 by Andrew Bossi. Licensed under a Creative Commons Attribution-ShareAlike 2.5 Generic License (CC BY-SA 2.5)

Figure 2.2 Shoulder rumble strips and centerline rumble strips on rural two-lane highways

Shoulder rumble strips contributed to a 21.1 % crash reduction in single-vehicle run-off-the-road crashes on rural freeways in California and Illinois (Griffith, 1999). Another study conducted in Kansas to evaluate large track crashes on rural two-lane curved segment concluded that the crashes are less likely to occur on wet pavement with shoulder rumble strips present (Fitzsimmons, Schrock, Lindheimer, 2012). However, some studies showed mixed effects from implementing shoulder rumble strips on all crash types and single-vehicle run-off-road-type crashes. A study conducted in Minnesota, Missouri, and Pennsylvania showed that installing shoulder rumble strips could have both increasing and decreasing effects on all crash types and single-vehicle run-off-road-type crashes (Torbic, 2009). Another study conducted in Washington state for rural two-lane undivided highways found that shoulder rumble strips caused a 12.3 % increase in lane-departure collisions for all injury severities (Olson, Sujka, & Manchas, 2013b). Centerline rumble strips were shown to reduce cross-centerline crashes by 27.3 %, and a combination of centerline and shoulder rumble strips reduced crashes by 32.8 % on two-lane rural highways in Michigan (Kay et al., 2015).

A study conducted in Kentucky, Missouri, and Pennsylvania on rural two-lane roads showed lane-departure crashes decreased by 26.7 % as a result of centerline and shoulder rumble strips (B. Persaud, Lyon, Eccles, & Soika, 2015). Another study showed lane-departure crashes in Washington state decreased by 63.3% on rural two-lane undivided highways due to centerline and shoulder rumble strips (Olson, Sujka, & Manchas, 2013b). However, a study conducted in North Dakota showed mixed results for the combined treatment of centerline and shoulder rumble strips (Kubas, Kayabas, Vachal, & Berwick, 2013). The same study showed that due to centerline and shoulder rumble strips, all crashes and fatal crashes decreased by 2.1% and 44.7%, respectively, while increasing injury crashes by 20.7% on rural roadways. Furthermore, the same study showed that the combined treatment reduced head-on crashes by 17%, but tended to increase side-swipe same-direction and side-swipe opposite-direction crashes by 24.5% and 148.9%, respectively.

2.1.3. Chevrons

Chevrons are used in curved-road segments to provide better direction and sharpness to the horizontal curve better than any other traffic control devices (Hallmark et al., 2013; McGee & Hanscom, 2006). Figure 2.3 shows the chevrons on a rural two-lane undivided road segment.

© Google Street view

Figure 2.3 Chevrons on rural two-lane undivided curved road segment

A study conducted in Naples–Canosa, Italy, showed that the chevrons reduced total crashes by 2.6%, while reducing run-off-road-type crashes by 10%. Also, it has been found that chevrons are more effective in rainy periods. The use of chevrons showed 59.4% crash reduction in rainy periods. However, in the same research, other results indicated that nighttime crashes could be increased by 92% due to chevrons (Montella, 2009). Another study conducted in Washington and Connecticut showed that chevrons reduced non-intersection lane-departure crashes by 9.7%, non-intersection fatal and injury crashes by 18%, and non-intersection lane-departure crashes during dark conditions by 25.4% (Srinivasan et al., 2009).

2.1.4. Post-mounted delineators

According to the Manual on Uniform Traffic Control Devices (MUTCD), post-mounted delineators are “light-retro reflecting devices mounted at the side of the roadway, in series, to indicate the roadway alignment” (U.S Department of Transportation, Federal Highway Administration, 2009). Figure 2.4 shows the post-mounted delineators on rural two-lane undivided curved segment.

© Google Street view

Figure 2.4 Post-mounted delineators on rural two-lane undivided curved road segment

The purpose of post delineation is to outline the edges of the roadway and accident critical locations. According to the Handbook of Road Safety Measures, post-mounted delineators have a crash-increasing effect on serious and minor injuries of all crash types by 4%, and property damage only by 5% on rural two-lane undivided-road segments (R. Elvik & Vaa, 2004). Another study conducted in Korea for its freeways showed that installing post-mounted delineators increased all-severity all-crash types by 19% (Choi, Kho, Lee, & Kim, 2015).

2.1.5. Median cable barriers

Median cable barriers are effective in reducing median cross-over crashes. Since the cables are used as barriers, it allows barriers to deflect much more, hence the impact force is less on the vehicle (Ross Jr, Sicking, Zimmer, & Michie, 1993). Figure 2.5 shows the median cable barriers on four-lane divided highway.

Figure 2.5 Median cable barriers on four-lane divided highways

Bahar et al. reported crash-reduction effects of median cable barriers on three-lane highways were 100% and 26% for fatal and injury crashes, respectively. Furthermore, they had a 29% crash-reduction effect on injury severity of all crash types on multilane divided highways, and a 92% crash-reduction effect on head-on fatal crashes on rural highways. However, it has been reported that median cable barriers have a 34% crash-increase trend of all-severity all-crash types on three-lane highways (Bahar, Masliah, Wolff, & Park, 2007). A study conducted in

Oregon reported that median cable barriers have reduced potential cross-over crashes by 40%. Also, the fatal crash rate reduced to zero per year from 0.6 per year. However, injury crashes have increased from 0.7 per year to 3.8 per year (Sposito & Johnston, 1998). A study conducted in Washington reported that annual serious cross-median collisions and annual fatal cross-median collisions were reduced by 80% and 58%, respectively, due to median cable barriers. In the same study, it was found that annual serious-injury median roll-over collisions and annual fatal median-rollover collisions were reduced by 65% and 31%, respectively, due to median cable barriers (Olson, Sujka, & Manchas, 2013a). Furthermore, a study conducted in North Carolina concluded that even though some crash types such as ran-off-road-left and hit-fixed-object increased due to median cable barriers, overall safety of the roadway was improved by reducing serious and fatal crashes, as well as fewer head-on crashes (Hunter et al., 2001)

2.1.6. Safety edges

According to the Federal Highway Administration (FHWA), a safety edge treatment where the edge of the pavement is shaped by 30 degrees is an effective solution for lane-departure-type crashes. A safety edge is useful for the drivers to return to the roadway when a pavement edge drop-off happens. If the safety edge has not been implemented, drivers might overcorrect when they attempt to steer back onto the pavement and then meet with an accident (Hallmark et al., 2013).Therefore, many transportation agencies have implemented the safety edge treatment to reduce pavement drop-off-type crashes. Figure 2.6 shows a safety edge treatment.

Figure 2.6 Safety edge treatment

The states of Georgia and Indiana have shown a 5.7-9.5% crash-reduction effect on all crash types due to safety edge treatment. Furthermore, Georgia and Indiana have experienced a 4.8-14.2% crash-reduction effect on total run-off-road-type crashes, and a 23.1% crash-reduction effect on fatal and injury run-off-road crashes. However, there is an increasing trend of fatal and injury run-off-road-type crashes by 20% and 2.6%, respectively, due to safety edge treatment on two-lane roads with unpaved and combined shoulders (Graham, Richard, O'Laughlin, & Harwood, 2011)

2.2. Methods of developing crash modification factors

Existing methods of developing CMFs can be divided into two main categories, namely, before-and-after studies and cross-sectional studies. Neither method can be used in every situation due to limitations on the required data and expected accuracy. Before-and-after studies require crash data of the before-and-after time period of the countermeasure implementation for treatment and non-treatment sites (Hallmark et al., 2012); and cross-sectional studies require only after-crash data for treatment and non-treatment sites(Bonneson & Lord, 2005; Dissanayake & Esfandabadi, 2015; Gross & Jovanis, 2007; Hallmark et al., 2012). However, results can vary from methods used to evaluate safety effectiveness (Torbic, 2009).

2.2.1. Before-and-after studies

Different types of before-and-after studies have been used to evaluate safety effectiveness of the countermeasures listed below.

- Naïve before-and-after study (Izadpanah, Hadayeghi, & Zarei, 2009)
- Before-and-after study with Yoked comparison (Griffin & Flowers, 1997; Harwood et al., 2003; Izadpanah et al., 2009)
- Before-and-after study with comparison group (Izadpanah et al., 2009)
- Before-and-after study with empirical Bayes approach (Hauer, 1997; Izadpanah et al., 2009) Before-and-after full Bayesian models (Lan et al., 2009; Yanmaz-Tuzel & Ozbay, 2010).

Data requirements for before-and-after studies are higher than that for cross-sectional studies. For such studies, crash frequencies of the before-and-after period at a treated site and crash frequencies of a before-and-after period at a non-treatment site, or the safety performance function (SPF) of the treated sites are required (Highway Safety Manual, 2010). However, it may be difficult to identify the clear cut-off point for the before-and-after time periods for a treatment, because the date of implementation of that treatment is not known or is difficult to accurately identify. Furthermore, it is necessary to collect geometric data such as segment length, Average Annual Daily Traffic (AADT), road width, and number of lanes to develop a safety performance function. The following sections provide an overview of two commonly used before-and-after study approaches in the recent past to estimate CMFs.

2.2.1.1. Before-and-after empirical Bayes method

The before-and-after Empirical Bayes (EB) method was introduced to identify the safety effectiveness of countermeasures on specific crash type or types (Hauer, 1997). Both observed and expected number of crashes in the before-and-after period are considered to estimate the safety effectiveness of a countermeasure in the after period (Park & Abdel-Aty, 2015). The strength of the EB method is that it overcomes the limitation of the Naïve and Comparison Group Methods by accounting for the regression-to-the-mean effect (Park & Abdel-Aty, 2015; Shen & Gan, 2003). Furthermore, the EB method accounts for observed changes in crash frequencies in the before- and-after periods and AADT changes (Park & Abdel-Aty, 2015). Since it has a strength of evaluating safety effectiveness of the countermeasures, the method has been widely used around the world.

Studies conducted in Idaho, California, Illinois, British Colombia/Canada, and Minnesota used the EB method to identify the safety effectiveness of shoulder rumble strips (Griffith, 1999; Khan et al., 2015; Patel, Council, & Griffith, 2007; Sayed, deLeur, & Pump, 2010). A study conducted using data of seven states — California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington — used the EB method to evaluate safety effectiveness of centerline rumble strips (Persaud, Retting, & Lyon, 2004), while another study in Kentucky, Missouri, and Pennsylvania used the EB method to evaluate the safety effectiveness of the combined effect of shoulder and centerline rumble strips (Persaud et al., 2015). A study conducted in Tucson, Arizona, to evaluate the safety effectiveness of a High intensity Activated Cross Walk (HAWK) pedestrian crosswalk treatment used the EB method (Fitzpatrick, Lord, & Park, 2008). Studies conducted in Connecticut and Washington to evaluate safety effectiveness of curve delineation through signing improvements and post-mounted delineators (Srinivasan et al., 2009), and a study conducted in Nebraska to evaluate safety effectiveness of an actuated advance-warning dilemma zone-protection system (Appiah, Naik, Wojtal, & Rilett, 2011) used the EB method. Furthermore, a study conducted in San Francisco, California, to evaluate the safety effectiveness of high-visibility school crosswalks (Feldman, Manzi, & Mitman, 2010) also used the EB method for analysis. Finally, some researchers have used the EB method to find out the combined effect of multiple treatments on rural two-lane roadways such as installing both shoulder rumble strips and widening of shoulder widths in Florida (Park & Abdel-Aty, 2015).

2.2.1.2. Before-and-after full Bayesian method

The before-and-after full Bayesian method is one of the two commonly used before-and-after study methods in the recent past. The main difference between the EB and full Bayesian (FB) method is that in the EB method, safety effectiveness is calculated by combining the accident record for the treatment site and the SPF function, showing how different factors affect accident occurrence. However, in the FB method, a distribution of expected crash frequencies was estimated instead of its point estimates as in the EB method, which enhances the precision of the uncertainty of the results (Lan et al., 2009). Furthermore, in the FB method, the probability distribution of the model parameters is also estimated and the subsequent distributions of the parameters are drawn by sampling directly from the conditional distributions (Yanmaz-Tuzel & Ozbay, 2010).

The FB method was found to be very useful and provided better estimates than the EB method when working with a small number of observations (Miranda-Moreno & Fu, 2007). This is because in the FB method, SPF and treatment estimation can be conducted in one step, while it needs several steps in the EB method. Also, the FB method provides more information, including distributions of the calibrated parameters, thus allowing researchers to select different forms such as the Poisson-Gamma model and Poisson-log normal model with or without trend (Lan et al., 2009). Therefore, this method was used by many safety researchers in the recent past, such as studies conducted in Iowa, to estimate the safety effectiveness of the road diet (Pawlovich, Li, Carriquiry, & Welch, 2006) and converting roads from four lanes to three lanes (W. Li, Carriquiry, Pawlovich, & Welch, 2008). Also, a study conducted in Minnesota to estimate the safety effectiveness of converting unsignalized intersections to signalized intersections (Aul & Davis, 2006) and a study conducted in Michigan, California, Washington, and Illinois to estimate the safety performance functions for two-lane highways (Qin, Ivan, Ravishanker, & Liu, 2005), used the FB method. Furthermore, studies conducted in California and Washington state to evaluate the safety effectiveness of conversion from stop to signalized control on rural intersections and to predict crash count by severity on rural two-lane highways, used the FB method for the analysis (Lan et al., 2009; Lan et al., 2009; Ma, Kockelman, & Damien, 2008).

2.2.2. Estimating CMFs for multiple treatments

Even though the before-and-after methods such as EB method have proven to provide accurate results, those methods usually estimate the combined CMF due to multiple treatments if the road segment had multiple treatments at the same time. Many methods have been introduced in the past to combine individual crash modification factors to predict combined safety effectiveness due to multiple treatments. Same methods can be used to estimate CMFs of one treatment if the CMFs of the combined treatments and the other individual treatments are known. Following are few of the commonly used approaches that have been utilized to combine individual CMFs to estimate the safety effectiveness due to multiple treatments (HSM 2010; Gross & Hamadi, 2011; Park, Abdel-Aty, & Lee, 2014; Turner et al, 2011).

- Organize CMFs based on crash types and their applications into groups
- Previous experience and expert judgment
- Apply a weightage factor to a multiplication of CMFs
- Assume independence between the treatments and take the product of all the CMFs
- Apply only the most effective CMF

However, non of these methods have been proven to be effective in all the regions. Therefore each method should be tested before applying in another region other than the regions that they have been proven to be effective.

2.2.3. Cross-sectional studies

2.2.3.1. Studies using the cross-sectional method

The cross-sectional method is commonly used to estimate the expected number of crashes in transportation safety research (Gross & Donnell, 2011). A study conducted in Texas used the cross-sectional method to calculate CMFs for median characteristics on urban and rural freeways or rural multilane highways (Fitzpatrick et al., 2008). Another study used the cross-sectional method to calculate CMFs for the presence of wider lanes, shoulder widths, and edge markings in rural frontage roads in Texas (Lord & Bonneson, 2007). Studies conducted in Minnesota and Pennsylvania also used the cross-sectional method to calculate CMFs for the presence of roadway lighting at grade intersections, and lane and shoulder widths on rural two-lane highways (Gross & Jovanis, 2007; Gross & Donnell, 2011). The cross-sectional method has also been used to calculate CMFs in order to evaluate safety effectiveness of composite shoulders, wide unpaved shoulders, and wide paved shoulders on rural two-lane undivided roadways in Kansas (Zeng et al., 2013).

However, the cross-sectional method has inherent strengths and weaknesses, where strengths include its ability to be used when multiple treatments are applied on corresponding road segments (Lee, Abdel-Aty, Park, & Wang, 2015) and for sensitivity analysis to identify alternative highway improvements (Benekohal & Hashmi, 1992). The cross-sectional method also does not require the date of implementation of the countermeasure (Highway Safety Manual, 2010). However, one weakness of the cross-sectional method is that it does not capture the effects of the factors not included in the model (Benekohal & Hashmi, 1992). Therefore, the effect of the environment and driver behaviors cannot be captured by this method since the commonly used explanatory variables are the road geometric and traffic-related characteristics. This method also requires a relatively large sample size, and accuracy of estimates often varies according to data quality (Gan, Shen, & Rodriguez, 2005). In addition, calculation of CMFs using the cross-sectional method requires a model to predict crashes (Lee et al., 2015), and regression methods can be used to estimate the systematic relationship between crashes and highway design attributes (Strathman, Dueker, Zhang, & Williams, 2001).

2.2.3.2. Studies using the case-control method

The case-control method has been used for many safety studies in the transportation sector (Davis, Davuluri, & Pei, 2006; Dissanayake & Esfandabadi, 2015; Gross & Jovanis, 2007; Gross

& Donnell, 2011; Zeng et al., 2013). Defining case and control is essential in this method. Cases are defined as road segments that have experienced at least one crash during a particular year; controls are the segments that have not experienced a single crash during that same year (Gross & Jovanis, 2007; Gross & Donnell, 2011). Although few studies have focused on the effects of geometric elements in the past, recent studies have used the case-control method to estimate CMFs for geometric improvements of a road network (Gross Jr, 2006). Two studies in Pennsylvania used the case-control method to estimate CMFs for change in shoulder width, and safety effectiveness of lane and shoulder widths of rural two-lane undivided-road segments (Gross & Jovanis, 2007; Jovanis & Gross, 2007). CMFs for bypass lanes at rural intersections in Kansas and presence of lighting at intersections in Minnesota were also estimated using the case-control method (Dissanayake & Esfandabadi, 2015; Gross & Donnell, 2011).

The case-control method demonstrates unique strengths and weaknesses. Strengths of the method include its ability to study rare events, calculate multiple risk factors from one sample, and control confounding variables using the matched design (Gross et al., 2010; Gross & Donnell, 2011). Weaknesses of this method are its inability to measure the probability of an event, and its need to collect retrospective data for risk factors and outcome status (Gross & Donnell, 2011). In addition, the traditional case-control method cannot distinguish whether the segment has had a single crash or multiple crashes (Gross Jr, 2006). Even though the matched case-control method can control for confounding variables, it increases the complexity of data collection and sample selection, especially if there are many matching variables to be considered (Gross & Donnell, 2011).

Chapter 3 Methodology and Data

3.1. Methodology

By considering available options, methodologies were selected to estimate CMFs for identified countermeasures related to lane-departure crashes. If the existing methodologies are not adequate or have limitations, novel methodologies were introduced. Also, consideration was given to data availability of the road segments where the countermeasures had been implemented. The following sections provide the descriptive methodology of how the CMFs were estimated based on available data.

3.1.1. Methods of developing CMFs for each countermeasure

This section summarizes four methods of developing CMFs for lane-departure countermeasures in Kansas namely cross-sectional method, case-control methods, regression based before-and-after method, and EB method. Cross-sectional and case-control methods were implemented where the date of implementation of the countermeasure was not known. Regression based before-and-after method was introduced to overcome the drawbacks of EB method. Finally, the CMFs were estimated using EB method to compare the results with the proposed regression based before-and-after method.

3.1.1.1. Cross-sectional method

A commonly used approach of estimating CMFs using the cross-sectional method is to develop generalized linear regression models, assuming either Poisson or negative binomial error distribution. In this case, the considered lane-departure countermeasures are used as explanatory variables with other road geometric and traffic-related characteristics. Then the estimated regression parameters for considered countermeasures are used to estimate CMFs for respective countermeasures. However, it is necessary to check the multi-collinearity between explanatory variables before using those in the model (Kutner, Nachtsheim, & Neter, 2004). Therefore, correlation matrices were developed for the explanatory variables that were considered in developing models for tangent and curved segments, in order to identify multi-collinearity, hence to select statistically significant explanatory variables. Even though different values were used in the literature as cut-off level for identifying the variables with multi-collinearity effect, the commonly used value in previous traffic-related research, which is 0.5, was used as a cut-off level in this study (Dissanayake & Kotikalapudi, 2012; Oh, Kang, Kim, & Kim, 2005).

