Estimating Crash Modification Factors for Lane Departure Countermeasures in Kansas

Final Report
December 2017

Sponsored by
Kansas Department of Transportation
Midwest Transportation Center
U.S. Department of Transportation
Office of the Assistant Secretary for
Research and Technology

MIDWEST TRANSPORTATION CENTER
IOWA STATE UNIVERSITY
Institute for Transportation

About MTC

The Midwest Transportation Center (MTC) is a regional University Transportation Center (UTC) sponsored by the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology (USDOT/OST-R). The mission of the UTC program is to advance U.S. technology and expertise in the many disciplines comprising transportation through the mechanisms of education, research, and technology transfer at university-based centers of excellence. Iowa State University, through its Institute for Transportation (InTrans), is the MTC lead institution.

About InTrans

The mission of the Institute for Transportation (InTrans) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

ISU Non-Discrimination Statement

Iowa State University does not discriminate on the basis of race, color, age, ethnicity, religion, national origin, pregnancy, sexual orientation, gender identity, genetic information, sex, marital status, disability, or status as a U.S. veteran. Inquiries regarding non-discrimination policies may be directed to Office of Equal Opportunity, 3410 Beardshear Hall, 515 Morrill Road, Ames, Iowa 50011, Tel. 515-294-7612, Hotline: 515-294-1222, email eooffice@iastate.edu.

Notice

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the sponsors.

This document is disseminated under the sponsorship of the U.S. DOT UTC program in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The U.S. Government does not endorse products or manufacturers. If trademarks or manufacturers' names appear in this report, it is only because they are considered essential to the objective of the document.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. The FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Estimating Crash Modification Factors for Lane Departure Countermeasures in Kansas		**5. Report Date** December 2017 **6. Performing Organization Code**
7. Author(s) Sunanda Dissanayake and Uditha Galgamuwa		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Kansas State University 2118 Fielder Hall 1701C Platt St. Manhattan, KS 66506		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** Part of DTRT13-G-UTC37
12. Sponsoring Organization Name and Address Midwest Transportation Center 2711 S. Loop Drive, Suite 4700 Ames, IA 50010-8664 Kansas Department of Transportation Eisenhower State Office Building 700 S.W. Harrison Street Topeka, KS 66603-3745	U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes Visit www.intrans.iastate.edu for color pdfs of this and other research reports.		

16. Abstract

This project was conducted to estimate crash modification factors (CMFs) for lane departure countermeasures in Kansas. Cross-sectional, case-control, and before-and-after empirical Bayes (EB) methods were employed. Results showed that centerline rumble strips on rural two-lane road segments have crash-reduction effects on all lane departure and fatal and injury lane departure crashes on both tangent and curved road segments. Shoulder rumble strips were effective in reducing all lane departure and fatal and injury lane departure crashes on tangent road segments but showed less effectiveness on curved road segments. The combination of centerline and shoulder rumble strips showed significant safety effectiveness on both tangent and curved road segments.

Shoulder rumble strips on four-lane road segments also showed crash-reduction effects on all lane departure and fatal and injury lane departure crashes on both tangent and curved road segments. Cable median barriers showed a crash-reduction effect on all lane departure crashes, and fatal and injury lane departure crashes on four-lane divided road segments. Chevrons and post-mounted delineators also showed effectiveness on both all lane departure crashes and fatal and injury lane departure crashes. The safety edge treatment also showed a crash-reduction effect on all lane departure crashes and fatal and injury lane departure crashes.

Finally, all models were validated to check for accuracy. Models developed for the cross-sectional method were validated using mean square error and mean of the residuals. Case-control models were validated using the specificity, accuracy, and sensitivity of the models. The significance of the CMFs developed using the before-and-after EB method was realized using the method given in the Highway Safety Manual.

17. Key Words		18. Distribution Statement	
crash mitigation—crash modification factors—lane departure countermeasures—run-off-road countermeasures—rural road safety		No restrictions.	
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	88	NA

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

ESTIMATING CRASH MODIFICATION FACTORS FOR LANE DEPARTURE COUNTERMEASURES IN KANSAS

Final Report
December 2017

Principal Investigator
Sunanda Dissanayake, Professor
Department of Civil Engineering, Kansas State University

Research Assistant
Uditha Galgamuwa

Authors
Sunanda Dissanayake and Uditha Galgamuwa

Sponsored by
Kansas Department of Transportation,
Midwest Transportation Center, and
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology

A report from
Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
www.intrans.iastate.edu

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors would like to thank the Midwest Transportation Center, the Kansas Department of Transportation (KDOT), and the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology for sponsoring this research.