Before developing models, the dataset was randomly divided into two parts containing two-thirds and one-third of the total dataset to be treated as a model developing dataset and a validation dataset. A model-developing dataset was used to develop the models and a validation dataset was used to validate the accuracy of the developed models. Since the predictor variable, which is crashes per segment per year is a rate, generalized linear regression models assuming Poisson distribution was employed to develop cross-sectional models. Poisson model modified for crash frequency modeling is shown in Equation 1 (Poch & Mannering, 1996; Washington, Karlaftis, & Mannering, 2010).

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

Where;

$P(y_i)$ = the probability of y_i accidents occurring on highway segment *i*

λ_i = E(y_i) = the mean accident for road segment *i*

Furthermore, log-linear models were used in this study to link response variable with the explanatory variables as shown in Equation 2.

$$ln(\lambda_i) = \boldsymbol{\beta}'\boldsymbol{x}_i \tag{2}$$

Where;

$\boldsymbol{x}_i$ = the vector of explanatory variables for highway segment i, i.e. geometric and traffic related characteristics, diver behaviors, environmental conditions, road surface characteristics and light conditions, etc.,

$\boldsymbol{\beta}$ = the vector of unknown estimable coefficients, and

$\boldsymbol{\beta}'$ = the transpose of vector **β.**

The standard maximum likelihood method was used to estimate **β** as in Equation 3.

$$\lambda_i = \exp(\boldsymbol{\beta}'\boldsymbol{x}_i) \tag{3}$$

However, later it was found that models developed for paved shoulders, rumble strips, and median cable barriers were overdispersed. Therefore, the negative binomial log linear models which are commonly used in the cross-sectional method to develop crash-frequency models were employed to overcome the overdispersion issue in the Poisson models (Gross & Donnell, 2011; Shankar, Mannering, & Barfield, 1995; Tarko, Eranky, & Sinha, 1998; Vogt & Bared, 1998). Equation 3 shows the general form of the negative binomial regression model, which is modified for the crash-frequency modeling (Montgomery, Peck, & Vining, 2015; Poch & Mannering, 1996; Washington, Karlaftis, & Mannering, 2010).

$$\lambda_i = \exp(\beta X_i + \varepsilon_i) \tag{4}$$

Where;

λi = expected crash frequency per year in road segment i

β = vector of estimable coefficients

Xi = geometric and traffic related explanatory variables of highway segment i

$\mathrm{EXP}(\varepsilon_i)$ = gama distributed error term with mean 1 and variance α^2

The mean–variance relationship of NB distribution can be expressed as in Equation 5.

$$VAR\,(yi) = E(yi) + \alpha\, E(yi)^2 \qquad (5)$$

Where;

$VAR\,(yi)$ = variance of observed crashes

$E(yi) = \mu$ = expected crash frequency

α = overdispersion parameter

The maximum likelihood method estimates the coefficient in the linear regression model, as described in Equation 6 (Washington, Karlaftis, & Mannering, 2010).

$$L(\lambda_i) = \prod_i \frac{\Gamma((1+\alpha)+yi)}{\Gamma\left(\frac{1}{\alpha}\right)yi!} \left[\frac{1/\alpha}{(1/\alpha)+\lambda_i}\right]^{1/\alpha} \left[\frac{\lambda_i}{(1/\alpha)+\lambda_i}\right]^{yi} \qquad (6)$$

Before developing models, outliers should be identified because they could affect the model fitness. In some cases, if the model fitness is not good or many variables become insignificant, outliers should be treated to enhance the model fitness. A commonly used method to identify the outliers in a given dataset is to calculate Cook’s distance by comparing the fitted values with the corresponding fitted values when a data point is deleted in fitting the regression model (Kutner et al., 2004). If Cook’s distance of any data point is greater than 1, it is considered as an outlier (Montgomery et al., 2015). Therefore, Cook’s distance was calculated for the predictor variable, which is the number of crashes per year in road segments, for outlier analysis. The stepwise method of selecting significant variables from the candidate variables was used to develop models. Number of crashes per year per segment was taken as the predictor variable, and previously selected variables were considered as explanatory variables to develop regression models according to Equations 1-6.

Model validation was carried out using two commonly used criteria, which was to check the mean of the residuals and root mean square error (RMSE) after fitting the estimated model using validation dataset. If the mean of the residuals is approximately equal to zero and the RMSE calculated using the validation dataset is approximately equal to the model RMSE, the model is considered as a good model for predicting lane-departure crashes in considered road segments.

3.1.1.2. Case-control method

The commonly used method of matched case-control design is to develop a conditional logistic regression model to investigate the relationship between the outcome and risk factor (Gross & Donnell, 2011; Jovanis & Gross, 2007; Woodward, 2013). Such models can be used to identify whether having a specific lane-departure countermeasure has a likelihood of reducing crashes or not. Another advantage of employing a matched case-control design is that it directly controls confounding variables, which have a hidden effect on the predictor variable (Gross & Jovanis, 2007). Also, confounding variables will provide erroneous results by suggesting a relationship between some explanatory variables and the predictor variable, when in fact, there aren’t any relationship. Therefore, the matched case-control design was used in this study. A typical matched case-control method uses a logistic regression model, as shown in Equation 7 (Montgomery et al., 2015).

$$E(y_i) = \pi_i = \frac{\exp(X_i'\beta)}{1+\exp(X_i'\beta)} \qquad (7)$$

Where;

$E(y_i)$ = expected crashes at location i

β_i = estimated coefficients for explanatory variables

x_i = unmatched explanatory variables associated with road geometry

The predictor variable of the extracted dataset must be modified so that if the number of crashes are equal to or greater than 1, then 1 must be assigned as the number of crashes on the corresponding road segment, otherwise zero. The same dataset used in the cross- sectional method was used for the model development by modifying the predictor variable as mentioned previously. The same variables used in the cross-sectional method were used in the case-control method and the maximum likelihood estimation was used to estimate regression parameters, as shown in Equation 8.

$$L(y_1, y_1, \ldots.\, y_1, \beta) = \prod_{i=1}^{n} \pi_i{}^{y_i}(1 - \pi_i{}^{y_i})^{1-y_i} \tag{8}$$

Stepwise method was used to select the variables for the models. A Receiver Operational Characteristic (ROC) was used to evaluate the predictive power of models for a binary outcome and classification tables were used to implement this method (Allison, 2012). Validation was carried out by fitting a regression model on a validation dataset using previously estimated regression parameters. If the predicted probability of crash occurrence is equal to or greater than 0.5, it is considered as 1 (crash), or otherwise considered as 0 (no-crash). Accuracy, sensitivity, and specificity were then calculated for each model. Accuracy is the proportion of correct predictions to the total number of observations. Sensitivity and specificity are the proportion of events (crash segments) correctly predicted to the total number of crash segments, and proportion of non-events (no-crash segments) correctly predicted to the total number of no-crash segments, respectively.

3.1.1.2.1. Modification to the existing cross-sectional and case-control method to develop CMFs for chevrons and post-mounted delineators

For this study, the data for chevrons and post-mounted delineators are not readily available. Therefore, it is required to acquire the information manually. Since lot of effort and time have to be spend on full scale data collection where there are more than 6,000 curved two-lane undivided road segments in Kansas, it was decided to develop model using a representative data sample. Therefore, a minimum sample size was calculated as in Equation 9 (Shin, Lee, & Dadvar, 2014).

$$\mathrm{n} = \frac{(n_0 \times N)}{(n_0 + (N-1))} \tag{9}$$

Where:

n = minimum sample size,

N = population, and

$n_0 = \frac{Z^2 \times \mathrm{P} \times (1-\mathrm{P})}{e^2}$

Where;

Z = area under normal curve corresponding to the desired confidence level.

P = true proportion of factor in the population, or the expected frequency value.

e = Margin of error.

However, the population of this study, which is the number of two-lane curved road segments with chevrons and post-mounted delineators was not known. Therefore, the number of two-lane curved road segments were considered as the population which indeed overestimated the required minimum sample size. Previous research showed that the prediction power increases with the sample size and the optimum sample size, the prediction power become constant at its peak. Furthermore, research showed that the Mean Square Error (MSE) of the models decreases with increasing of the sample size (Mao, London, Ma, Dvorkin, & Da, 2006). Following calculations show the data and steps used to estimate minimum sample size for the study according to Equation 9.

N= Number of two-lane curved road segments = 6,442

Z = 1.96 for 95% confidence interval

P = 0.4, 0.5 and 0.6

e = 0.05

For P = 0.4; 90% CI; n_0 = 250

P = 0.4; 95% CI; n_0 = 349

For P = 0.5; 90% CI; n_0 = 260

P = 0.5; 95% CI; n_0 = 363*

For P = 0.6; 90% CI; n_0 = 250

P = 0.6; 95% CI; n_0 = 349

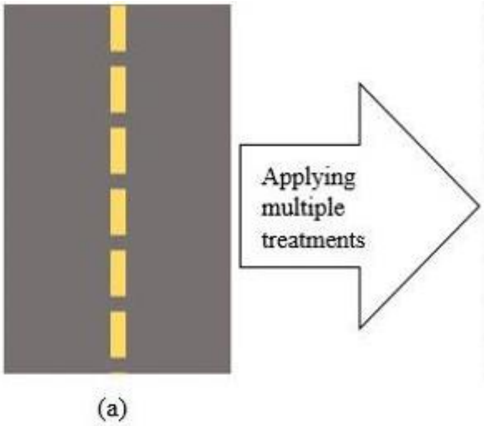
Note: * - is the maximum value of the minimum sample size.

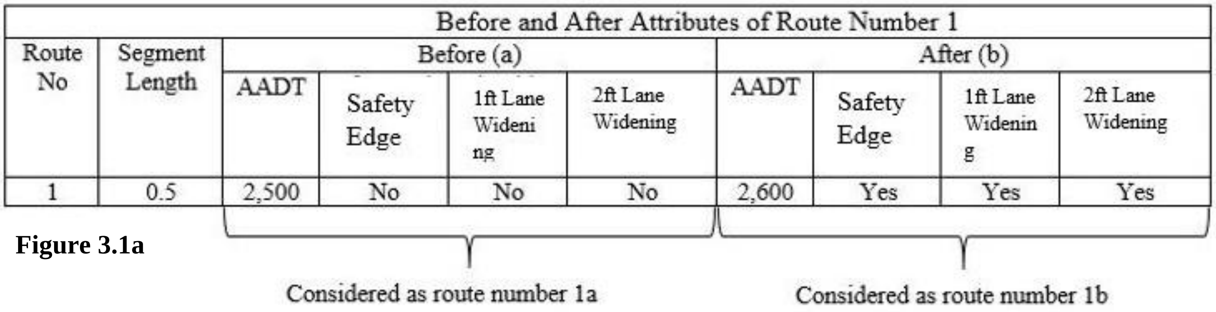
Since the P, is not known, it was decided to use the estimated minimum sample size for P=0.5 for 95% confidence level. The reason of using those values is that it gives the highest sample size hence the power of the model will be higher and the minimum sample size estimated is reliable at 95% confidence level. At least one curved road segment was selected from one county allowing the sample to be distributed throughout Kansas.

Since the consecutive road segments which are closely located to each other were not considered in the model development, the existing cross-sectional method may not be suitable. The important crash contributory factors which can be captured by consecutive or closely located road segments will not be captured by the selected data sample. Hence the traditional cross-sectional methods which incorporate only the geometric and traffic-related characteristics as explanatory variables may not be accurate. Therefore, the traditional cross-sectional method was modified by introducing some additional variables such as environmental and human-related characteristics into the models. However, as mentioned before, not incorporating such variables into a segment level safety performance functions is understandable due to difficulties of finding those data at segment level. However, those information can be found at county level. Since the consideration was given to select few curved road segment from each county, it was decided to incorporate impaired driving, weather and environmental characteristics into the models to estimate CMFs for chevrons and post-mounted delineators. The method of extracting those data is described in a later section.

3.1.1.3. Regression based method to estimate crash modification factors using before-and-after data

As described in the literature, EB method estimated only the safety effectiveness of combined treatments when the multiple treatments are applied on a road segment at the same time. Since the data collected to evaluate the safety effectiveness of safety edges experienced multiple treatments which are 1ft and 2ft lane widening at the same time, an alternative method should be employed to estimate the safety effectiveness due to individual treatments. Therefore, a novel method based on regression equations was introduced in this section. The data extraction for safety edge treatment is described later in the “Data” section. The concept of the proposed method is illustrated using a hypothetical example as shown in Figure 3.1, which assumed that the considered road segment had safety edge tratment with 1ft and 2ft lane widening at the same time.



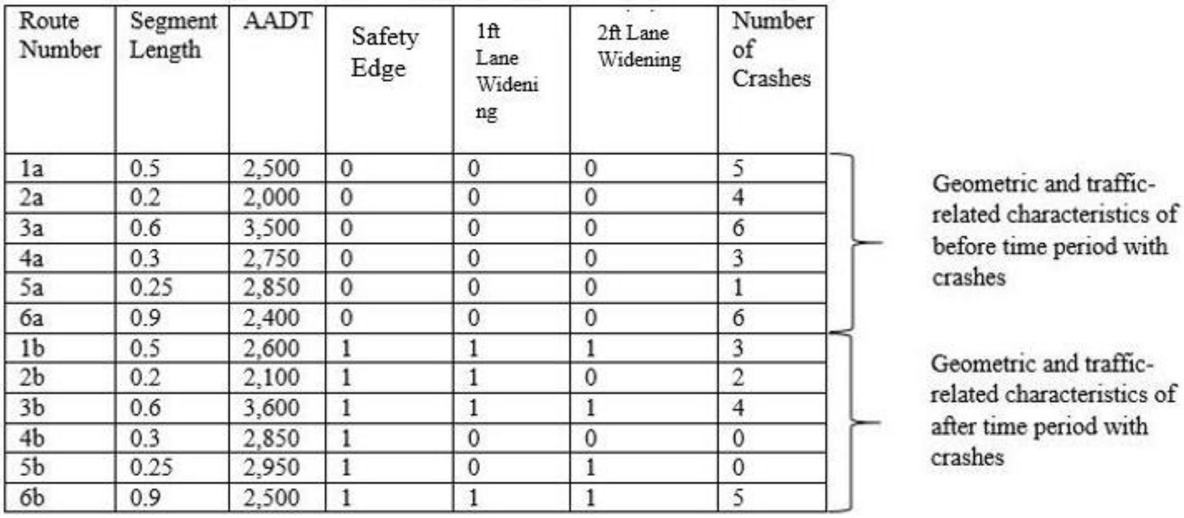


Before and After Attributes of Route Number 1									
Route No	Segment Length	Before (a)				After (b)			
		AADT	Safety Edge	1ft Lane Widening	2ft Lane Widening	AADT	Safety Edge	1ft Lane Widening	2ft Lane Widening
1	0.5	2,500	No	No	No	2,600	Yes	Yes	Yes

Considered as route number 1a

Considered as route number 1b

Figure 3.1a



Route Number	Segment Length	AADT	Safety Edge	1ft Lane Widening	2ft Lane Widening	Number of Crashes
1a	0.5	2,500	0	0	0	5
2a	0.2	2,000	0	0	0	4
3a	0.6	3,500	0	0	0	6
4a	0.3	2,750	0	0	0	3
5a	0.25	2,850	0	0	0	1
6a	0.9	2,400	0	0	0	6
1b	0.5	2,600	1	1	1	3
2b	0.2	2,100	1	1	0	2
3b	0.6	3,600	1	1	1	4
4b	0.3	2,850	1	0	0	0
5b	0.25	2,950	1	0	1	0
6b	0.9	2,500	1	1	1	5

Geometric and traffic-related characteristics of before time period with crashes

Geometric and traffic-related characteristics of after time period with crashes

Figure 3.1b

Figure 3.1. Hypothetical example of data preparation for proposed regression based method

As shown in Figure 3.1a, before the treatments have been applied, the road segment did not have safety edge treatments, or 1ft and 2ft lane widening treatments. Therefore, respective variable in the before period is zero as shown in the Figure 3.1b, for route number 1a. However, the considered road segment had safety edge treatment and 1ft or 2ft lane widening tratments at the same time. Therefore, the corresponding values for those treatment variables are one, as shown in Figure 1b, route number 1b. Segment length remains the same since the same road segment was considered, however, AADT and number of lane-departure crashes were varied as shown in Figure 3.1b, route number 1a, and 1b. Since the before and after characteristics of the same road segment was considered, it minimises the effect of not considering the driver behaviour and environmental-related characteristics in the SPF in EB method

After preparing the dataset as described in this section, a generalized linear regression model using Negative Binomial error structure was employed to develop models to estimate individual effect of each treatment as shown in the cross-sectional method from Equations 1 - 6. To validate the results, EB models were developed for the same dataset as described in following section.

3.1.1.4. Before-and-after empirical Bayes method

The empirical Bayes method is used when the date of implementation of the respective countermeasure is known. Since the date of implementation of the safety edge treatment and lane widening is known, EB method was employed to estimate CMFs for the combined treatments. The results were then compared with the proposed regression based method. However, it should be noted that the CMFs were developed using EB method only to compare the accuracy of the proposed regression based method to estimate CMFs using before-and-after data. The following steps have been widely used to develop CMFs using the EB method (Sun et al., 2014).

***Step 1**:*

Estimate expected crashes in the before-and-after period of safety edge treatment implementation using a safety performance function (SPF). Generalized linear regression models, assuming negative binomial error structure, were used to develop SPF using the format shown in Equation 10.

$$\hat{E}(k_{iy}) = \text{AADT} \times L_i \times e^{(\beta X_i)} \qquad (10)$$

where

$\hat{E}(k_{iy})$ = predicted total crash frequency for roadway segment i in year y

AADT = Annual Average Daily Traffic,

L_i = length of roadway segment i (mi), and

β = p×1 vector of estimated regression parameters corresponding to geometric design and traffic-volume-related explanatory variables

x =n×p known explanatory model matrix of geometric design and traffic-volume-related variables

Equation 11 and Equation 12 show the summation of the SPF estimates on segment i over three years before the safety edge implementation (P_i), and three years after implementation (Q_i), respectively.

$$P_i = \sum_{y=1}^{3} \hat{E}(k_{iy}) \qquad (11)$$

$$Q_i = \sum_{y=5}^{7} \hat{E}(k_{iy}) \qquad (12)$$

Also, the ratio of the SPF estimates before and after safety edge implementation for segment i can be calculated using equation 13.

$$C_i = \frac{\sum_{y=5}^{7} \hat{E}(k_{iy})}{\sum_{y=1}^{3} \hat{E}(k_{iy})} = \frac{Q_i}{P_i} \tag{13}$$

Step 2.

The expected number of crashes (M_i), before safety edge implementation were estimated using Equation 10.

$$M_i = w_i\, P_i + (1- w_i\,)\, K_i \tag{14}$$

$$w_i = \frac{1}{1+\frac{P_i}{k}}$$

$$\text{k} = \frac{0.236}{L}$$

where,

K_i = total number of crashes during the before period at site i,

w_i = weight factor

k = over-dispersion parameter

Over-dispersion is one of the issues which needed to be addressed when estimating CMFs using the EB method. Also, it was found that the over-dispersion parameter is a function of a roadway-segment length (Sun et al., 2014).

Equation 15 can be used to estimate the variance of M_i. Equation 16 and Equation 17 can be used to estimate the sum of the expected number of crashes (Mi), before safety edge implementation ($\widehat{M}$) and to estimate the variance of $\widehat{M}$.

$$\text{Var}\ (M_i) = (1- w_i\,)\ M_i \tag{15}$$

Thus,

$$\widehat{M} = \sum_{i=1}^{I} M_i \tag{16}$$

$$\widehat{var}(\widehat{M}) = \sum_{i=1}^{I} var\ (M_i) \tag{17}$$

Step 3:
After estimating the expected number of crashes before safety edge implementation and its variance, estimate the number of EB-predicted crashes, $\hat{\pi}_i$, for the after time period and its variance as shown in Equations 18 and 19.

$$\hat{\pi}_i = C_i\ M_i \qquad (18)$$

$$\widehat{var}(\pi_i) = C_i^2\,\widehat{var}(M_i) = C_i^2(1 - w_i)\ \mathrm{M_i} \qquad (19)$$

Where,

$\widehat{var}(\pi_i)$ equals the variance of the estimate of EB predicted crashes

$\hat{\pi} = \sum_{i=1}^{I} \pi_i$

$\widehat{var}(\hat{\pi}_i) = \sum_{i=1}^{I} var(\hat{\pi}_i)$

Step 4.

The final step is to estimate the index of effectiveness of the safety edge ($\hat{\theta}$), and its variance with 95% confidence as shown in Equation 21 and Equation 22.

$$\hat{\theta} = \frac{L}{\hat{\pi}\ [1+\frac{\widehat{var}(\hat{\pi}_i)}{\hat{\pi}^2}]} \qquad (21)$$

$$\sigma\ (\hat{\theta}) = \frac{\hat{\theta} \times \sqrt{\frac{1}{L} + \frac{\widehat{var}(\hat{\pi}_i)}{\hat{\pi}^2}}}{1 + \frac{\widehat{var}(\hat{\pi}_i)}{\hat{\pi}^2}} \qquad (22)$$

where L is the total observed crash counts from the after time period and $\sigma\ (\hat{\theta})$ equals the standard error of the index of effectiveness.

However, as mentioned previously, EB method estimates the combined safety effectiveness of the multiple treatments. Three commonly used methods were identified as in Equations 23, 24, and 25 to isolate the safety effectiveness of individual treatments using the safety effectiveness of combined treatments. However, it should be noted that these methods have been used to estimate the combined effect of the multiple treatments where the safety effectiveness of the individual treatments are known (HSM 2010; Park, Abdel-Aty, & Lee, 2014; Turner et al, 2011).

Method 1: Assume Independence of Treatment

$$CMF_{CT} = CMF_1 \times CMF_2 \times \ldots\ldots\ldots \times CMF_n \tag{23}$$

where,

CMF_{CT} = CMF of combined treatments

CMF_1 = CMF of 1st treatment

CMF_2 = CMF of 2nd treatment

CMF_n = CMF of nth treatment

Method 2: Systematic reduction of safety effect of less effective reduction

$$CMF_{CT} = CMF_1 \times CMF_{2,\text{ Reduced}} \tag{24}$$

where,

CMF_{CT} = CMF of combined treatments

CMF_1 = CMF of 1st treatment

$CMF_{2,\text{ Reduced}} = \frac{1 - \mathrm{CMF2}}{2} + CMF_2$; CMF_2 is the less effective treatment

Method 3: Multiply by weighted factor

$$CMF_{CT}\ [\text{Turner Method}] = 1 - [\tfrac{2}{3} - (1 - (\mathrm{CMF1} \times \mathrm{CMF2}))] \tag{25}$$

where;

CMF_{CT} = CMF of combined treatments

CMF_1 = CMF of 1st treatment

CMF_2 = CMF of 2nd treatment

Even though these methods were introduced to estimate CMFs for combined treatments using CMFs of individual treatments, these methods can be used to estimate individual CMF, if the CMF due to multiple treatments and other individual CMFs are known. Since one of the objectives of this study is to compare the CMFs obtained from proposed regression method with the EB method, individual CMFs should be estimated using the CMFs estimated using EB method. Therefore, Equations 23, 24, and 25 were used to estimate individual CMFs based on the estimated CMFs for multiple treatments using EB method. However, CMFs for other treatments such as increasing lane width could not be found for Kansas two-lane rural road segments. Therefore, CMFs estimated from the regression method was used when calculating individual CMFs using previously mentioned methods.

3.2. Data and model variables

3.2.1. Data availability

Data for the previously identified lane-departure countermeasures were collected. Two data sources were used, namely Kansas Crash and Analysis Reporting System (KCARS) and the Control Section Analysis System - State Highway Network Data (CANSYS). A brief description of each database is given below.

3.2.1.1. KCARS

KCARS database provides a wide range of crash attributes such as crash severity, number of people involved by their severity level, contributory courses, accident type, accident location, first harmful event, most harmful event, weather and road surface conditions, and coordinates of the crash location. Using the database, it is possible to extract “fatal and injury” and “all severity" lane-departure crashes with coordinates of the accident location. Later, it can be exported into Excel and used in ArcGIS to map the crashes on Kansas road network.

3.2.1.2. CANSYS

CANSYS is the Kansas state highway system database that provides a wide range of geometric characteristics of the roadways such as lane width, number of lanes, road surface type, median type, median width, shoulder type, shoulder width, rumble strips, horizontal curvature and passing restrictions; traffic-related characteristics such as AADT, percent heavy commercial vehicles, and AADT of trucks and medium trucks; and other important information such as area type, terrain type, and coordinates of beginning and end of the road segment. This data can be used in ArcGIS and combined with the KCARS data to divide the road network into homogeneous road segments with respect to traffic and geometric characteristics on the roads.

Data obtained from CANSYS and KCARS databases were divided into three main categories: road geometry data, traffic-related data, and date of implementation. Methods of estimating CMFs were finalized after considering available data for each countermeasure. Table 3.1 shows availability of data fields for each countermeasure considered for this research and the proposed method of estimating CMFs for each countermeasure.

Table 3.1. Data availability of considered countermeasures on the Kansas Road Network

Selected Countermeasures with Road Type	**Road Geometry Data**	**Traffic-Related Data**	**Date of Implementation**	**Proposed Method of Safety Evaluation**
Paved shoulders (rural 2-lane road segments/4-lane divided-road segments)	Available	Available	Not Available	Cross- Sectional Method
Centerline rumble strip (rural 2-lane road segments)	Available	Available	Not Available	Cross- Sectional Method
Shoulder rumble strips (rural 2-lane road segments/4-lane divided-road segments)	Available	Available	Not Available	Cross- Sectional Method
Chevrons (rural 2-lane road segments)	Available	Available	Not Available	Cross -Sectional Method
Post-mounted delineators (rural 2-lane road segments)	Available	Available	Not Available	Cross- Sectional Method
Median cable barriers (4-lane road segments)	Available	Available	Not Available	Cross- Sectional Method
Safety edges (2-lane and 4-lane road segments)	Available	Available	Available	Before-and-After EB Method Before-and-After Regression Based Method

Based on Table 3.1, for paved shoulders and shoulder rumble strips on rural two-lane and four-lane road segments, centerline rumble strips on rural two-lane road segments and post-mounted delineators on two-lane road segments, and median cable barriers should employ cross-sectional or case-control methods to estimate their CMFs. Since safety edge treatment has the date of implementation, the proposed regression based method can be used to estimate CMFs and the EB method will be used to compare the CMFs obtained from the proposed regression based method.

The predictor variable for the cross-sectional method is crashes per segment per year. For the case-control method, the predictor variable is whether the considered segment is where a crash has occurred or not. Therefore, number of crashes in each segment were extracted and combined with geometric and traffic-related characteristics of the road. This section summarizes the data extracted for each countermeasure on different road segments using KCARS and CANSYS data.

3.2.1.3. Rumble strips and paved shoulders on rural two-lane and four-lane divided road segments

Step 1:

KCARS database was used to extract lane-departure crashes in Kansas from 2009 to 2014. Fatal and injury crashes and all severity lane-departure crashes were extracted separately from the database. Accident keys, latitudes, and longitudes were used to map the crash data on the Kansas road network using ArcGIS 10.1 software as shown in the Figure 3.2.

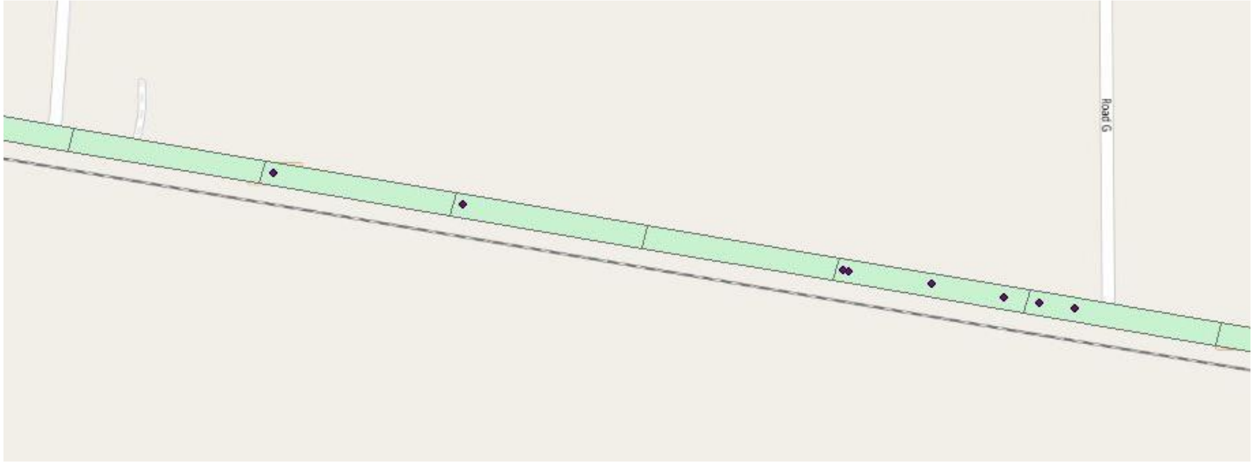
Step 2:

Geometric characteristics and traffic characteristics of the road network, including passing restrictions, area type, average lane width, rumble strips, posted speed, AADT, percent heavy commercial vehicles, median type, terrain type, horizontal curvature, number of lanes, beginning and ending mile posts of a homogeneous segment, AADT of medium trucks, AADT of heavy trucks, shoulder width, and shoulder type were exported into ArcGIS 10.1.

Figure 3.2. Lane-departure crashes on Kansas roadways from 2009 to 2014

Step 3:

By considering number of lanes, the road network was divided into several groups such as two-lane highways and four-lane highways. Then the buffer zones were created separately for those road segments to identify crashes within each buffer zone so that crashes in each segment could be identified. When creating a buffer zone, an allowance was made by selecting a higher buffer distance to include shoulder-related crashes and run-off-road crashes as shown in Figure 3.3.



© Google Maps 2015

Figure 3.3. Lane-departure crashes in buffered road segments of Kansas road network

Step 4:

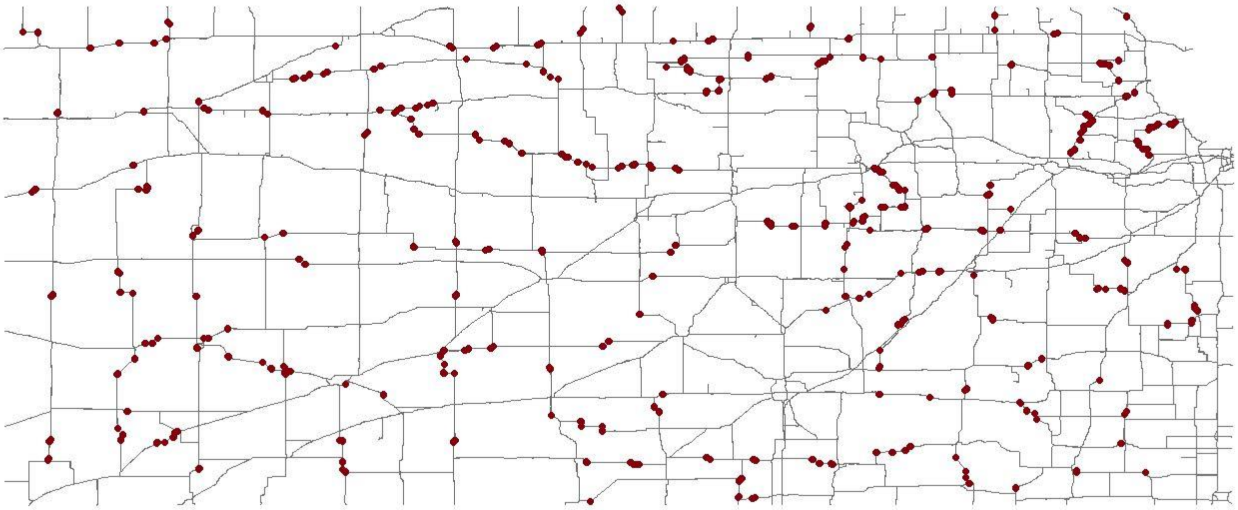
ArcGIS 10.1 was used to count the number of all lane-departure crashes, and fatal and injury lane-departure crashes, within each road segment. Furthermore, road geometric and traffic-related characteristics obtained from CANSYS database were combined with the respective road segments. Output was exported into Excel so that it could be used in SAS to develop models. Finally, segment lengths were calculated using beginning and ending mileposts of the road segments. However, HSM (Highway Safety Manual, 2010) provides guideline for the minimum length as 0.1 miles. Therefore, before developing models, segments less than 0.1 miles were removed from the dataset.

2.3.1.4.Chevrons and post-mounted delineators on two-lane-road segments

Following steps were employed to collect data manually from the Kansas road network and to extract impaired driving-related and weather and environmental—related information at county level.

Step 1:

Google Street View was used to locate curves with and without chevrons and post-mounted delineators, which were mapped on Google Earth as shown in the Figure 3.4.



© Google Maps 2015

Figure 3.4. Selected locations of chevrons and post-mounted delineators on Kansas two-lane roadways

Step 2:

Identified points were saved as a Keyhole Markup Language (KML) file, which was then imported into ArcGIS 10.1. The road network shape file with its attributes, all lane-departure crashes, and fatal and injury lane-departure crashes, were then imported into ArcGIS 10.1 as shown in Figure 3.5. Then the road segments with both chevrons and post-mounted delineators, road segments with chevrons or post-mounted delineators, and road segments without chevrons or post-mounted delineators were identified.

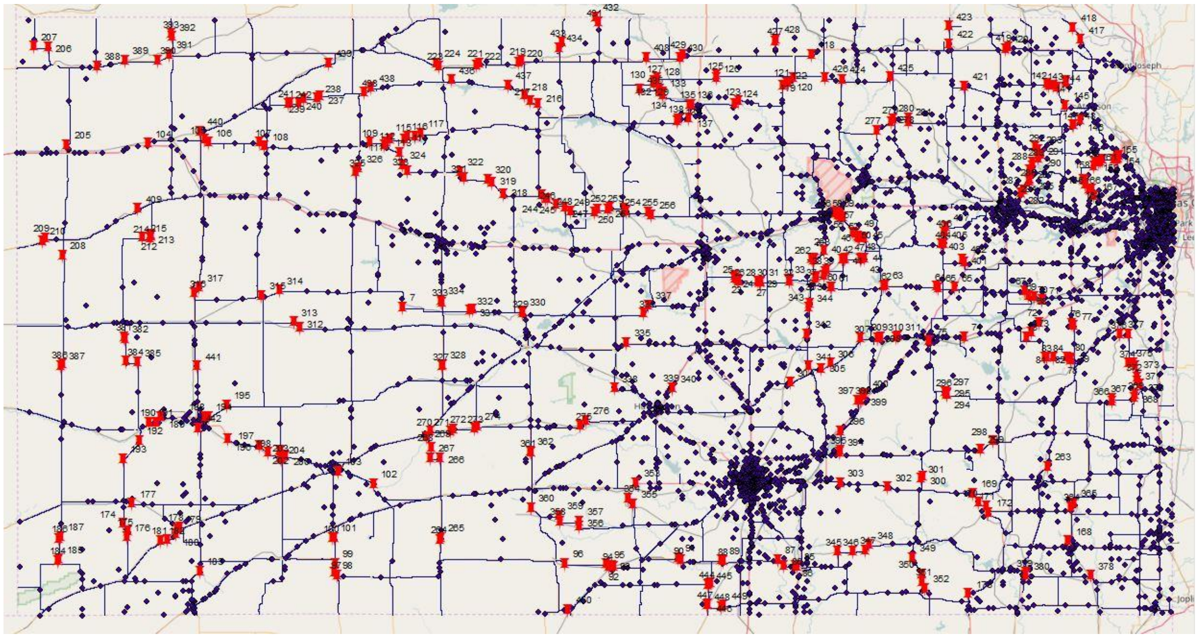


Figure 3.5. Location map of chevrons, post-mounted delineators, and crashes on Kansas two-lane roadways

Step 3:

Environmental-related information: Environment-related information cannot be found at the road segment level. Therefore, those information were found at county-level from 2013 to 2015 using National Oceanic and Atmospheric Administration (NOAA), National Weather Service (National Oceanic and Atmospheric Administration [NOAA], 2017). However, those information were available at weather station level. Therefore, Inverse Distance Weighted (IDW) interpolation was used to interpolate the weather station data throughout the county and the zonal statistics was used to estimate the annual average weather condition of the county using ArcGIS 10.1 (Childs, 2004; Soyal et al, 2012). Figure3.6 shows the interpolated rainfall dataset for the year 2013.

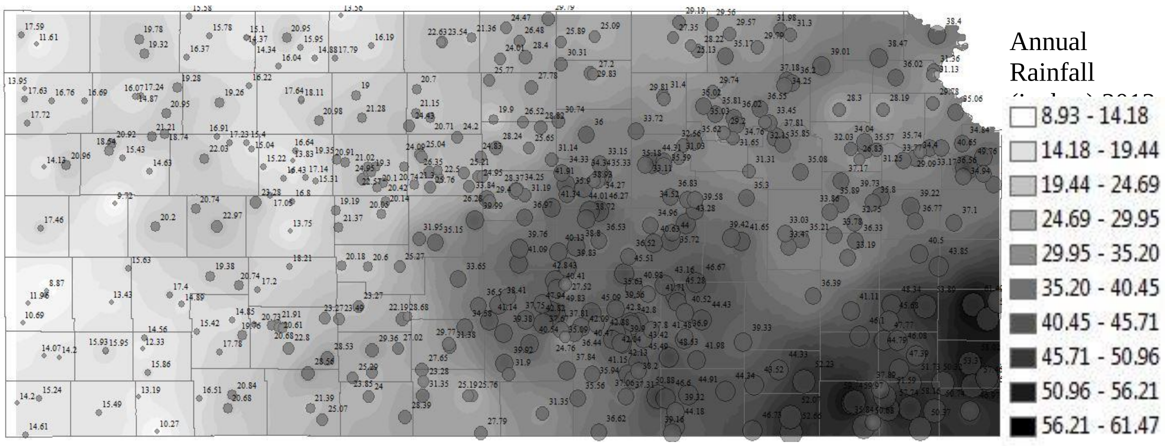


Figure 3.6. Inverse distance weighted interpolation of rainfall data in 2013

Driver-related information: County-level annual alcohol tax collected was used as an indicator variable to the driver behavior, specifically the impaired driver related crashes. County-level information on alcohol tax was obtained from US Census Bureau, American FactFinder (U.S. Census Bureau, 2017). Each road segment was assigned with the respective county-level annual alcohol tax calculated per adult.

Obtained county level information were then merged with the Kansas road network obtained from the CANSYS database using ArgGIS 10.1.

Step 4:

ArcGIS 10.1 was used to count the number of all lane-departure crashes, and fatal and injury lane-departure crashes from 2013 to 2015 within each road segment with their geometric and traffic-related characteristics. Output was exported into Excel so that it can be used in SAS to develop models. Finally, the segment lengths were calculated using beginning and ending mileposts of the road segment. However, HSM (Highway Safety Manual, 2010) provides guidelines for minimum section length as 0.1 miles. Therefore, before developing models, the segments shorter than 0.1 miles were removed from the dataset.