The authors would also like to thank Steven Buckley and Elsit Mandal from KDOT for providing information on countermeasures and traffic and geometric data on Kansas roadways. Additional thanks go to Greg Schieber, Troy Howard, Wayne Gudmonson, Donna Schmit, Hugh Bogle, and Jeff Stewart, area engineers from KDOT, for providing information on safety edge treatments.

EXECUTIVE SUMMARY

Lane departure crashes make up a significant percentage of Kansas motor vehicle fatalities, so the Kansas Department of Transportation (KDOT) is looking at various countermeasures to reduce the number of these crashes in the state. However, it is important to know which countermeasures will be most effective, because implementing and evaluating the effectiveness of these countermeasures can be costly and time consuming.

The objectives of this project were as follows:

- Identify suitable methods to develop crash modification factors (CMFs) for lane departure countermeasures given the data available
- Estimate CMFs for lane departure countermeasures in Kansas
- Provide recommendations for implementing lane departure countermeasures in the future based on roadway characteristics

Background

Nearly 80% of transportation agencies in the US use CMFs for safety evaluations of design alternatives, expectations, and consistency evaluations. The use of CMFs to estimate the safety effectiveness of countermeasures such as composite shoulders, unpaved shoulders, wide shoulders, and bypass lanes in work zones has not been fully developed specifically for lane departure crashes.

The safety effectiveness of countermeasures can vary due to traffic, environmental, and demographic characteristics; human behavior; road culture; and geometric characteristics of the roadway. It may not be accurate to assume that a countermeasure successful in reducing crashes in a specific location in one region may prevent a similar type of crash in a different region.

Existing methods of developing CMFs can be divided into two main categories: 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 to be gathered from treatment and non-treatment sites and dated before and after the crash time period. Cross-sectional studies require only after-crash data for treatment and non-treatment sites; however, results can vary depending on the methods used to evaluate safety effectiveness.

Research Methodology

Following discussions with KDOT, six lane-departure countermeasures were selected for further analysis:

- Centerline and shoulder rumble strips
- Paved shoulders

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

Only two-lane undivided road segments and four-lane divided road segments were considered for the analysis. These make up a large percentage of the total road network in Kansas, and a majority of lane departure crashes occur on these roadways. Also, consideration was given to data availability for the road segments where the countermeasures had been implemented.

After reviewing the available methods for developing CMFs, the CMFs were estimated for each of the six lane-departure countermeasures using a different, appropriately selected method.

Three methods of developing CMFs were used. Cross-sectional and case-control methods based on cross-sectional data were used to develop CMFs when the date of implementation of the countermeasure was not known. The empirical Bayes (EB) method was selected to develop CMFs where the date of implementation was known, which was the case for safety edge treatments. To check the predictive power of the model validation methods, cross-sectional and case-control methods were employed.

Key Findings

Estimated CMFs from both the cross-sectional and case-control methods showed that the combination of centerline and shoulder rumble strips was the most effective countermeasure to reduce all lane departure crashes on rural two-lane tangent (14% to 33% reduction) and curved road (11% to 24% reduction) segments.

Shoulder rumble strips were shown to have a statistically positive relationship with all lane departure crashes on rural two-lane road segments, which implies that this countermeasure might have a crash increasing effect of 2% to 26%.

Of the two countermeasures considered for the models developed for four-lane divided road segments, shoulder rumble strips with paved shoulders greater than or equal to 2 ft were found to be the most effective countermeasure for reducing all lane departure crashes on tangent road segments, with a 9% to 20% crash-reduction effect.

For the curved road segments, paved shoulders greater than or equal to 2 ft were shown to be the most effective countermeasure, reducing crashes by 16% to 26%. For fatal and injury crashes on four-lane, divided tangent and curved segments, shoulder rumble strips with paved shoulders greater than or equal to 2 ft showed significant crash-reduction effects of 50% to 68% and 69% to 70%, respectively.

Models developed to estimate the safety effectiveness of cable median barriers on four-lane divided road segments showed that cable median barriers reduced all lane departure crashes by 50% to 65% and reduced fatal and injury lane departure crashes by 18% to 61%.

Models developed for chevrons and post-mounted delineators on rural two-lane curved-road segments showed that the presence of chevrons led to a safety effectiveness of 10% to 27% for all lane departure crashes and 12% to 47% for fatal and injury lane departure crashes. Post-mounted delineators showed a safety effectiveness of 15% to 31% for all lane departure crashes and 10% to 32% for fatal and injury crashes. Even though the models were developed to estimate CMFs, they accurately predicted crashes on their respective road segments.

Implementation Readiness and Benefits

Those who rely on modeling methods to test for highway safety effectiveness can use the results of this analysis when considering the choice of their next model methodology.

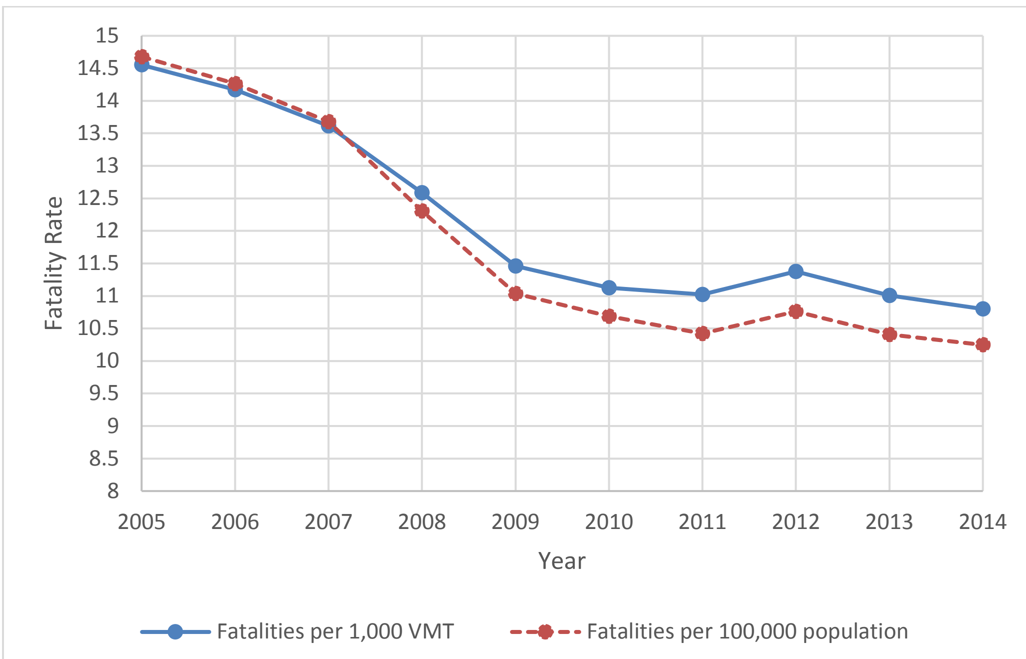
This study suggests that the case-control method is better suited to develop models for road segments where there are fewer crashes or fewer variations in crashes that do occur. The cross-sectional method is more appropriate for developing models for road segments where there is a larger range in the number of crashes. Furthermore, these two approaches (including the before-and-after EB method) are useful to estimate CMFs for the countermeasures where the implementation date is known.

These findings on the safety effectiveness of the countermeasures considered are based on data from the Kansas road network. The results can be used as a decision-making tool when implementing lane departure countermeasures on similar roadways in Kansas and other states.

1. INTRODUCTION

1.1. Background

Motor vehicle injuries are one of the top 10 leading causes of death in the world, resulting in approximately 1.3 million fatalities every year (WHO 2015). Similarly, in the United States, motor vehicle injuries were the 11th leading cause of death in 2014 (Dwyer-Lindgren et al. 2016). According to the Fatality Analysis Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA 2016), more than 32,000 people died yearly from 2009 to 2014 due to motor vehicle injuries in the United States (NHTSA 2016). Figure 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 through 2014.