2.3.1.5.Cable median barriers on four-lane divided-road segments

The same dataset which was used to develop models for rumble strips and paved shoulders on four-lane-road segments were used for this model by selecting the road segments with cable median barriers. Since few road segments have median cable barriers, a comparison was done with the four-lane-road segments with rigid and semi-rigid barriers and depressed medians. Following are the steps used to extract data for developing models for cable median barriers.

Step 1:

Selected the road segments with median cable barriers, depressed medians, and rigid and semi-rigid median barriers.

Step 2:

To select the similar road segments to the road segments with cable median barriers, the whole dataset was filtered using median widths of 30’-39,’ 40’-49,’ and 50’-60’ lane widths equal to 12 feet, posted speed limits of 60mph and 70mph, area type urban, shoulder rumble strips, and paved shoulders. Also, road segments less than 0.1 mile were removed as specified in HSM.

Safety edge treatments on rural, two-lane, undivided-road segments

Information on road segments with safety edge treatments were obtained by contacting KDOT district engineers. Five such locations were identified with their dates of implementation and other treatments within the analysis period are listed below.

I. US 69 Miami/Linn County line north 4.68 miles in 2015

II. US 36 from east US36/K383 Junction to the Phillips County in 2011

III. K 23 from the Lane County line to 0.5miles south of Grove in 2010

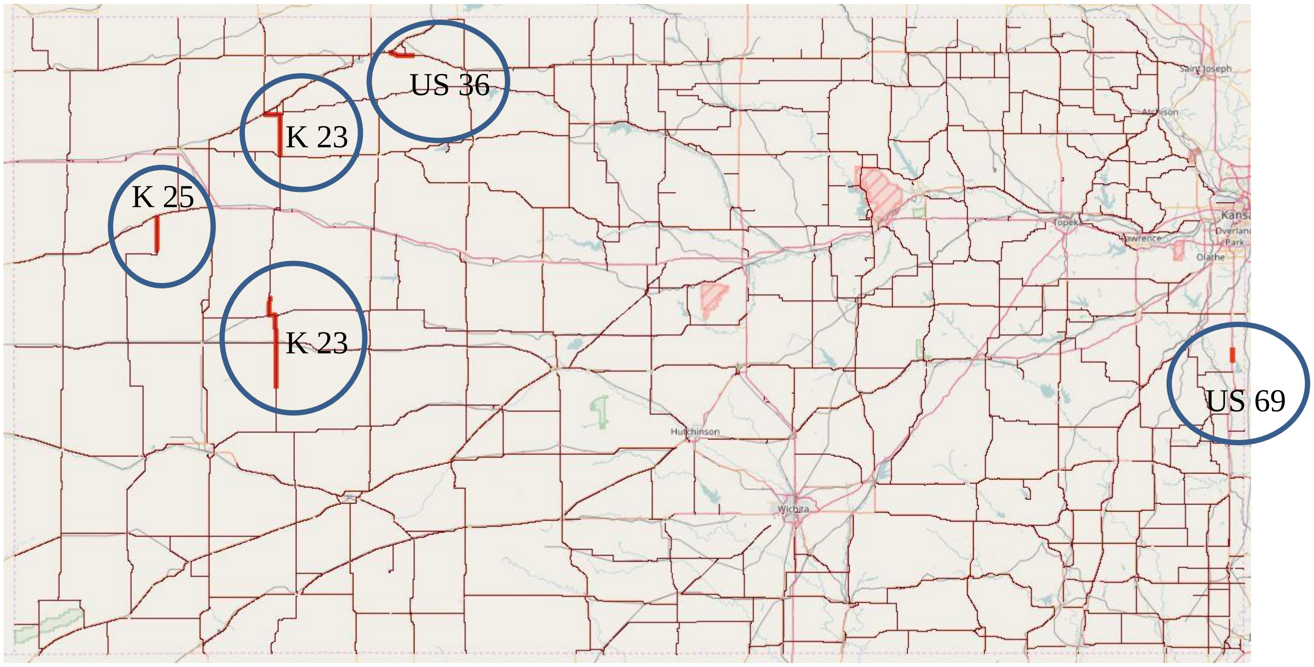
IV. K 25 from Russell Spring to US 40 in 2012

V. K 23 from Hoxie to the US 83/K 383 junction in 2012

Since date of implementation of the safety edge treatment is known, it was decided to employ regression based before-and-after method to estimate CMFs. EB study approach was used to estimate CMFs and to check the similarity of the CMFs obtained from regression based before-and-after method. However, the US 69 road segment was not considered since the after-crash data aren't available at the time of this study. The following steps were taken when extracting data to evaluate the safety effectiveness of the safety edge treatments.

Step 1:

Road segments with the safety edge treatments were identified and mapped on Google Earth. Locations were saved as a KML file to import into ArcGIS 10.1. Figure 3.7 shows the locations with the safety edge treatments after mapped on ArcGIS 10.1.



© Google 2015

Figure 3.7. Road segments with safety edge treatments

Step 2:

Lane-departure crashes were mapped together with the year of crashes using data from the KCARS database. Also, geometric and traffic characteristics in the CANSYS database were used to divide the long road stretch with safety edge treatment into homogeneous road segments. Figure 3.8 shows the mapped crashes on K 23 from the Lane County line to 0.5 miles south of Grove.

Step 3:

Finally, all lane-departure crashes, and fatal and injury lane-departure crashes, each year from 2007 to 2015 were counted in each homogeneous road segment separately; the output was exported into an Excel spread sheet. However, the HSM (Highway Safety Manual, 2010) provides guidelines for the minimum length as 0.1 miles. Therefore, before developing models, segments less than 0.1 miles were removed from the dataset.

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Figure 3.8. Mapped crashes on K-23 from Lane County line to 0.5 miles south of Grove

Step 4:

Finally, the rural two-lane undivided-road segments with no rumble strips, AADT of less than 1,900 vehicles/day, and percentage of heavy vehicles between 10% to 50% were selected as the reference sites to fit the generalized linear regression models to predict before-and-after crashes.

3.2.2. Model variables

After extracting data for each roadway type, correlation matrices were developed for each dataset to identify the multi-collinearity among explanatory variables. If the correlation coefficient was greater than 0.5 between two explanatory variables, those were considered to have multi-collinearity. Therefore, one of the variables was removed. Then the variables for the final models were finalized.

3.2.2.1. Rumble strips and paved shoulders on two-lane-road segments

According to the correlation matrix developed for two-lane rural road segments, AADT correlated with AADT of medium trucks (0.706) and AADT of heavy trucks (0.729) for tangent and curved-road segments. AADT of heavy trucks also correlated with rumble strips (-0.659) and paved shoulders (0.565). Therefore, AADT of medium trucks and AADT of heavy trucks were removed from consideration when developing the models. The final dataset contained nine variables including five categorical variables and four continuous variables, namely passing restriction, average lane width, rumble strips, posted speed, AADT, percent heavy commercial vehicles, horizontal curvature, shoulder type, and segment length. Reference levels for categorical variables were selected as no no-passing; lane width less than 12 feet; no rumble strips; posted speed less than 60 mph; and no paved shoulders for the categorical variables of passing restrictions, average lane width, rumble strips, posted speed, and shoulder type.

3.2.2.2. Rumble strips and paved shoulders on four-lane divided-road segments

Correlation matrix developed for four-lane divided-road segments showed posted speed limits of 60-65mph and 70-75mph (-0.74) and percent heavy commercial vehicles, and posted speed limits of 70-75mph (0.52) have high multi-collinearity. Therefore the speed limit of 70-75mph variable was removed from the dataset. The final dataset contained 12 variables, which included eight categorical and four continuous variables, namely passing restrictions, median type, area type, average lane width, rumble strips, posted speed, terrain type, AADT, percent heavy commercial vehicles, horizontal curvature, shoulder type, and segment length. Models were developed afterwards by considering crashes per year per segment from 2009 to 2014 as a predictor variable. Before developing the models, the entire dataset was divided into one-third and two-thirds of datasets for model building and model validation. For all lane-departure crashes on tangent and curved-road segments, data were used to develop models without paying any regards to outliers. However, many outliers were found in the dataset extracted using fatal and injury lane-departure crashes for tangent and curved-road segments. Therefore, the Cook’s distance was used to remove the outliers from the dataset used in developing the model. Reference levels for categorical variables were set as the no no-passing, painted median, area type urban, average lane width equal to or less than 12 feet, no rumble strips, posted speed limit less than 60 mph, terrain type rolling, and no paved shoulders for the categorical variables of passing restrictions, median type, area type, average lane width, rumble strips, posted speed, terrain type, and shoulder type. Four models were developed using all lane-departure crashes and fatal and injury lane-departure crashes on tangent and curved-road segments.

3.2.2.3. Chevrons and post-mounted delineators on two-lane-road segments

Correlation matrix developed for the explanatory variables considered for two-lane-road segments showed paved shoulders ≥2_ft correlated with AADT (0.59) and chevrons (-0.52). Therefore, the paved shoulders ≥2_ft variable was removed from the dataset. The final dataset contained 13 variables including nine categorical and four continuous variables, namely passing restrictions, area type, average lane width, rumble strips, posted speed, terrain type, AADT, percent heavy commercial vehicles, horizontal curvature, segment length, chevrons, post-mounted delineators, and both chevrons and post-mounted delineators. Models were developed afterwards by considering crashes per year per segment from 2009 to 2014 as a predictor variable. Reference levels for categorical variables used in developing models were set as no no-passing, area type urban, average lane width of less than 12 feet, no rumble strips, terrain type rolling, and no chevrons or post-mounted delineators for categorical variables of passing restrictions, area type, average lane width, rumble strips, posted speed, terrain type, chevrons, and post-mounted delineators. Before developing the models, the whole dataset was divided into one-third and two-thirds of datasets for model building and model validation.

3.2.2.4. Cable median barriers on four-lane divided-road segments

When considering the cable median barrier, the sample size was not large enough to develop models for the curved-road segments. Therefore, the models were only developed for the tangent road segments using all lane-departure crashes, and fatal and injury lane-departure crashes. Before developing the models, multi-collinearity was checked among explanatory variables. A correlation matrix was developed for the explanatory variables considered for four-lane divided-road segments. Posted speed limits were correlated with terrain type (-0.535) and median width of 40-49 feet (-0.586). Therefore, posted speed limit was removed from the dataset. The final dataset contained seven variables which included three categorical and four continuous variables, namely terrain type, median width, barrier type, AADT, percent heavy commercial vehicles, segment length, and side-slope gradient. Models were developed afterward by considering crashes per year per segment from 2009 to 2014 as a predictor variable. Reference levels of the categorical variables were set as terrain type rolling, median width of 30-39 feet, and depressed median for categorical variables of terrain type, median width, and barrier type.

3.2.2.5. Safety edge treatments on rural two-lane undivided-road segments

Since it was decided to estimate CMFs based on the regression method using before-and-after data for all lane-departure crashes and fatal and injury lane- departure crashes, generalized linear regression models were developed as shown in Equations 1-6. Explanatory variables were selected and checked for the multi-collinearity effect. No multi- collinearity effect was found among considered explanatory variables. The final dataset contained eight variables, namely AADT, segment length, passing restrictions, lane width, speed limit, percentage of commercial vehicles, paved shoulders, and horizontal curvature.

Chapter 4 Results and Model Validation

This section summarizes results of the different methods used to estimate CMFs and validation of the obtained results.

4.1. Rumble strips and paved shoulders on two-lane road segments

4.1.1. Descriptive statistics

Descriptive statistics were calculated for categorical and continuous variables, which had been identified as model variables in the preliminary stage. Levels in some categorical variables were combined, since some levels did not have enough sample size. There were 22,060 tangent road segments and 6,442 curved-road segments with total lengths of 9,027 miles and 1,468 miles, respectively, considered in developing models. Tables 4.1 and 4.2 show descriptive statistics of continuous and categorical variables identified as potential explanatory variables to develop models for rumble strips and paved shoulders on two-lane-road segments.

Table 4.1. Descriptive statistics of continuous variables used in the model for rumble strips and paved shoulders on two-lane-road segments

Continuous Variables	**Tangent Road Segments**				**Curved Road Segments**			
	Min	**Max**	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**
AADT (vehicles per day)	30	15,900	1,596	1,419	50	8,550	1,721	1,475
Percentage of Commercial Heavy Vehicles (%)	1.26	73.58	19.33	10.38	2	73.58	19.05	10.05
Segment Length (miles)	0.1	10.60	0.40	0.68	0.1	2.29	0.28	0.22
Horizontal Curvature (Degree of curvature)	*na**	*na**	*na**	*na**	0.1	133.25	3.37	7.07

na-not applicable for the developed model, Min/Max-Minimum/Maximum, Avg-Average, SD-Standard Deviation*

Table 4.2. Descriptive statistics of categorical variables used in the model for rumble strips and paved shoulders on two-lane-road segments

Categorical Variables	Tangent Road Segments			Curved-Road Segments		
	Number of Segments	Total Length of Segments (miles)	Percentage of Length (%)	Number of Segments	Total Length of Segments (miles)	Percentage of Length (%)
Passing Restrictions (both directions)	3,544	934	10.35	1,895	145	9.77
Passing Restrictions (one direction)	11,407	2,420	26.81	3,561	806	54.21
No No-Passing Zones	7,110	5,673	62.84	986	518	34.81
Lane Width (<12-ft)	2,872	913	10.11	671	88	5.99
Lane Width (≥12-ft)	19,188	8,115	89.89	5,751	1,380	94.01
Speed Limit (<60 mph)	5,729	1,489	16.49	2,004	500	33.69
Speed Limit (≥60 mph)	16,332	7,538	83.51	4,438	986	66.31
Centerline Rumble Strips	1,906	1,055	11.68	665	486	32.71
Centerline and Shoulder Rumble Strips	1,016	598	6.62	280	118	7.91
Shoulder Rumble Strips	1,980	1,070	11.85	757	232	15.60
No Rumble Strips	17,159	6,304	69.84	4,740	651	43.78
2-ft Paved Shoulder (both sides)	9,205	7,787	53.02	3,188	742	49.91
No Paved Shoulders	12,856	4,241	46.98	3,254	745	50.09

4.1.2. Models developed using lane-departure crashes

4.1.2.1. Cross-sectional method

SAS 9.4 (SAS Institute, 2014) was used to develop two models each for tangent and curved-road segments using all lane-departure crashes and fatal and injury lane-departure crashes from 2009 to 2014. Table 4.3 shows parameters estimated for the final models, which were developed using the cross-sectional method with standard deviation and *p*-value of the estimates.

Even though the centerline rumbles strips, and both centerline and shoulder rumble strips were insignificant in some models, those variables were kept in the models, as had been done in previous research which also used the cross sectional method (Gross & Jovanis, 2007; Gross & Donnell, 2011). The major reason for keeping these insignificant variables was that those were the countermeasures to be evaluated where parameter estimates were used to estimate CMFs. Therefore, entry and exist values were increased when using the step-wise method to develop models by giving every variable an equal chance.

Estimated regression parameters for the presence of 2-ft paved shoulders on both sides, centerline rumble strips, shoulder rumble strips, and both shoulder and centerline rumble strips were transformed into CMFs using the expression, $CMF = exp(\beta)$(Gross et al., 2010). A CMF less than 1 implied the respective treatment had reduced the number of crashes on those road segments. Maximum and minimum values for CMFs were calculated using the standard error and the results are shown in Table 4.4.

Table 4.3. Parameter estimates of the model developed using the cross-sectional method for rural two-lane-road segments

Variables	All Lane-Departure Crashes				Fatal and Injury Lane- Departure Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
	Parameter Estimate	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**
Intercept	0.552	0.025 (<.0001)	0.483	0.036 (<.0001)	0.564	0.037 (<.0001)	0.390	0.0630 (<.0001)
Passing Restrictions (both directions)	0.057	0.026 (0.026)	*ns**	*ns**	-0.283	-0.289 (<.0001)	-0.090	0.039 (0.021)
Passing Restrictions (one direction)	0.047	0.022 (0.038)	*ns**	*ns**	-0.182	-0.187 (<.0001)	-0.062	0.041 (0.131)
Speed Limit ≥ 60 mph	0.050	0.022 (0.025)	0.030	0.029 (0.285)	0.030	0.023 (0.205)	*ns**	*ns**
Lane Width ≤ 12_ft	*ns**	*ns**	*ns**	*ns**	*ns**	*ns**	0.183	0.071 (0.010)
Percentage of Commercial Heavy Vehicles	-0.002	0.001 (0.022)	*ns**	*ns**	*ns**	*ns**	-0.002	0.001 (0.145)
Centerline Rumble Strips	-0.039	0.027 (0.153)	-0.062	0.047 (0.193)	-0.039	0.027 (0.149)	-0.051	0.039 (0.195)
Shoulder Rumble Strips	-0.062	0.027 (0.024)	-0.047	0.050 (0.347)	-0.051	0.027 (0.060)	-0.060	0.038 (0.113)
Centerline and Shoulder Rumble Strips	-0.154	0.038 (<.0001)	-0.120	0.039 (0.004)	-0.059	0.037 (0.111)	-0.134	0.067 (0.046)
2-ft Paved Shoulder	-0.126	0.021 (<.0001)	-0.112	0.033 (0.008)	-0.058	0.022 (0.009)	-0.074	0.041 (0.072)
Horizontal Curvature	na*	na*	-0.004	0.002 (0.136)	na*	na*	0.036	0.007 (<.0001)
ln(Segment length)	0.274	0.010 (<.0001)	0.132	0.016 (<.0001)	0.233	0.013 (<.0001)	0.149	0.023 (<.0001)
ln(AADT)	0.209	0.013 (<.0001)	0.025	0.018 (0.160)	0.077	0.013 (<.0001)	0.089	0.024 (.0002)

ns-not significant for the developed model, na*-not applicable for the developed model*

Table 4.4. CMFs for paved shoulders and rumble strips using the cross-sectional method for rural two-lane-road segments

Countermeasures	All Lane- Departure Crashes		Fatal and Injury Lane-Departure Crashes	
	Tangent Road Segments	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
	CMF (CMF_{min}, CMF_{max})	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**
Centerline Rumble Strips	0.96 (0.94,0.99)	0.94 (0.90,0.99)	0.96 (0.94,0.99)	0.95 (0.91,0.99)
Shoulder Rumble Strips	0.94 (0.91,0.97)	0.95 (0.91,1.01)	0.95 (0.92,0.98)	0.94 (0.91,0.98)
Centerline and Shoulder Rumble Strips	0.86 (0.83,0.89)	0.89 (0.85,0.92)	0.94 (0.91,0.98)	0.87 (0.82,0.94)
2-ft Paved Shoulder (both sides)	0.88 (0.86,0.90)	0.89 (0.87,0.92)	0.94 (0.92,0.96)	0.93 (0.89,0.97)

According to results of the cross-sectional method, centerline and shoulder rumble strips can be identified together as the most effective countermeasure in reducing the number of all lane-departure crashes, and fatal and injury lane-departure crashes in tangent and curved-road segments. Even though the CMF for shoulder rumble strips for all lane-departure crashes in curved-road segments is 0.95, it might not always reduce number of lane- departure crashes since the range of CMF includes 1.

Similarly, CMFs were developed using all crash types on tangent and curved road segments as shown in Appendix A. Parameter estimates of the developed models and the estimated CMFs are shown in Appendixes A1 and A2, respectively.

4.1.2.2. Case-control method

Two models were developed for tangent and curved-road segments using SAS 9.4 (SAS Institute, 2014) for all lane-departure crashes, and fatal and injury lane-departure crashes. Model parameter estimates with the standard deviation and *p*-value of each estimate, are presented in Table 4.5. Odds ratios were calculated using estimated parameters.