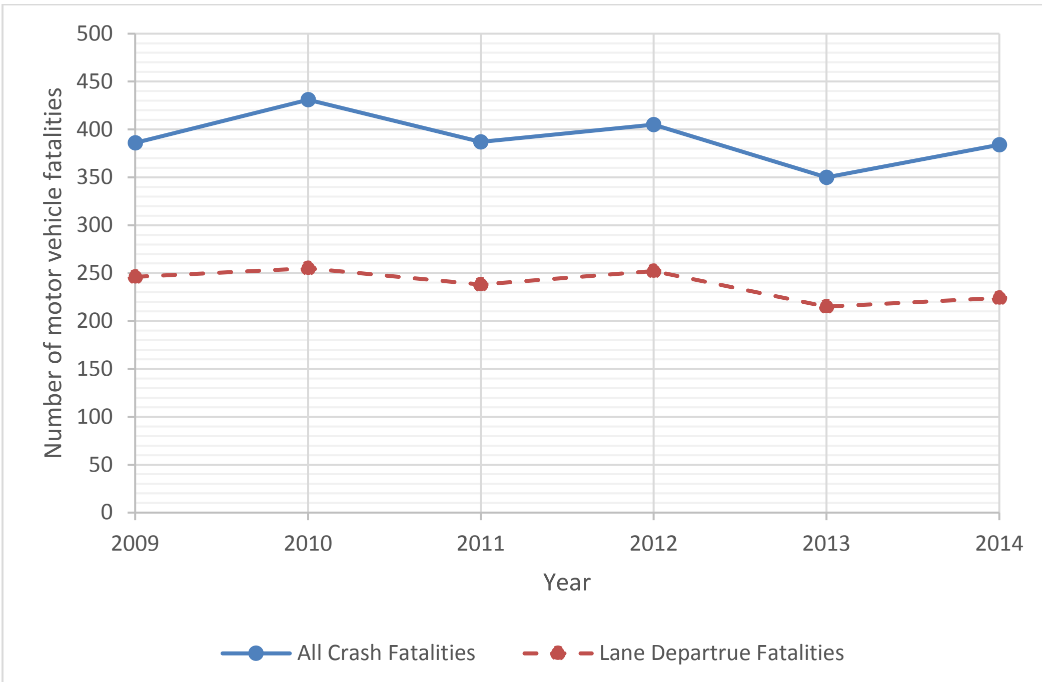
NHTSA 2016

Figure 1. Trend in motor vehicle fatality rates in the United States from 2005 through 2014

Even though fatality rates are falling due to advances in vehicle technologies and engineering countermeasures (Bonneson et al. 2002, Insurance Institute for Highway Safety Highway Loss Data Institute 2015, Retting et al. 2003), fatalities due to motor vehicle injuries continue to have a considerable effect on society.

1.2. Motor Vehicle Crashes in Kansas

Most motor vehicle fatalities are not attributed 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. Of these many crash types, lane departure-type crashes are the predominant cause of US motor vehicle fatalities. Defined as a "non-intersection event that occurs after a vehicle crosses an edge line or center line, or otherwise leaves the traveled way" (FHWA 2013), these lane departure crashes account for approximately 54% of total US motor vehicle fatalities (NHTSA 2016). Nationally and in Kansas, there are a higher number of lane departure crashes that result in fatalities (60%) compared to fatalities associated with other crash types. Furthermore, lane departure crashes constitute 47% of disabling crashes in Kansas (KDOT 2015). Figure 2 summarizes all motor vehicle fatalities and lane departure crash fatalities in Kansas from 2009 through 2014.



Data source: KDOT 2015

Figure 2. Trend in motor vehicle fatalities in Kansas from 2009 through 2014

Since lane departure crashes play a large role in the number of motor vehicle fatalities, the Kansas Department of Transportation (KDOT) has identified them as one of the six emphasis areas in the Strategic Highway Safety Plan (SHSP) (KDOT 2015). Furthermore, lane departure crashes in Kansas display different crash attributes such as different light conditions, road surface conditions, first harmful events, and most harmful events. Table 1 shows environmental conditions at the time of crashes on the Kansas roadway network using combined crash data from 2009 through 2014.

Table 1. Crash environment when lane departure crashes occurred on Kansas roadways from 2009 through 2014

Crash Attributes	Description	Crash Severity: Fatal	Disable	Non-incapacitating	Possible injury	PDO	Total crashes
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
	Daylight	**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

PDO = Property damage only crashes

Table 1 shows that most of these crashes occur in daylight on dry road surface conditions, leading researchers to believe that such crashes can be avoided by improving road geometry, signage, and road surfaces. It also is evident that many crashes occur in dark lighting conditions without street lights. Therefore, consideration should be given to improving signage so that it is visible in the dark with no street lights. Table 2 shows attributes of crashes occurring on the Kansas roadway network using combined crash data from 2009 through 2014.

Table 2. Lane departure crash attributes with crash severity on Kansas road network from 2009 through 2014

Crash Attributes	Description	Crash Severity: Fatal	Disable	NIC*	Possible injury	PDO	Total crashes
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

* NIC = Non-incapacitating, PDO = Property damage only crashes

Since a majority of the first harmful events (FHEs) and most harmful events (MHEs) 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 employed as remedial measures. Pavement surface improvement in curved road segments also could be made to improve safety. KDOT has implemented countermeasures such as rumble strips, paved shoulders, median cable barriers, safety edges, high-friction surface treatments (HFST), oversized chevrons, optical speed bars, and pavement legends in many road segments to reduce lane departure crashes. Numerous agencies and researchers have used methods such as statistical parametric and non-parametric analysis, crash rates, and crash modification factors (CMFs) to evaluate the safety effectiveness of these implemented countermeasures (AASHTO 2010, Council et al. 1980). CMFs are currently the most widely used and easily understood method. An advantage of using CMFs is that it is relatively easy to develop regression models for estimating regression coefficients, which then are used to estimate the CMFs of the considered countermeasures.