Table 4.5. Parameter estimates of the model developed using the case-control method for rural two-lane-road segments

Variables	All Lane-Departure Crashes				Fatal and Injury Lane- Departure Crashes			
	Tangent Road Segments		Curved-Road Segments		Tangent Road Segments		Curved-Road Segments	
	Parameter Estimate	Standard Error (p-value)	Parameter Estimate	Standard Error (p-value)	Parameter Estimate	Standard Error (p-value)	Parameter Estimate	Standard Error (p-value)
Intercept	-1.890	0.080 (<.0001)	-1.883	0.119 (<.0001)	-2.762	0.100 (<.0001)	-3.079	0.136 (<.0001)
Passing Restrictions (both directions)	-0.047	0.067 (0.500)	-0.116	0.110 (0.291)	-0.064	0.090 (0.479)	*ns**	*ns**
Passing Restrictions (one direction)	-0.319	0.055 (<.0001)	0.091	0.104 (0.380)	-0.418	0.083 (<.0001)	*ns**	*ns**
Speed Limit ≥60 mph	0.081	0.059 (0.166)	0.134	0.098 (0.173)	0.313	0.077 (<.0001)	*ns**	*ns**
Percentage of Commercial Heavy Vehicles	-0.017	0.003 (<.0001)	*ns**	*ns**	-0.011	0.003 (0.0014)	*ns**	*ns**
Centerline Rumble Strips	-0.093	0.086 (0.284)	-0.137	0.152 (0.367)	-0.121	0.103 (0.242)	-0.125	0.177 (0.478)
Shoulder Rumble Strips	-0.164	0.084 (0.049)	0.223	0.164 (0.176)	-0.109	0.100 (0.272)	-0.211	0.172 (0.172)
Centerline and Shoulder Rumble Strips	-0.381	0.116 (0.001)	-0.294	0.247 (0.233)	-0.314	0.134 (0.019)	-0.679	0.258 (0.008)
2-ft Paved Shoulder (both sides)	-0.201	0.060 (0.009)	-0.414	0.107 (<.0001)	-0.169	0.074 (0.022)	-0.235	0.137 (0.087)
Horizontal Curvature (degree of curvature)	na*	na*	-0.011	0.007 (0.097)	na*	na*	0.095	0.020 (<.0001)
AADT (vehicles per day)	0.367	0.020 (<.0001)	0.044	0.036 (0.215)	0.301	0.022 (<.0001)	0.327	0.040 (<.0001)
Segment Length (miles)	1.092	0.054 (<.0001)	2.527	0.186 (<.0001)	0.888	0.044 (<.0001)	2.054	0.210 (<.0001)

ns-not significant for the developed model, na*-not applicable for the developed model*

Since no rumble strips and no paved shoulders were set as reference levels for rumble strips and paved shoulders, odds ratios can be directly considered as the CMF. Calculated CMFs for the four countermeasures are shown in Table 4.6, with maximum and minimum values for CMF. The same as in the cross-sectional method, some important variables needed to be in the model to estimate the CMFs where respective countermeasures were insignificant. To keep them in the model, entry and exist values were increased in step-wise method when developing models, so that every variable had an equal chance. As a result of this, AADT in one model became insignificant (p-value = 0.26) in one of the developed models.

Table 4.6. CMFs for paved shoulders and rumble strips using the case-control method for rural two-lane-road segments

Countermeasures	**All Lane-Departure Crashes**		**Fatal and Injury Lane-Departure Crashes**	
	Tangent Road Segments	**Curved-Road Segments**	**Tangent Road Segments**	**Curved-Road Segments**
	CMF (CMF_{min}, CMF_{max})	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**
Centerline Rumble Strips	0.91 (0.84,0.99)	0.87 (0.75,1.02)	0.89 (0.80,0.98)	0.88 (0.74,1.05)
Shoulder Rumble Strips	0.85 (0.78,0.92)	1.25 (1.06,1.47)	0.90 (0.81,0.99)	0.81 (0.68,0.96)
Centerline and Shoulder Rumble Strips	0.68 (0.61,0.77)	0.75 (0.58,0.95)	0.73 (0.64,0.84)	0.51 (0.39,0.66)
2-ft Paved Shoulder (both sides)	0.82 (0.77,0.87)	0.66 (0.59,0.74)	0.84 (0.78,0.91)	0.79 (0.69,0.91)

Results shown in Table 4.6 indicates that centerline and shoulder rumble strips, and 2-ft paved shoulders have greater effect on reducing all lane-departure, and fatal and injury lane-departure crashes on both tangent and curved-road segments. It is difficult to identify the crash-reduction effect of centerline rumble strips, because ranges of CMFs include 1, except for the CMF of fatal and injury lane-departure crashes in tangent road segments. Shoulder rumble strips turned out to be ineffective in reducing all severity of lane-departure crashes on curved-road segments.

Similarly, CMFs were developed using all crash types on tangent and curved road segments. Parameter estimates of the developed models and the estimated CMFs are shown in Appendixes A3 and A4, respectively.

4.1.3. Validation of the models developed using lane-departure crashes

4.1.3.1. Cross-sectional method

Model validation was carried out using two commonly used criteria — check the mean of the residuals and MSE after fitting the estimated model, using the validation dataset as mentioned in the methodology. Table 4.7 shows the calculated MSE and mean of the residuals for the validation dataset, and the MSE obtained for the model using the model-building dataset. Based on results in Table 4.7, it can be clearly seen that in all models, mean of the residuals are close to zero, and MSE of the validation dataset are approximately equal to the model MSE. Therefore, the developed models using the cross-sectional method are accurate enough to predict lane-departure crashes in two-lane-rural highways; hence, the estimated CMFs based on estimated regression parameters were accurate. Similarly, Appendix A5.1 shows the model validation statistics calculated for the cross-sectional models developed using all crash types on tangent and curved road segments.

Table 4.7. Model validation for models developed using the cross-sectional method for two-lane rural-road segments

Validation Statistics	**All Lane-Departure Crashes**				**Fatal and Injury Lane- Departure Crashes**			
	Tangent Road Segments		**Curved-Road Segments**		**Tangent Road Segments**		**Curved-Road Segments**	
	Model	**Validation Dataset**	**Model**	**Validation Dataset**	**Model**	**Validation Dataset**	**Model**	**Validation Dataset**
MSE	0.207	0.110	0.126	0.075	0.117	0.082	0.088	0.096
Mean of the Residuals	-	0.176	-	0.193	-	0.100	-	0.271

4.1.3.2. Case-control method

A Receiver Operational Characteristic (ROC) was used to evaluate the predictive power of models for a binary outcome. Classification tables were used to implement this method as mentioned in the methodology. Table 4.8 shows calculated accuracy, sensitivity, and specificity for the developed models using the case-control method. Based on these results, it is seen that the developed models predict the outcome with an accuracy close to 90%, while predicting no crashes with an accuracy of more than 90%. Furthermore, the developed models predict crash events more with the accuracy of 50%, which is reasonable for such models. Similarly, Appendix A5.2 shows the model validation statistics calculated for the case-control models developed using all crash types on tangent and curved road segments.

Table 4.8. Model validation for models developed using the case-control method for two-lane rural-road segments

Validation Statistics	All Lane-Departure Crashes		Fatal and Injury Lane- Departure Crashes	
	Tangent Road Segments	Curved-Road Segments	Tangent Road Segments	Curved-Road Segments
Accuracy	0.86	0.85	0.92	0.90
Sensitivity	0.66	0.61	0.51	0.50
Specificity	0.92	0.92	0.98	0.96

4.2. Rumble strips and paved shoulders on four-lane divided road segments

4.2.1. Descriptive statistics

There were 12,065 tangent road segments and 4,095 curved-road segments, with total length of 2,316 miles and 597 miles, respectively, considered for developing models. It seemed some levels of categorical variables had small sample sizes. Therefore, those levels were combined for use as categorical variables for the model. Table 4.9 shows the categorical variables used in the model after combining some levels, and Table 4.10 shows the descriptive statistics of continuous variables.

Table 4.9. Descriptive statistics of categorical variables used in the model for shoulder rumble strips and paved shoulders on four-lane divided-road segments

Categorical Variables	Tangent Road Segments			Curved-Road Segments		
	Number of Segments	**Total Length of Segments (miles)**	**Percentage of Length**	**Number of Segments**	**Total Length of segments (miles)**	**Percentage of Length**
Median Barrier	2,053	358	15.46	808	105	17.59
Depressed Median	9,223	1,851	79.92	2,993	459	76.88
Other Medians	789	107	4.62	294	33	5.53
No Passing Restrictions	12,039	2,314	99.86	4,087	596	99.83
Passing is restricted	26	3	0.14	8	1	0.17
Rural	8,417	1,716	74.05	2,550	411	68.86
Urban	3,648	601	25.95	1,545	186	31.14
Lane Width ≤ 12_ft	11,655	2,260	97.57	3,984	586	98.07
Lane Width >12_ft	410	56	2.43	111	12	1.93
Speed Limit < 60mph	1,251	176	7.61	416	45	7.59
Speed Limit 60_65mph	2,026	364	15.73	772	102	17.09
Speed Limit 70_75mph	8,788	1,776	76.66	2,907	450	75.32
Paved Shoulders ≥ 2_ft and Shoulder Rumble Strips	10,853	1,972	85.11	3,303	478	80.20
Only Paved Shoulders ≥ 2_ft	602	258	11.14	698	110	18.46
No Paved Shoulders	283	41	1.77	13	1	0.17
Curb and Gutter	327	46	1.99	81	7	1.17
Flat Terrain	7,687	1,453	62.72	2,673	385	64.48
Rolling Terrain	4,378	864	37.28	1,422	212	35.52

Table 4.10. Descriptive statistics of continuous variables used in the model for rumble strips and paved shoulders on four-lane divided-road segments

Continuous Variables	**Tangent Road Segments**				**Curved-Road Segments**			
	Min	**Max**	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**
Segment Length (miles)	0.10	2.00	0.19	0.23	0.10	1.00	0.15	0.12
AADT (vehicles/day)	570	80,400	15,258	10,302	1,050	72,900	16,149	11,149
Percent Heavy Commercial Vehicles (vehicles/day)	1.76	39.89	18.99	9.31	1.58	39.89	17.42	8.66
Horizontal Curvature (degree of curvature)	*na**	*na**	*na**	*na**	0.06	23.00	1.13	1.35

na - not applicable for the corresponding road segments*

4.2.2. Results

4.2.2.1. Cross-sectional method

SAS 9.4 (SAS Institute, 2014) was used to develop two models each, for tangent and curved-road segments, using all lane-departure crashes, and fatal and injury lane-departure crashes from 2009 to 2014. Table 4.11 shows parameter estimates for the final models developed using the cross-sectional method with standard deviations and *p*-values of the estimates.

Similar to previous models developed for rural two-lane-road segments, shoulder rumble strips and paved shoulders ≥2_ft became insignificant for the 0.1 significant level in some models. However, it is necessary to include the variable into the models to estimate CMFs of shoulder rumble strips and paved shoulders ≥2_ft. Therefore, entry and exist levels were increased when using the step-wise method so that every variable had an equal chance. As a result, area type and percent heavy commercial vehicles had to be included in the models, even though p-values of those variables were higher.

Table 4.11. Parameter estimates of models developed using the cross-sectional method for shoulder rumble strips and paved shoulders on four-lane divided-road segments

Variables	**All Lane-Departure Crashes**				**Fatal and Injury Lane- Departure Crashes**			
	Tangent Road Segments		**Curved-Road Segments**		**Tangent Road Segments**		**Curved-Road Segments**	
	Parameter Estimate	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**
Intercept	1.135	1.135 (<0.0001)	1.880	0.234 (<0.0001)	-0.717	0.171 (<0.0001)	0.637	0.231 (0.006)
Depressed Median	0.056	0.056 (0.002)	*ns**	*ns**	0.395	0.023 (<0.0001)	-0.229	0.030 (<0.0001)
Passing Restricted	*ns**	*ns**	-0.767	0.269 (0.005)	*ns**	*ns**	*ns**	*ns**
Area Type (rural)	0.032	-0.032 (0.113)	0.043	0.031 (0.169)	-0.036	0.026 (0.172)	0.288	0.037 (<0.0001)
Shoulder Rumble Strips and Paved Shoulders ≥2_ft	-0.089	-0.089 (0.0002)	-0.045	0.034 (0.180)	-0.693	0.029 (<0.0001)	-1.220	0.041 (<0.0001)
Only Paved Shoulders ≥2_ft	0.069	0.069 (0.068)	-0.169	0.083 (0.042)	-0.362	0.028 (<0.0001)	-1.046	0.046 (<0.0001)
Terrain Type (flat)	*ns**	*ns**	*ns**	*ns**	0.307	0.019 (<0.0001)	-0.069	0.024 (0.004)
Ln (segment length)	0.026	-0.026 (0.01)	0.039	0.021 (0.061)	0.282	0.010 (<0.0001)	0.247	0.020 (<0.0001)
Ln (AADT)	-0.162	-0.162 (<0.0001)	-0.195	0.023 (<0.0001)	-0.027	0.017 (0.121)	-0.132	0.023 (<0.0001)
% Heavy Commercial Vehicles	-0.003	-0.003 (0.006)	-0.003	0.002 (0.153)	0.005	0.001 (0.0002)	-0.004	0.002 (0.002)
Horizontal Curvature	*na**	*na**	-0.014	0.008 (0.092)	*na**	*na**	*ns**	*ns**

ns-not significant for the developed model, na*-not applicable for the developed model*

After developing the models, CMFs were estimated using the expression, CMF= exp(β), where β is the estimated regression parameter for the corresponding variable. Table 4.12 shows the estimated CMFs with their maximum and minimum estimated CMFs. Results showed that shoulder rumble strips and paved shoulders ≥2_ft had a greater effect on reducing both all lane-departure crashes, and fatal and injury lane-departure crashes. Paved shoulders without rumble strips ≥2_ft also showed a crash-reduction effect, except for all lane-departure crashes on tangent road segments. Similarly, Models were developed for all crash types on tangent and curved road segments. The estimated regression parameters and the CMFs are shown in Appendices B1 and B2.

Table 4.12. CMFs for paved shoulders and rumble strips using the cross-sectional method

Countermeasures	**All lane- departure crashes**		**Fatal and injury lane- departure crashes**	
	Tangent Road Segments	**Curved-Road Segments**	**Tangent Road Segments**	**Curved-Road Segments**
	CMF (CMF_{min}, CMF_{max})	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**
Shoulder Rumble Strips and Paved Shoulders ≥2_ft	0.91 (0.84,1.00)	0.96 (0.92,0.99)	0.50 (0.49,0.51)	0.30 (0.28,0.31)
Paved Shoulders without Rumble Strips ≥2_ft	1.07 (1.00,1.15)	0.84 (0.78,0.92)	0.70 (0.68,0.72)	0.35 (0.34,0.37)

4.2.2.2. Case-control method

Two models each, for tangent and curved-road segments, were developed using SAS 9.4 (SAS Institute, 2014) for all lane-departure crashes, and fatal and injury lane -departure crashes. Model parameter estimates with standard deviations and *p*-values of each estimate are presented in Table 4.13. Similar to the previously mentioned cross-sectional models, shoulder rumble strips and paved shoulders ≥2_ft and paved shoulders ≥2_ft without rumble strips became insignificant for the 0.1 significant level in some models. Since those variables must be in the models to estimate the CMFs, entry and exist values of the step-wise method were increased when developing the models. As a result, posted speed limit and average lane width had to be included in the models, even though the p-values of those variables were higher.

Table 4.13. Parameter estimates of the model developed using the case-control method of shoulder rumble strips and paved shoulders on four-lane divided-road segments

Variables	**All Lane-Departure Crashes**				**Fatal and Injury Lane- Departure Crashes**			
	Tangent Road Segments		**Curved-Road Segments**		**Tangent Road Segments**		**Curved-Road Segments**	
	Parameter Estimate	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**	**Parameter Estimate**	**Standard Error (p-value)**
Intercept	-1.89	0.156 (<.0001)	-2.50	0.311 (<.0001)	-6.95	0.938 (<.0001)	-3.15	0.449 (<.0001)
Depressed Median	-0.38	0.063 (<.0001)	-0.37	0.107 (0.0006)	-1.56	0.537 (0.004)	-0.31	0.182 (0.088)
Passing Restricted	ns*	ns*	1.56	0.788 (0.047)	ns*	ns*	ns*	ns*
60_65mph	0.28	0.126 (0.024)	0.28	0.228 (0.223)	ns*	ns*	0.69	0.435 (0.111)
Average Lane Width >12_ft	0.19	0.165 (0.247)	ns*	ns*	ns*	ns*	ns*	ns*
Area Type (Rural)	ns*	ns*	ns*	ns*	-2.16	0.768 (0.005)	-0.25	0.210 (0.232)
Shoulder Rumble Strips and Paved Shoulders ≥2_ft	-0.22	0.137 (0.101)	-0.08	0.301 (0.793)	-1.14	0.904 (0.205)	-1.17	0.515 (0.023)
Paved Shoulders ≥2_ft without Rumble Strips	-0.10	0.146 (0.500)	-0.30	0.308 (0.328)	-0.29	0.942 (0.755)	-0.92	0.509 (0.071)
Terrain Type (Flat)	0.10	0.05 (0.050)	ns*	ns*	ns*	ns*	-0.22	0.160 (0.164)
Segment Length	1.05	0.104 (<.0001)	0.57	0.360 (0.116)	4.26	0.579 (<.0001)	3.72	0.463 (<.0001)
AADT	0.04	0.003 (<.0001)	0.06	0.005 (<.0001)	0.04	0.016 (0.007)	0.04	0.007 (<.0001)
% Heavy Commercial Vehicles	0.01	0.004 (0.021)	0.02	0.007 (0.003)	ns*	ns*	ns*	ns*
Horizontal Curvature	na*	na*	0.09	0.033 (0.007)	na*	na*	0.10	0.039 (0.007)

ns-not significant for the developed model, na*-not applicable for the developed model*

Odds ratios were calculated using estimated parameters. Since no-paved shoulder was set as reference level for rumble strips and paved shoulders, odds ratios can be directly considered as the CMF. Calculated CMFs for the two countermeasures considered are shown in Table 4.14 with maximum and minimum values for CMF.

Table 4.14. Estimated CMFs for paved shoulders and rumble strips on four-lane roadways using the case-control method

Countermeasures	All Lane-Departure Crashes		Fatal and Injury Lane- Departure Crashes	
	Tangent Road Segments	Curved-Road Segments	Tangent Road Segments	Curved-Road Segments
	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})
Shoulder Rumble Strips and Paved Shoulders ≥2_ft	0.80 (0.61,1.05)	0.92 (0.51,1.67)	0.32 (0.05,1.87)	0.31 (0.11,0.85)
Paved Shoulders without Rumble Strips ≥2_ft	0.91 (0.68,1.21)	0.74 (0.41,1.35)	0.75 (0.12,4.72)	0.40 (0.15,1.08)

Similar to the cross-sectional models, shoulder rumble strips and paved shoulders ≥2_ft showed a crash-reduction effect on both tangent and curved-road segments for all lane-departure crashes, and fatal and injury lane-departure crashes. Furthermore, paved shoulders without rumble strips ≥2_ft were shown effective in reducing both all lane-departure crashes, and fatal and injury lane-departure crashes on tangent and curved-road segments. However, all the ranges of estimated CMFs for paved shoulders without rumble strips ≥2_ft included 1, which suggested the considered countermeasure might have a crash-increase effect on some road segments. Similarly, Models were developed for all crash types on tangent and curved road segments using case-control method. The estimated regression parameters and the CMFs are shown in Appendices B3 and B4.

4.2.3. Model validation

4.2.3.1. Cross-sectional method

Table 4.15 shows the calculated MSE and mean of the residuals for the validation dataset, and the MSE obtained for the model using the model-building dataset. Based on results in Table 4.15, it can be clearly seen that in all models, mean of the residuals is close to zero and MSE of the validation datasets is approximately equal to model MSE. Therefore, developed models using the cross-sectional method are accurate enough to predict lane-departure crashes on two-lane rural highways, hence the developed CMFs using regression parameters are accurate. Similarly, the model validation was done for the models developed using all crash types and shown in Appendix B5.1.

Table 4.15. Model validation for models developed using the cross-sectional method for four-lane divided-road segments

Validation Statistics	**All Lane-Departure Crashes**				**Fatal and Injury Lane- Departure Crashes**			
	Tangent Road Segments		**Curved-Road Segments**		**Tangent Road Segments**		**Curved-Road Segments**	
	Model	**Validation Dataset**	**Model**	**Validation Dataset**	**Model**	**Validation Dataset**	**Model**	**Validation Dataset**
MSE	0.407	0.412	0.359	0.343	0.072	0.253	0.379	0.455
Mean of the Residuals	-	0.006	-	0.022	-	-0.392	-	0.673

4.2.3.2. Case-control method

Table 4.16 shows the calculated accuracy, sensitivity, and specificity for the developed models using the case-control method.

Table 4.16. Model validation for models developed using the case-control method for four-lane divided-road segments

Validation Statistics	All Lane-Departure Crashes		Fatal and Injury Lane- Departure Crashes	
	Tangent Road Segments	Curved-Road Segments	Tangent Road Segments	Curved-Road Segments
Accuracy	0.68	0.70	0.98	0.96
Sensitivity	0.49	0.45	0.74	0.49
Specificity	0.87	0.77	0.95	0.99

Based on these results, it is seen that developed models using all lane-departure crashes predict the outcome with an accuracy close to 70%, while predicting fatal and injury lane-departure crashes with an accuracy more than 95%. Similarly, the model developed using all lane-departure crashes predicts no crash segments with an accuracy close to 80% ,while predicting fatal and injury lane-departure crashes with an accuracy of more than 95%. Finally, the developed models predict crash events with accuracy closer to 50%, except the model developed for tangent road segments using fatal and injury lane-departure crashes. Model validation for the models developed using all crash types is shown in Appendix B5.2.

4.3. Chevrons and post-mounted delineators on two-lane road segments

4.3.1. Descriptive statistics of the site selected

A total of 500 curved-road segments, with a total length of 279.9 miles, were considered for developing models. It seemed that some levels of the categorical variables had small sample sizes. Therefore, those levels were combined for use as categorical variables for the model. Table 4.17 shows the descriptive statistics of continuous variables. Table 4.18 shows categorical variables used in the models after combining some levels.

Table 4.17. Descriptive statistics of continuous variables used to develop models for chevrons and post-mounted delineators on two-lane-road segments

Contentious Variables	Mean	Standard Deviation	Minimum	Median	Maximum
% of Heavy Vehicles	19.896	11.267	3.140	18.217	60.663
AADT	1,440	1,349	107	882	8,746
Annual alcohol tax per county (in million $)	0.390	0.566	0.018	0.187	3.191
Rainfall (inches)	29.338	9.233	16.278	31.806	46.488
Snowfall (inches)	20.205	4.788	13.582	20.808	31.316
Temperature (°F)	52.298	9.636	51.618	54.075	56.722
Average Wind Speed (mph)	15.285	0.015	17.404	18.867	21.052
Horizontal Curvature (degree of curvature)	2.746	4.850	0.260	1.440	54.430

Table 4.18. Descriptive statistics of categorical variables used to develop models for chevrons and post-mounted delineators on two-lane-road segments

Categorical Variable	Number of Road Segments	Total Segment Length	% of the Length
Chevrons	142	60.35	21.56
Post-Mounted Delineators	76	46.19	16.50
Without Chevrons or Post-Mounted Delineators	282	173.35	61.94
Access Control: No	452	244.14	87.23
Access Control: Full	42	33.39	11.93
Access Control: Partial	6	2.36	0.84
Paved Shoulders	118	58.39	20.86
No Paved Shoulders	265	149.86	53.54
Shoulder Rumble Strips	50	29.11	10.40
Centerline Rumble Strips	46	28.50	10.18
Shoulder and Centerline Rumble Strips	21	14.03	5.01
Lane Width ≥ 12 ft	434	242.28	86.56
Lane Width < 12 ft	66	37.60	13.44
Speed Limit ≤ 45 mph	29	3.02	1.08
Speed Limit 50 to 60 mph	164	80.10	28.62
Speed Limit > 60 mph	307	196.76	70.30

4.3.2. Results

4.3.2.1. Cross-sectional method

Two models were developed for chevrons and post-mounted delineators using cross-sectional method with and without incorporating driver and environmental-related characteristics. Table 4.19(a) shows the regression parameters estimated using the conventional cross-sectional method which only used road geometric and traffic-related characteristics as explanatory variables. Table 4.19(b) shows the regression parameters estimated using the modified cross-sectional method with driver and environmental-related characteristics as the explanatory variables in addition to road geometric and traffic-related characteristics. All lane-departure crashes, and fatal and injury lane-departure crashes on curved-road segments were considered when developing the models.

It is seen that the AIC of the modified cross-sectional models are slightly smaller than the conventional cross-sectional models which implies the proposed methods have a better model fitness over the conventional models for the considered dataset. Therefore, the CMFs were estimated based on the regression parameters of the modified cross-sectional models using the expression $CMF=exp(\beta)$, where β is the estimated regression parameter. Results are shown in Table 4.20. Similarly, the models were developed using all crash types. Estimated regression coefficients and the CMFs for all crash types on tangent and curved road segments are shown in Appendix C1 and C2, respectively.

Table 4.19. Parameter estimates of models developed to estimate CMFs of chevrons and post-mounted delineators on two-lane-road segments using the cross-sectional method

a: Regression parameter estimates of the cross-sectional model without driver and environmental-related characteristics (conventional method)

Variables	**All Lane-Departure Crashes**			**Fatal and Injury Lane-Departure Crashes**		
	Parameter Estimates	**Standard Error**	**Pr > |t|**	**Parameter Estimates**	**Standard Error**	**Pr > |t|**
Intercept	10.330	1050.46	0.9922	8.320	1047.930	0.994
Chevron	-0.325	0.1427	0.0234	-0.337	0.212	0.054
Post-Mounted Delineators	-0.375	0.1556	0.0165	-0.429	0.241	0.071
Area Type Rural	-0.328	0.1937	0.0909	*ns*	*ns*	*ns*
Shoulder Rumble Strips	-0.557	0.1825	0.0024	-0.603	0.292	0.029
Ln(AADT)	0.330	0.05018	<.0001	0.326	0.075	<.0001
AIC	744.79			465.30		

b: Regression parameter estimates of the cross-sectional model with driver and environmental-related characteristics in addition to road geometric and traffic-related characteristics (Modified cross-sectional method)

Intercept	4.492	9.870	0.649	8.042	1047.380	0.994
Chevron	-0.404	0.148	0.006	-0.427	0.220	0.054
Post-Mounted Delineators	-0.391	0.156	0.013	-0.439	0.242	0.071
Shoulder Rumble Strips	-0.622	0.193	0.001	-0.667	0.304	0.029
Ln(AADT)	0.334	0.052	<.0001	0.326	0.078	<.0001
Alcohol Tax	0.046	0.020	0.022	0.051	0.032	0.107
AIC	742.69			464.09		

ns-not significant for the developed model*

Table 4.20. Estimated CMFs for chevrons and post-mounted delineators on two-lane-road segments using the cross-sectional method

Countermeasure	All Lane-Departure Crashes			Fatal and Injury Lane-Departure Crashes		
	CMF	CMF$_{max}$	CMF$_{min}$	CMF	CMF$_{max}$	CMF$_{min}$
Chevrons	0.67	0.89	0.50	0.65	1.01	0.42
Post-Mounted Delineators	0.68	0.92	0.50	0.64	1.04	0.40

Furthermore, see the effect of the sample size selected for the model building, MSE vs sample size graph was prepared. Randomly selected samples with sample size of 250, 350, 450, and 500 were considered and the models were developed using the selected samples. Figure 4.1 shows the variation of MSE with the different sample sizes.

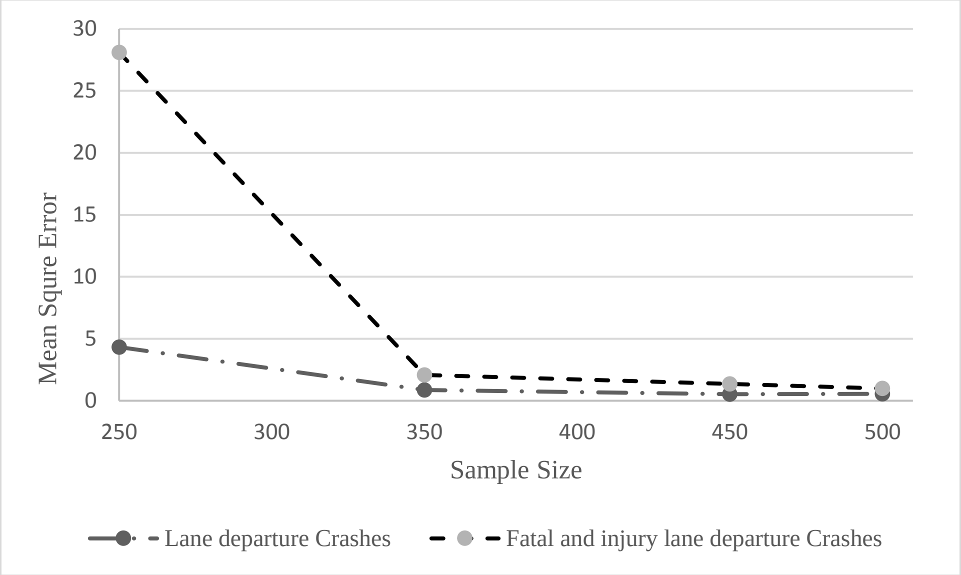

Figure 4.1. Variation of MSE with the sample size

It was seen that the sample size of 250 gave a higher MSE values which suggested that the sample size is not enough for the model development. However, when the sample size is more than 263 which is the minimum sample size, the MSE values tend to decrease dramatically. The MSE values were decreased only a little when the sample size increased from 350 to 500. Therefore, the decision of selecting 500 as the sample size is reasonable.

4.3.2.2. Case-Control Method

Two case-control models were developed with and without driver and environmental-related characteristics. Table 4.21(a) shows the regression parameters estimated using the conventional case-control method which only used road geometric and traffic-related characteristics as explanatory variables. Table 4.21(b) shows the regression parameters estimated using the modified case-control method with driver and environmental-related characteristics as the explanatory variables in addition to road geometric and traffic-related characteristics.

Table 4.21. Parameter estimates of models developed to estimate CMFs of chevrons and post-mounted delineators on two-lane-road segments using the case-control method

a: Regression parameter estimates of the cross-sectional model without driver and environmental-related characteristics (conventional method)

Variables	**All Lane-Departure Crashes**			**Fatal and Injury Lane-Departure Crashes**		
	Parameter Estimates	**Standard Error**	**Pr > |t|**	**Parameter Estimates**	**Standard Error**	Pr > |t|
Intercept	-0.403	1.124	0.7199	-1.599	1.178	0.1744
Chevron	-0.272	0.326	0.4038	-0.524	0.417	0.209
Post-Mounted Delineators	-0.555	0.340	0.1023	-0.800	0.455	0.0784
Segment Length	0.257	0.142	0.071	0.230	0.167	0.1673
Area Type Rural	-0.807	0.939	0.39	-0.611	0.881	0.4881
Centerline Rumble Strips	-0.534	0.437	0.2217	-0.639	0.564	0.2574
Shoulder Rumble Strips	-1.311	0.546	0.0163	-1.471	0.690	0.0329
Centerline and Shoulder Rumble Strips	-0.932	0.641	0.1459	-1.019	0.772	0.1868
AADT	0.572	0.122	<.0001	0.479	0.133	0.0003
AIC	597.823			428.838		

b: Regression parameter estimates of the cross-sectional model with driver and environmental-related characteristics in addition to road geometric and traffic-related characteristics (Modified cross-sectional method)

Intercept	-0.351	1.312	0.789	-1.862	1.455	0.201
Chevron	-0.325	0.341	0.341	-0.688	0.436	0.115
Post-Mounted Delineators	-0.589	0.344	0.087	-0.840	0.462	0.069
Segment Lengths	0.275	0.143	0.055	0.245	0.169	0.147
Centerline Rumble Strips	-0.428	0.446	0.338	-0.625	0.579	0.280
Shoulder Rumble Strips	-1.261	0.556	0.023	-1.507	0.700	0.031
Centerline and Shoulder Rumble Strips	-0.893	0.655	0.173	-1.070	0.802	0.182
AADT	0.586	0.131	<.0001	0.452	0.141	0.001
Alcohol Tax	0.320	0.231	0.167	0.396	0.272	0.146
AIC	573.580			426.608		

ns-not significant for the developed model*

It is seen that the AIC of the modified cross-sectional models are slightly smaller than the conventional case-control models which implies the proposed methods have a better model fitness over the conventional models for the considered dataset. Therefore, the CMFs were estimated based on the regression parameters of the modified case-control models using the expression *CMF=exp(β)*, where β is the estimated regression parameter. Results are shown in Table 4.22. Similarly, the models were developed using all crash types. Estimated regression coefficients and the CMFs for all crash types on tangent and curved road segments are shown in Appendix C3 and C4, respectively.

Table 4.22. Estimated CMFs for chevrons and post-mounted delineators on two-lane-road segments using the case-control method

Countermeasure	All Lane-Departure Crashes			Fatal and Injury Lane-Departure Crashes		
	CMF	CMF_{max}	CMF_{min}	CMF	CMF_{max}	CMF_{min}
Chevrons	0.72	1.41	0.37	0.50	1.18	0.21
Post-Mounted Delineators	0.56	1.09	0.28	0.43	1.07	0.17

4.3.3. Model validation

4.3.3.1. Cross-sectional method

Model validation was carried out using MSE and mean of the residuals for the cross-sectional method. Table 4.23 shows the validation statistics calculated using the model validation dataset and the estimated MSE from the developed models.

Table 4.23. Model validation for the model developed using chevrons and post-mounted delineators on two-lane-road segments for the cross-sectional method

Validation Statistics	All Lane-Departure Crashes		Fatal and Injury Lane-Departure Crashes	
	Model	Validation Dataset	Model	Validation Dataset
MSE	0.607	0.570	1.117	0.994
Mean of the Residuals	-	-0.413	-	-0.930

Based on results in Table 4.23, it can be clearly seen that in all models, mean residuals are close to zero and MSE of the validation datasets are less than the model MSE. Therefore, developed models using the cross-sectional method are accurate enough to predict lane-departure crashes on two-lane rural highways; hence, the CMFs obtained using estimated regression parameters are accurate. Similar validation statistics were calculated for the models developed using all crash types and are shown in Appendix C5.1.

4.3.3.2. Case-control method

After developing the models, validation was carried out using classification tables. Table 4.24 shows validation statistics calculated using the model validation dataset for case-control method.

Table 4.24. Model validation for the model developed using chevrons and post-mounted delineators on two-lane-road segments for the case-control method

Validation Statistics	All Severity Crashes	Fatal and Injury Severity Crashes
Accuracy	50	88
Sensitivity	36	92
Specificity	87	72

Based on results in Table 4.24, it can be seen that developed models can predict crashes or no-crashes with accuracy close to 90%, while predicting no-crash events with accuracy more than 90%. Furthermore, developed models using all lane-departure crashes, and fatal and injury lane-departure crashes can predict crash events with the accuracies of 72% and 80%, respectively. Similar validation statistics were calculated for the models developed using all crash types and are shown in Appendix C5.2.

4.4. Cable median barriers

4.4.1. Descriptive statistics of sites selected

A total of 1,545 tangent segments, with total lengths of 258.2 miles, were considered for developing models. The dataset contained 18 road segments with rigid and semi-rigid median barriers, 99 road segments with cable median barriers, and 1,428 road segments with depressed medians. To make an unbiased dataset for developing models, stratified sampling was used to select 150 data points which contained 70 road segments with cable median barriers, 70 road segments with depressed medians, and 10 road segments with rigid and semi-rigid road segments. Table 4.25 shows descriptive statistics of continuous variables, and Table 4.26 shows descriptive statistics of categorical variables of the whole dataset, which contained 1,545 road segments, and the sample selected using stratified sampling, which contained 150 road segments.

Table 4.25. Descriptive statistics of continuous variables used in the model for cable median barriers on four-lane-road segments

Variables	**Tangent Road Segments in Complete Dataset**				**Tangent Road Segments in the Selected Sample Using Stratified Sampling**			
	Max	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**
Segment Length	1.3	0.1	0.17	0.17	1	0.1	0.17	0.17
AADT	79,800	2,670	26,920	14,478	79,800	6,300	36,049	16,934
% Heavy Commercial Vehicles	39.9	3.1	10.11	5.48	28.32	3.35	8.14	4.88
Side Slope Gradient	6.0	4.0	5.55	0.83	6.0	4.0	5.66	0.75

Table 4.26. Descriptive statistics of categorical variables used in the model for cable median barriers on four-lane-road segments

Variables	Tangent Road Segments in Complete Dataset			Tangent Road Segments in the Selected Sample Using Stratified Sampling		
	Number of Segments	Total Segment Length	% of the Length	Number of Segments	Total Segment Length	% of the Length
Cable Median Barriers	97	15.6	6.04	70	11.7	45.17
Rigid or Semi-Rigid Pavements	18	3.1	1.20	10	1.6	6.18
Depressed Median	1,430	239.5	92.76	70	12.6	48.65
Posted Speed Limit 65mph	711	103	39.89	65	8.7	33.59
Posted Speed Limit 70mph	834	155.2	60.11	85	17.2	66.41
Median Width 30 to 39 feet	123	24.2	9.37	18	2.7	10.42
Median Width 40 to 49 feet	181	26.1	10.11	42	6.3	24.32
Median Width 50 to 60 feet	1,241	207.9	80.52	90	16.9	65.25
Terrain Type Flat	931	144.7	56.04	85	13.4	51.74
Terrain Type Rolling	614	113.5	43.96	65	12.5	48.26

4.4.2. Results

4.4.2.1. Cross-sectional method

Table 4.27 shows regression parameters estimated for the model developed using the cross-sectional method to estimate CMFs for cable median barriers on four-lane divided-road segments with their standard deviations and p-values. All lane-departure crashes, and fatal and injury lane-departure crashes on tangent road segments were considered when developing models. Estimated regression parameters were then converted into CMFs using the expression CMF=exp(β), where β is the estimated regression parameter and results are shown in Table 4.28. Similarly, models were developed using all crash types on tangent road segments. The estimated regression parameters and the CMFs are shown in Appendixes D1 and D2, respectively.

Table 4.27. Parameter estimates of the model developed to estimate CMFs of cable median barriers on four-lane divided-road segments using the cross-sectional method

Variables	All Lane-Departure Crashes		Fatal and Injury Lane-Departure Crashes	
	Parameter Estimates	Standard Error (p-value)	Parameter Estimates	Standard Error (p-value)
Intercept	-0.116	0.545 (0.832)	-0.257	0.078 (0.001)
Median Width 50 to 60 Inches	-0.378	0.179 (0.037)	*ns**	*ns**
Terrain Type Flat	*ns**	*ns**	-0.066	0.027 (0.015)
Cable Median Barriers	-0.696	0.192 (0.0005)	-0.204	0.056 (0.0002)
Rigid and Semi-Rigid Barriers	-0.586	0.313 (0.064)	*ns**	*ns**
Ln(segment length)	0.321	0.102 (0.002)	0.185	0.020 (<.0001)
Ln(AADT)	0.223	0.144 (0.13)	0.082	0.022 (0.0002)

ns-not significant for the developed model*

Table 4.28. Estimated CMFs for cable median barriers on four-lane divided-road segments using the cross-sectional method

	All Lane-Departure Crashes	Fatal and Injury Lane-Departure Crashes
Countermeasure	CMF (CMF$_{min}$, CMF$_{max}$)	CMF (CMF$_{min}$, CMF$_{max}$)
Cable Median Barriers	0.50 (0.41,0.6)	0.82 (0.77,0.86)

4.4.2.2. Case-control method

Using the same variables and same datasets used to develop cross-sectional models for cable median barriers, case-control models were developed. Table 4.29 shows estimated parameters using the case-control method with their standard deviations and p-values. Since the depressed median was used as the reference level for median type, the estimated odds ratio can be considered as the CMF of the cable median barrier.

Table 4.29. Parameter estimates of the model developed to estimate CMFs for cable median barriers on four-lane divided-road segments using the case-control method

Variables	All Lane-Departure Crashes		Fatal and Injury Lane-Departure Crashes	
	Parameter Estimates	Standard Error	Estimates	Standard Error
Intercepts	-2.961	1.046 (0.0046)	5.222	3.064 (0.0888)
Median Width 40 to 49 feet	-2.262	1.192 (0.0578)	-1.237	1.061 (0.243)
Median Width 50 to 60 feet	-2.310	1.065 (0.03)	-3.326	0.936 (0.0004)
% of Heavy Vehicles	*ns**	*ns**	-0.058	0.065 (0.375)
Side Slope Gradient	*ns**	*ns**	-0.577	0.476 (0.225)
Terrain Type Flat	*ns**	*ns**	0.400	0.749 (0.59)
Cable Median Barrier	-1.045	0.678 (0.124)	-0.936	0.913 (0.305)
Segment Length	4.254	1.322 (0.0013)	2.004	1.256 (0.1107)
AADT	0.089	0.024 (0.0002)	-0.036	0.027 (0.179)

ns-not significant for the developed model*

Results are shown in Table 4.30. Case-control models were developed using all crash types and the estimated regression parameters and CMFs are shown in Appendixes D3 and D4, respectively.

Table 4.30. Estimated CMFs for cable median barriers on four-lane divided-road segments using the case-control method

Countermeasure	All Lane-Departure Crashes	Fatal and Injury Lane-Departure Crashes
	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})
Cable Median Barriers	0.35 (0.18,0.69)	0.39 (0.16, 0.98)

4.4.3. Model validation

4.4.3.1. Cross-sectional method

Model validation carried out using MSE and mean of the residuals for the cross-sectional method. Table 4.31 shows validation statistics calculated using the model validation dataset and estimated MSE from the developed model. Appendix D5.1 shows the same validation statistics calculated for the models developed using all crash types.

Table 4.31. Model validation for the model developed using cable median barriers on four-lane divided-road segments for the cross-sectional method

Validation Statistics	All Lane-Departure Crashes		Fatal and Injury Lane-Departure Crashes	
	Model	Validation Dataset	Model	Validation Dataset
MSE	0.50	0.41	0.26	0.47
Mean of the Residuals	0	0.035	0	0.219

Based on results in Table 4.31, it can be clearly seen that in all models, mean residuals are close to zero and the MSE value of the validation datasets is approximately equal to the model MSE. Therefore, developed models using the cross-sectional method are accurate enough to predict lane-departure crashes on four-lane divided highways; hence, the CMFs obtained using estimated regression parameters are accurate.

4.4.3.2. Case-control method

After developing the models, validation was carried out using classification tables. Table 4.32 shows validation statistics calculated using the model validation dataset.

Table 4.32. Model validation for the model developed using cable median barriers on four-lane divided-road segments for the case-control method

Validation Statistics	All Lane-Departure Crashes	Fatal and Injury Lane-Departure Crashes
Accuracy	86	90
Sensitivity	50	53
Specificity	97	97

Based on results in Table 4.32, it can be seen that developed models can predict crashes or no-crashes with accuracy close to 90%, while predicting no-crash events with accuracy more than 97%. Furthermore, developed models using all crash severities, and fatal and injury crash severities, predict crash events with accuracy of more than 50%.

4.5. Safety edge treatment on rural two-lane undivided-road segments

4.5.1. Descriptive statistics of the site selected

Three years before and three years after data were extracted for the considered treatments excluding the year of the treatment. Three roads were identified as having safety edge treatment with lane widening with the total length of 72 miles. Road segments with safety edge and lane widening treatment experienced 42 crashes and 7 fatal and injury crashes in before period, 29 crashes and 7 fatal and injury crashes in after period. Furthermore, those road segments experienced 12 lane-departure crashes and 6 fatal and injury lane-departure crashes in before period, 17 lane-departure crashes and 3 fatal and injury lane-departure crashes in after period. In order to understand the main characteristics of the selected road segments, descriptive statistics of road segments were calculated and shown in Table 4.33.

Table 4.33. Descriptive statistics of road geometric/traffic and crash characteristics of road segments with safety edge treatments

Road Name	Other treatments		Data of implementation	Segment length (miles)	AADT (vehicles per day)	
	Lane widening 12ft to 13ft	Lane widening 12ft to 14ft		Mean (SD)	Before Mean (SD)	After Mean (SD)
K-23$^{(1)}$ from Lane County	No	Yes	2010	1.02 (1.745)	826 (501)	884 (253)
K-23$^{(2)}$ to US 83/K 383 junction	No	Yes	2012	1.58 (2.32)	640 (253)	633 (281)
K 25$^{(3)}$ from Russell Spring	Yes	No	2012	1.67 (3.19)	200 (18)	234 (15)

Note:- $^{(1)}$K 23 from the Lane County line to 0.5 miles south of Grove, $^{(2)}$K 23 from Hoxie to the US 83/K 383 junction, , $^{(3)}$K 25 from Russell Spring to US 40.

4.5.2. Results

4.5.2.1. Estimated CMFs using proposed regression based method

Separate models were developed using SAS 9.4 for each combined treatment as mentioned in the methodology (SAS Institute, 2014). Results of the two models are shown in Table 4.34 with their standard errors and p-values.

The results showed that the p-values of the variables of interests in models developed using all crash types are smaller than in the models developed using lane-departure crashes. Also, the results showed higher p-values for segment length variable and AADT variable which indicated that the variation of that variables in the considered time period cannot explain the variation in crash frequencies. The major reason is that the most noticeable change on the road segments for the variation of crash frequency is having treatments on the respective road segments.

Table 4.34. Developed regression models to identify the crash reduction effect of individual treatments

Model variables	**All crash type**				**Lane-departure crashes**			
	Fatal and injury		**All crashes**		**Fatal and injury**		**All crashes**	
	Parameter Estimates	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**
Intercept	-8.901	3.4037 (0.0089)	-8.176	4.3537 (0.0604)	18.216	30.5747 (0.5513)	-16.039	7.409 (0.0304)
Safety edge	-0.243	0.1521 (0.1103)	-0.261	0.2904 (0.3692)	-0.154	0.2934 (0.6004)	-0.277	0.3023 (0.3593)
Segment Length	0.333	0.0586 (<.0001)	0.319	0.1062 (0.0026)	0.223	0.0949 (0.0186)	0.336	0.1045 (0.0013)
Posted speed limit	4.285	1.359 (0.0016)	0.007	0.0035 (0.0569)	0.521	2.1276 (0.8064)	5.286	3.4684 (0.1275)
AADT	2.031	0.4064 (<.0001)	2.210	0.8797 (0.012)	0.270	0.6846 (0.6929)	2.052	0.8257 (0.013)
Average lane width	0.093	0.0982 (0.3418)	0.288	0.195 (0.14)	0.217	0.0914 (0.0178)	0.301	0.1704 (0.0774)

Estimated regression parameters were used to develop CMFs, and *CMF = exp(β)* was used to back transform the estimated regression parameters to find individual CMFs (Gross, & Persaud, 2011). Table 4.35 shows the estimated CMFs due to safety edge treatment with 1ft lane widening and 2ft lane widening.

Table 4.35. Estimated individual CMFs using regression parameters

Treatments	**All crash type**		**Lane-departure crashes**	
	All	**Fatal and injury**	**All**	**Fatal and injury**
Safety edge	0.784	0.770	0.858	0.758
1ft lane widening	1.098	1.333	1.242	1.351
2ft lane widening	1.205	1.778	1.542	1.825

4.5.2.2. CMFs estimated using before-and-after EB method

CMFs were estimated using before-and-after EB method to check whether there are similarities to the estimated CMFs using regression method. The method given in HSM was used to develop models as shown in the methodology. Calibration factors were calculated using the reference sites. Calibration factors for before and after periods were found to be 1.37 and 1.29. Also, the proportion of lane-departure crashes to all crash types was 0.50 and the fatal and injury crash proportions in before and after time periods were 0.24 and 0.22. The estimated CMFs for considered multiple treatments are shown in Table 4.36.

Table 4.36. Estimated safety effectiveness of multiple treatments using before-and-after EB method

Crash Type	Severity	Crashes in after period		CMF for combined treatments	SE	95% CI	% Reduction	Significance
		Observed	EB estimate					
All	All	29	50	0.51	0.115	(0.29,0.74)	49	Significant at 95% CI
	Fatal and injury	7	11	0.6	0.240	(0.13,1.07)	40	Not significant at 90% CI
Lane-departure	All	24	17	0.65	0.177	(0.30,1.00)	35	Significant at 90% CI
	Fatal and injury	3	6	0.53	0.312	(0, 1.14)	47	Not significant at 90% CI

Based on the results it can be seen that the CMFs estimated for safety edge treatments with lane widening are not significant except for all crashes. Since Table 4.36 shows the estimated CMFs for the combined treatments. Finally, the individual CMFs were calculated using Equations 23, 24, and 25.

4.5.2.3. Estimated individual CMFs

Since the main focus was to identify the safety effectiveness of safety edge treatment, individual CMFs were calculated for respective treatment. However, the CMFs for lane widening on two-lane undivided road segments were not available for Kansas. Therefore, it was decided to use CMFs estimated from regression method for considered road segments. Table 4.37 shows the calculated individual CMFs for safety edge treatment and adding 2ft paved shoulders on considered road segments.

Table 4.37. Estimated CMFs for individual treatments

	All crashes				Lane-departure crashes			
	All		**Fatal and injury**		**All**		**Fatal and injury**	
[a] Combined CMF (CMF_{CT})	0.51		0.6		0.65		0.53	
[b]CMF for increasing lane width (CMF_2)	1.10^{1*}	1.21^{*}	1.33^{1*}	1.78^{2*}	1.24^{1*}	1.54^{2*}	1.35^{1*}	1.83^{2*}
Method 1:								
[c]CMF for safety edge (CMF_1)	0.46^{3*}	0.42^{4*}	0.45^{3*}	0.34^{4*}	0.52^{3*}	0.42^{4*}	0.39^{3*}	0.29^{4*}
Method 2:								
[c]CMF for safety edge (CMF_1)	0.53^{3*}	0.56^{4*}	0.70^{3*}	**0.83^{4*}**	0.73^{3*}	**0.83^{4*}**	0.62^{3*}	**0.75^{4*}**
Method 3: [c]CMF for safety edge (CMF_1)	**0.74^{3*}**	0.68^{4*}	0.55^{3*}	0.41^{4*}	0.55^{3*}	0.44^{4*}	0.59^{3*}	0.44^{4*}

Note:- [a] – CMFs were estimated using before-and-after EB method. [b] – CMFs were estimated using regression parameters for increasing lane width in Table 2. [c] – CMFs were estimated using the methods shown in Equation 23, 24 and 25.

It is seen that the individual CMFs estimated for all crashes from regression method shown in Table 4.36 is similar to CMFs estimated for safety edge treatments on the road segments with 1ft lane widening using Equation 25 shown in Table 4.37. For the fatal and injury all crash types and lane-departure crashes, CMFs estimated from regression method in Table 4.36 is similar to the individual CMFs calculated using Equation 24 shown in Table 4.37 for the safety edge treatments on the road segments with 2ft lane widening. However, it should be noted that this research was done to estimate CMFs due to individual treatment, not to find the relationship between individual treatments to the combined treatments. Therefore, having similar but not the exact CMFs are understandable since the emphasis was not given to identify the exact relationship of individual CMFs to the combined CMFs.

Chapter 5 Conclusions and Recommendations

This study employed cross-sectional, case-control, and before-and-after study approaches to estimate safety effectiveness of lane-departure countermeasures using CMFs. This study has a significant impact on the area of road safety in Kansas because the CMFs for lane-departure countermeasures haven’t been fully developed for Kansas. Even though there are some CMFs developed for other regions, the traffic characteristics, driver-behaviors, and environmental characteristics are different so that making decisions on such CMFs are questionable. Furthermore, this study provides state-of-art knowledge to the area of traffic safety by modifying the existing cross-sectional and case-control models and introducing a novel method of estimating CMFs using before-and-after data.

A Novel approach to estimate CMFs using before-and-after data was proposed in this study to overcome one of the major limitations in the before-and-after EB method which is the inadequacy of the EB method to identify the safety effectiveness of individual countermeasures when the multiple treatments have been applied on the considered road segment at the same time. One of the advantages of the method is that if the considered treatment was implemented with another treatment(s), this approach could be used to identify the individual safety effectiveness of each treatment. Hence decisions can be made whether to implement these treatments individually or collectively. Tables 5.1(a) and 5.1(b) summarize CMFs estimated from the cross-sectional and case-control method.

Table 5.1. Summary of the estimated CMFs using cross-sectional and case-control methods

Countermeasures	**All Crash Types**				**Lane-Departure Crashes**			
	Tangent Road Segments		**Curved Road Segments**		**Tangent Road Segments**		**Curved Road Segments**	
	All Crashes	**Fatal and Injury Crashes**	**All Crashes**	**Fatal and Injury Crashes**	**All Crashes**	**Fatal and Injury Crashes**	**All Crashes**	**Fatal and Injury Crashes**
(a) Cross-sectional method								
Two lane undivided road segments								
Centerline Rumble Strips	1.06	0.98	0.95	0.95	0.96	0.94	0.96	0.95
Shoulder Rumble Strips	0.79	0.97	0.94	0.94	0.94	0.95	0.95	0.94
Centerline and Shoulder Rumble Strips	0.90	0.97	0.84	0.94	0.86	0.94	0.89	0.87
2-ft Paved Shoulder (both sides)	0.81	0.98	0.90	0.81	0.88	0.94	0.89	0.93
Chevrons	*na**	*na**	0.70	0.64	*na**	*na**	0.67	0.65
Post-Mounted Delineators	*na**	*na**	0.82	0.83	*na**	*na**	0.68	0.64
Four-lane divided road segments								
Shoulder Rumble Strips and Paved Shoulders	1.02	0.98	1.01	0.96	0.91	0.50	0.96	0.30
Paved Shoulders without Rumble Strips	0.85	0.89	0.69	0.93	1.07	0.70	0.84	0.35
Cable median barriers	1.35	0.78	*na**	*na**	0.5	0.82	*na**	*na**
(b) Case-control method								
Two lane undivided road segments								
Centerline Rumble Strips	0.40	0.12	0.92	0.12	0.91	0.89	0.87	0.88
Shoulder Rumble Strips	0.20	0.10	0.98	0.07	0.85	0.90	1.25	0.81
Centerline and Shoulder Rumble Strips	0.06	0.09	0.63	0.07	0.68	0.73	0.75	0.51
2-ft Paved Shoulder (both sides)	0.27	0.94	0.36	0.09	0.82	0.84	0.66	0.79
Chevrons	*na**	*na**	0.11	0.56	*na**	*na**	0.72	0.50
Post-Mounted Delineators	*na**	*na**	0.76	0.58	*na**	*na**	0.56	0.43
Four-lane divided road segments								
Shoulder Rumble Strips and Paved Shoulders	1.63	0.81	2.34	0.64	0.80	0.32	0.92	0.31
Paved Shoulders without Rumble Strips	0.84	0.35	0.71	0.43	0.91	0.75	0.74	0.40
Cable median barriers	1.61	0.51	*na**	*na**	0.35	0.39	*na**	*na**

Note: na-not applicable*

Following conclusions were made based on the model development process and the estimated CMFs.

- Combination of both centerline and shoulder rumble strips were the most effective countermeasure to reduce all lane-departure crashes on a rural two-lane tangent and curved-road segments.
- Shoulder rumble strips were shown to have a statistically positive relationship with all lane-departure crashes on rural two-lane-road segments, which implied they might have a crash-increase effect.
- Out of the two countermeasures considered for the models developed for four-lane divided-road segments, shoulder rumble strips with paved shoulders ≥2 ft were found to be the most effective countermeasure for reducing all lane-departure crashes.
- Paved shoulders ≥2 ft were found to be most effective in reducing lane-departure crashes on four-lane curved road segments. For fatal and injury lane-departure crashes on a tangent and curved segments, shoulder rumble strips with paved shoulders ≥2 ft showed a significant crash-reduction effect.
- Models developed to estimate safety effectiveness of cable median barriers on four-lane divided-road segments showed cable median barriers reduced 50-65% of all lane-departure crashes while reducing 18-61% of fatal and injury lane-departure crashes.
- The modified cross-sectional and case-control models showed that incorporating driver and environmental characteristics in the cross-sectional and case-control models will improve the model fitness.

- Results suggested that having chevrons reduced all lane-departure crashes by 28-33% and fatal and injury lane-departure crashes by 35-50%. Furthermore, results suggested that having post-mounted delineators reduced all lane-departure crashes by 32-44% and fatal and injury crashes lane-departure crashes by 36-57%.
- The results of the model validation showed that the models developed using the case-control method had a higher standard error; hence, a larger range of percent of a crash-reduction effect than the cross-sectional method. The primary reason for having a higher range for estimated CMFs using the case-control method is that it assumed all road segments with one or more crashes on an equal basis so that the method might under-predict the crashes. Therefore, it can be concluded the case-control method is more suitable to develop models for road segments where there are fewer crashes or fewer variations in crashes, while the cross-sectional method is more appropriate to develop models for road segments where there is a higher range in the number of crashes.
- CMFs estimated for safety edge treatments showed that having the treatment all crashes as well as lane-departure crashes. The CMFs obtained from the regression based method are similar to the CMFs estimated form EB method.

Finally, it should be noted that each method has their own strengths and weaknesses as described under each methodology. Therefore, the consideration should be given to select appropriate method of estimating CMFs for available data and the required accuracy.

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Appendixes

Appendix A: CMFs for rumble strips and paved shoulders on rural two-lane undivided-road segments using all crash types

Appendix A1: Parameter estimates of models developed using cross-sectional method

Variables	All Crashes				Fatal and Injury Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
	Parameter Estimates	Standard Error (p-value)	Parameter Estimates	Standard Error (p-value)	Parameter Estimates	Standard Error (p-value)	Parameter Estimates	Standard Error (p-value)
Intercept	1.572	0.023 (<.0001)	1.049	0.044 (<.0001)	0.041	0.004 (<.0001)	0.259	0.024 (<.0001)
No Passing (Both Direction)	-0.051	0.016 (0.0013)	*ns**	*ns**	*ns**	*ns**	*ns**	*ns**
Lane Width <12_ft	*ns**	*ns**	0.054	0.034 (0.1065)	*ns**	*ns**	*ns**	*ns**
Horizontal Curvature	*na**	*na**	0.011	(0.0005)	*na**	*na**	0.009	0.003 (0.0051)
Speed Limit>60mph	0.025	0.018 (0.1658)	*ns**	*ns**	0.018	0.004 (<.0001)	*ns**	*ns**
Percent Heavy Commercial Vehicles	-0.008	0.001 (<.0001)	-0.006	0.001 (<.0001)	0.0003	0.0002 (0.0564)	*ns**	*ns**
Centerline Rumble Strips	0.060	0.045 (0.1843)	-0.050	0.028 (0.0782)	-0.023	0.004 (<.0001)	-0.056	0.014 (<.0001)
Shoulder Rumble Strips	-0.231	0.021 (<.0001)	-0.059	0.030 (0.0459)	-0.030	0.004 (<.0001)	-0.057	0.015 (0.0001)
Both Centerline and Shoulder Rumble Strips	-0.102	0.033 (0.0018)	-0.176	0.042 (<.0001)	-0.026	0.006 (<.0001)	-0.065	0.016 (<.0001)
2-ft Paved Shoulders	-0.206	0.017 (<.0001)	-0.107	0.024 (<.0001)	-0.020	0.004 (<.0001)	-0.205	0.023 (<.0001)
Ln(Segment Length)	0.486	0.009 (<.0001)	0.341	0.013 (<.0001)	0.016	0.001 (<.0001)	0.007	0.004 (0.0888)
Ln(AADT)	0.287	0.011 (<.0001)	0.190	0.014 (<.0001)	0.014	0.002 (<.0001)	0.012	0.007 (0.0805)

ns- model variable is not significant for the developed model, na*- model variable is not applicable for the model*

Appendix A2: Estimated CMFs based on the estimated regression parameters using cross-sectional method

Countermeasure	All Crashes		Fatal and Injury Crashes	
	Tangent Road Segments	Curved Road Segments	Tangent Road Segments	Curved Road Segments
	CMF (CMF_{min}, CMF_{max})	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**
Centerline Rumble Strips	1.06 (1.01,1.11)	0.95 (0.93, 0.98)	0.98 (0.97, 0.98)	0.95 (0.93, 0.96)
Shoulder Rumble Strips	0.79 (0.78,0.81)	0.94 (0.92, 0.97)	0.97 (0.97, 0.97)	0.94 (0.93, 0.96)
Both Centerline and Shoulder Rumble Strips	0.90 (0.87, 0.93)	0.84 (0.80, 0.87)	0.97 (0.97, 0.98)	0.94 (0.92, 0.95)
2-ft Paved Shoulders	0.81 (0.80, 0.83)	0.90 (0.88, 0.92)	0.98 (0.98, 0.98)	0.81 (0.80, 0.83)

Appendix A3: Parameter estimates of models developed using case-control method

Variables	All Crashes				Fatal and Injury Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
	Parameter Estimates	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**
Intercept	0.062	0.233 (0.7906)	-1.079	0.156 (<.0001)	-2.532	0.178 (<.0001)	-1.113	0.974 (0.2529)
Passing Restriction Both Sides	0.158	0.103 (0.1239)	*ns*	*ns*	-0.328	0.134 (0.0144)	0.367	0.524 (0.4841)
Passing Restriction Single Sides	-0.049	0.082 (0.5511)	*ns*	*ns*	-0.351	0.105 (0.0008)	0.977	0.450 (0.0297)
Average Lane Width >12_ft	-1.206	0.207 (<.0001)	-1.414	0.149 (<.0001)	*ns*	*ns*	*ns*	*ns*
Average Speed >60mph	2.506	0.098 (<.0001)	-0.290	0.111 (0.0088)	1.150	0.147 (<.0001)	*ns*	*ns*
AADT	0.554	0.032 (<.0001)	0.283	0.036 (<.0001)	0.289	0.033 (<.0001)	0.483	0.119 (<.0001)
% of Heavy Commercial Vehicles	-0.023	0.004 (<.0001)	-0.019	0.004 (<.0001)	-0.017	0.005 (0.0016)	*ns*	*ns*
Centerline Rumble Strips	-0.928	0.214 (<.0001)	-0.084	0.125 (0.499)	-2.101	0.140 (<.0001)	-2.090	0.521 (<.0001)
Shoulder Rumble Strips	-1.604	0.103 (<.0001)	-0.016	0.135 (0.9055)	-2.346	0.147 (<.0001)	-2.605	0.603 (<.0001)
Centerline + Shoulder Rumble Strips	-2.865	0.156 (<.0001)	-0.469	0.186 (0.0116)	-2.422	0.191 (<.0001)	-2.700	0.627 (<.0001)
2_ft Paved Shoulders	-1.310	0.091 (<.0001)	-1.033	0.109 (<.0001)	-0.065	0.125 (0.6014)	-2.398	0.824 (0.0036)
Segment Length	5.606	0.340 (<.0001)	5.000	0.347 (<.0001)	0.959	0.064 (<.0001)	3.167	0.828 (<.0001)
Horizontal Curvature	*na*	*na*	*ns*	*ns*	*na*	*na*	0.430	0.146 (0.0033)

ns- model variable is not significant for the developed model, na*- model variable is not applicable for the model*

Appendix A4: Estimated CMFs based on the estimated regression parameters using case-control method

Countermeasure	All Crashes		Fatal and Injury Crashes	
	Tangent Road Segments	Curved Road Segments	Tangent Road Segments	Curved Road Segments
	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})	CMF (CMF_{min}, CMF_{max})
Centerline Rumble Strips	0.40 (0.32, 0.49)	0.92 (0.81, 1.04)	0.12 (0.11, 0.14)	0.12 (0.07, 0.21)
Shoulder Rumble Strips	0.20 (0.18, 0.22)	0.98 (0.86, 1.13)	0.10 (0.08, 0.11)	0.07 (0.04, 0.14)
Both Centerline and Shoulder Rumble Strips	0.06 (0.05, 0.07)	0.63 (0.52, 0.75)	0.09 (0.07, 0.11)	0.07 (0.04, 0.13)
2-ft Paved Shoulders	0.27 (0.25, 0.30)	0.36 (0.32, 0.40)	0.94 (0.83, 1.06)	0.09 (0.04,0.21)

Appendix A5: Model validation

A5.1: Cross-sectional models

Model Validation Statistics	All Crashes		Fatal and Injury Crashes	
	Tangent Road Segments	Curved Road Segments	Tangent Road Segments	Curved Road Segments
Mean of Residuals of the Model	0	0	0	0
MSE of the Model	0.318	0.236	0.010	0.006
Mean of Residuals of the Validation Dataset	-0.032	0.058	-0.054	-0.003
MSE of the Validation Dataset	0.317	0.255	0.014	0.005

A5.2: Cross-sectional models

Model Validation Statistics	All Crashes		Fatal and Injury Crashes	
	Tangent Road Segments	Curved Road Segments	Tangent Road Segments	Curved Road Segments
Accuracy	82	12	90	92
Sensitivity	92	14	34	30
Specificity	51	08	97	98

Appendix B: CMFs for rumble strips and paved shoulders on four-lane divided-road segments using all crash types

Appendix B1: Parameter estimates of models developed using cross-sectional method

Variables	**All Crashes**				**Fatal and Injury Crashes**			
	Tangent Road Segments		**Curved Road Segments**		**Tangent Road Segments**		**Curved Road Segments**	
	Parameter Estimates	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**
Intercept	-0.031	0.099 (0.7515)	-0.434	0.169 (0.0101)	-0.405	0.090 (<.0001)	0.017	0.136 (0.8998)
Depressed Median	-0.206	0.033 (<.0001)	-0.236	0.044 (<.0001)	0.065	0.030 (0.0330)	0.105	0.035 (0.0027)
Passing is Restricted	0.273	0.163 (0.0952)	-0.168	0.316 (0.5949)	*ns*	*ns*	-0.238	0.262 (0.3648)
Area Type Rural	-0.076	0.037 (0.0403)	-0.073	0.051 (0.1519)	0.033	0.034 (0.3323)	*ns*	*ns*
Lane Width>12_ft	0.246	0.064 (0.0001)	-0.162	0.112 (0.1493)	0.068	0.058 (0.2402)	-0.184	0.091 (0.0438)
Speed Limit 60_65mph	-0.229	0.047 (<.0001)	0.049	0.074 (0.5096)	0.091	0.042 (0.0316)	*ns*	*ns*
Shoulder Rumble Strips	0.019	0.036 (0.5954)	0.010	0.050 (0.8425)	-0.020	0.033 (0.5481)	-0.045	0.039 (0.2516)
Paved Shoulders	-0.159	0.066 (0.0163)	-0.375	0.117 (0.0014)	-0.113	0.060 (0.0618)	-0.072	0.097 (0.4590)
lnSegmentL	0.768	0.014 (<.0001)	0.521	0.028 (<.0001)	0.176	0.012 (<.0001)	0.231	0.023 (<.0001)
lnAADT	0.782	0.024 (<.0001)	0.698	0.036 (<.0001)	0.129	0.022 (<.0001)	0.207	0.027 (<.0001)
% heavy vehicles	-0.007	0.002 (0.0003)	-0.005	0.003 (0.0735)	0.005	0.002 (0.0088)	0.003	0.002 (0.1480)
Horizontal Curvature	*na*	*na*	0.072	0.012 (<.0001)	*na*	*na*	-0.037	0.010 (0.0002)

ns- model variable is not significant for the developed model, na*- model variable is not applicable for the model*

Appendix B2: Estimated CMFs based on the estimated regression parameters using cross-sectional method

Countermeasure	**All Crashes**		**Fatal and Injury Crashes**	
	Tangent Road Segments	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
	CMF (CMF_{min}, CMF_{max})	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**
Shoulder Rumble Strips	1.02 (0.98, 1.06)	1.01 (0.96, 1.06)	0.98 (0.95, 1.01)	0.96 (0.92, 0.99)
2-ft Paved Shoulders	0.85 (0.80, 0.91)	0.69 (0.61, 0.77)	0.89 (0.84, 0.95)	0.93 (0.84, 1.03)

Appendix B3: Parameter estimates of models developed using case-control method

Variables	All Crashes				Fatal and Injury Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
	Parameter Estimated	**Standard Error (p-value)**	**Parameter Estimated**	**Standard Error (p-value)**	**Parameter Estimated**	**Standard Error (p-value)**	**Parameter Estimated**	**Standard Error (p-value)**
Intercept	-1.889	0.2509 (<.0001)	-2.024	0.3375 (<.0001)	-5.806	0.7272 (<.0001)	-2.977	0.3207 (<.0001)
Median Type								
Depressed Median	-0.549	0.1193 (<.0001)	-0.899	0.1458 (<.0001)	-0.471	0.3866 (0.223)	-0.474	0.1424 (0.0009)
Area Type Rural	-0.304	0.125 (0.015)	0.176	0.1548 (0.2556)	-0.084	0.6017 (0.8893)	-0.108	0.1773 (0.5437)
Passing is Restricted	-2.451	1.0542 (0.0201)	*ns**	*ns**	-11.112	921.3 (0.9904)	0.713	1.2092 (0.5554)
Average lane width >12	0.517	0.2061 (0.0122)	*ns**	*ns**	0.018	0.9228 (0.9845)	0.853	0.3847 (0.0267)
Speed Limit 60-65mph	-0.400	0.1616 (0.0134)	*ns**	*ns**	-0.386	0.7072 (0.5849)	-0.387	0.2954 (0.1905)
Speed Limit 70-75mph	-0.315	0.1599 (0.0485)	*ns**	*ns**	-0.187	0.7425 (0.8008)	-0.064	0.2809 (0.8201)
AADT	0.105	0.00711 (<.0001)	0.109	0.00988 (<.0001)	0.061	0.0128 (<.0001)	0.053	0.00646 (<.0001)
% of heavy vehicles	-0.024	0.00698 (0.0007)	-0.031	0.00865 (0.0003)	-0.011	0.0309 (0.7296)	0.006	0.00978 (0.5457)
Shoulder Rumble Strips	0.487	0.1205 (<.0001)	0.851	0.1534 (<.0001)	-0.215	0.4986 (0.6666)	-0.450	0.1932 (0.02)
Paved Shoulders	-0.173	0.2147 (0.4206)	-0.346	0.3105 (0.2646)	-1.055	0.9297 (0.2565)	-0.849	0.4675 (0.0695)
Segment Length	4.774	0.2291 (<.0001)	5.913	0.4071 (<.0001)	0.740	0.0965 (<.0001)	2.937	0.2832 (<.0001)
Horizontal Curvature	*na**	*na**	0.169	0.0474 (0.0004)	*na**	*na**	0.148	0.0388 (0.0001)

ns- model variable is not significant for the developed model, na*- model variable is not applicable for the model*

Appendix B4: Estimated CMFs based on the estimated regression parameters using case-control method

Countermeasure	All Crashes		Fatal and Injury Crashes	
	Tangent Road Segments	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
	CMF (CMF_{min}, CMF_{max})	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**	**CMF (CMF_{min}, CMF_{max})**
Shoulder Rumble Strips	1.63 (1.44, 1.84)	2.34 (2.01, 2.73)	0.81 (0.49, 1.33)	0.64 (0.53, 0.77)
2-ft Paved Shoulders	0.84 (0.68, 1.04)	0.71 (0.52, 0.96)	0.35 (0.14, 0.88)	0.43 (0.27, 0.68)

Appendix B5: Model validation

B5.1: Cross-sectional models

	All Crashes		**Fatal and Injury Crashes**	
Model Validation Statistics	**Tangent Road Segments**	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
Mean of Residuals of the Model	0	0	0	0
MSE of the Model	0.59	0.57	0.40	0.49
Mean of Residuals of the Validation Dataset	-0.238	-0.154	0.395	-0.526
MSE of the Validation Dataset	0.693	0.606	0.785	0.846

B5.2: Case-control models

	All Crashes		**Fatal and Injury Crashes**	
Model Validation Statistics	**Tangent Road Segments**	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
Accuracy	66	71	82	85
Sensitivity	45	39	44	45
Specificity	75	72	85	88

Appendix C: CMFs for chevrons and post-mounted delineators on two-lane road segments using all crash types

Appendix C1: Parameter estimates of models developed using cross-sectional method

Variables	All Crashes			Fatal and Injury Crashes		
	Parameter Estimates	Standard Error	Pr > |t|	Parameter Estimates	Standard Error	Pr > |t|
Intercept	3.230	0.629	<.0001	9.784	234.370	0.967
Chevron	-0.355	0.081	<.0001	-0.444	0.166	0.008
Post-Mounted Delineators	-0.199	0.075	0.008	-0.192	0.148	0.195
Area Type Rural	-0.308	0.108	0.005	*ns**	*ns**	*ns**
Access Control Full	-0.495	0.342	0.148	*ns**	*ns**	*ns**
Centerline Rumble Strips	-0.228	0.097	0.019	-0.809	0.234	0.001
Shoulder Rumble Strips	-0.224	0.092	0.015	-0.804	0.196	<.0001
Shoulder and Centerline Rumble Strips	-0.164	0.120	0.171	-0.546	0.233	0.019
Paved Shoulders				-0.313	0.145	0.032
AADT	0.244	0.028	<.0001	0.379	0.056	<.0001

ns- model variable is not significant for the developed model*

Appendix C2: Estimated CMFs based on the estimated regression parameters using cross-sectional method

Countermeasure	**All Crashes**			**Fatal and Injury Crashes**		
	CMF	**CMF_{max}**	**CMF_{min}**	**CMF**	**CMF_{max}**	**CMF_{min}**
Chevrons	0.70	0.82	0.60	0.64	0.89	0.46
Post-Mounted Delineators	0.82	0.95	0.71	0.83	1.10	0.62

Appendix C3: Parameter estimates of models developed using case-control method

Variables	All Crashes			Fatal and Injury Crashes		
	Parameter Estimates	Standard Error	Pr > |t|	Parameter Estimates	Standard Error	Pr > |t|
Intercept	-1.475	0.956	0.123	-1.941	0.614	0.0016
Chevron	-2.248	0.850	0.0082	-0.576	0.862	0.5043
Post-Mounted Delineators	-0.277	0.368	0.4523	-0.546	0.468	0.243
Area Type Rural	-0.554	0.278	0.0467	-0.198	0.369	0.591
Passing Restrictions	0.494	0.302	0.1019	0.475	0.405	0.241
Paved Shoulders	-0.864	0.358	0.0158	-0.400	0.479	0.4044
Horizontal Curvature	0.030	0.018	0.0985	0.011	0.017	0.529
% of Heavy Vehicles	-0.014	0.013	0.2797	-0.014	0.018	0.4451
AADT	1.192	0.201	<.0001	0.450	0.200	0.0242

Appendix C4: Estimated CMFs based on the estimated regression parameters estimated using case-control method

Countermeasure	All Crashes			Fatal and Injury Crashes		
	CMF	CMF_{max}	CMF_{min}	CMF	CMF_{max}	CMF_{min}
Chevrons	0.11	0.25	0.05	0.56	1.33	0.24
Post-Mounted Delineators	0.76	1.10	0.52	0.58	0.92	0.36

Appendix C5: Model validation

C5.1: Cross-sectional models

Model Validation Statistics	All Crashes	Fatal and Injury Crashes
Mean of Residuals of the Model	0	0
MSE of the Model	5.206	1.032
Mean of Residuals of the Validation Dataset	1.093	-0.849
MSE of the Validation Dataset	3.194	1.107

C5.2: Cross-sectional models

Model Validation Statistics	All Crashes	Fatal and Injury Crashes
Accuracy	40	85
Sensitivity	35	82
Specificity	85	75

Appendix D: CMFs for cable median barriers using all crash types

Appendix D1: Parameter estimates of models developed using cross-sectional method

Variables	All Crashes			Fatal and Injury Crashes		
	Parameter Estimates	Standard Error	Pr > |t|	Parameter Estimates	Standard Error	Pr > |t|
Intercept	-1.893	0.900	0.036	-3.568	0.420	<.0001
Posted Speed Limit	-0.020	0.013	0.112	*ns**	*ns**	*ns**
% of Heavy Vehicles	0.029	0.009	0.001	*ns**	*ns**	*ns**
Horizontal Curvature	0.127	0.045	0.005	0.165	0.075	0.027
Cable Median Barrier	0.298	0.198	0.134	-0.246	0.237	0.299
Segment Length	1.399	0.064	<.0001	1.261	0.090	<.0001
AADT	1.593	0.071	<.0001	0.478	0.115	<.0001

ns- model variable is not significant for the developed model*

Appendix D2: Estimated CMFs based on the estimated regression parameters using cross-sectional method

Countermeasure	All Crashes			Fatal and Injury Crashes		
	CMF	CMF_{max}	CMF_{min}	CMF	CMF_{max}	CMF_{min}
Cable Median Barrier	1.35	1.10	1.64	0.78	0.62	0.99

Appendix D3: Parameter estimates of models developed using case-control method

Variables	All Crashes			Fatal and Injury Crashes		
	Parameter Estimates	Standard Error	Pr > |t|	Parameter Estimates	Standard Error	Pr > |t|
Intercept	-2.3381	0.2541	<.0001	-5.260	0.412	<.0001
Segment Length	11.5589	1.3758	<.0001	3.264	0.367	<.0001
AADT	0.4792	0.4247	0.2592	-0.681	0.509	0.182
% of Heavy Vehicles	0.0817	0.0058	<.0001	0.035	0.006	<.0001
Area Type	0.0225	0.0113	0.047	0.017	0.017	0.327

ns- model variable is not significant for the developed model*

Appendix D4: Estimated CMFs based on the estimated regression parameters estimated using case-control method

Countermeasure	All Crashes			Fatal and Injury Crashes		
	CMF	CMF_{max}	CMF_{min}	CMF	CMF_{max}	CMF_{min}
Cable Median Barrier	1.61	1.06	2.47	0.51	0.30	0.84

Appendix D5: Model validation

D5.1: Cross-sectional models

Model Validation Statistics	**All Crashes**	**Fatal and Injury Crashes**
Mean of Residuals of the Model	0	0
MSE of the Model	1.818	2.150
Mean of Residuals of the Validation Dataset	0.922	1.301
MSE of the Validation Dataset	1.211	1.335

D5.2: Cross-sectional models

Model Validation Statistics	**All Crashes**	**Fatal and Injury Crashes**
Accuracy	80	82
Sensitivity	44	48
Specificity	82	95