1.3. Problem Statement

Lane departure crashes constitute a significant percentage of motor vehicle fatalities in Kansas. Therefore, KDOT has emphasized various countermeasures to reduce the number of lane departure crashes. However, it is important to know which countermeasures will be most effective, because implementing and evaluating the safety effectiveness of these countermeasures can be costly and time consuming.

The safety effectiveness of countermeasures could vary among countries or from state to state due to traffic, environmental, and demographic characteristics; human behavior; road culture; and geometric characteristics of the road. It may not be accurate to assume that a countermeasure successful in reducing crashes in a specific location in one region may prevent a similar type of crash in a different region. Therefore, having more localized safety effectiveness measures available is an advantage in addressing lane departure crashes. The results can be used by KDOT to decide on appropriate countermeasures before implementation. Although several studies have been conducted in Kansas using CMFs to estimate the safety effectiveness of countermeasures such as composite shoulders, unpaved shoulders, wide shoulders, and bypass lanes in work zones, CMFs specific to lane departure crashes have not been fully developed.

1.4. Selected Countermeasures for the Study

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

- Centerline and shoulder rumble strips
- Paved shoulders

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

Only two-lane undivided road segments and four-lane divided road segments were considered for the analysis. These two facility types make up a higher proportion of the total road network in Kansas, and a majority of lane departure crashes occur on these types of roads.

1.5. Study Objectives

Two main objectives were identified for this study to estimate CMFs for lane departure countermeasures:

- Identify suitable methods of developing CMFs for identified lane departure countermeasures and available data

- Estimate CMFs for lane departure countermeasures in Kansas and provide recommendations for implementing lane departure countermeasures in future projects based on roadway characteristics

1.6. Organization of the Report

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

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 et al. 2009). Therefore, evaluating effectiveness of road safety measures is one of the important facets of road safety studies. Of the many available methods, such as statistical parametric and non-parametric analysis, crash rates, and CMFs (AASHTO 2010, Council et al. 1980), nearly 80% of transportation agencies in the United States use CMFs for safety evaluations of design alternatives, expectations, and consistency evaluations (Bonneson 2005). A CMF can be defined as the expected number of crashes with a countermeasure divided by the expected number of crashes had the countermeasure not been implemented (Gross 2007). Depending on data availability, methods of developing CMFs vary. Commonly used methods of developing CMFs are as follows:

- Before-and-after with comparison group studies (Gross and Jovanis 2007, Zeng et al. 2013)
- Empirical Bayes before-and-after studies (Gross and Jovanis 2007, Khan and Williams 2015, Nambisan and Hallmark 2011, Sun et al. 2014, Zeng et al. 2013)
- Full Bayes studies (Gross and Jovanis 2007, Hallmark et al. 2015, Lan et al. 2009, Yanmaz-Tuzel and Ozbay 2010, Zeng et al. 2013)
- Cross-sectional studies (Dissanayake and Esfandabadi 2015, Gross and Jovanis 2007, Gross and Donnell 2011, Zeng et al. 2013)
- Case-control studies (Gross and Jovanis 2007, Gross 2010, Gross and Donnell 2011, Jovanis and Gross 2007, Zeng et al. 2013)
- Cohort studies (Gross et al. 2010, Jovanis and Gross, 2007)

2.1. Different Studies on Selected Countermeasures Used in Kansas Evaluations

Previous literature has identified different countermeasures to reduce vehicle crashes on tangent and curved road segments. The following list shows the countermeasures that have been most commonly implemented in the US on both tangent and/or road segments and that have proven to be effective in many states:

- Advance curve warning and advisory speed signing (Hallmark et al. 2013)
- Chevrons and oversized chevrons (Hallmark et al. 2013, Hallmark and Hawkins 2014, Nambisan and Hallmark 2011)
- Widening/adding paved shoulders (Hallmark, et al. 2012, Hallmark et al. 2013, Khan et al. 2015, Nambisan and Hallmark 2011)
- Reflective barrier delineation (Hallmark et al. 2013)
- Rumble strips (Hallmark et al. 2009, Hallmark et al. 2013, Khan et al. 2015, Nambisan and Hallmark 2011)
- Safety edge treatments (Gross and Jovanis 2007, Hallmark et al. 2006, Hallmark et al. 2016, Hallmark et al. 2011, Nambisan and Hallmark 2011)
- High-tension median cable barriers (Nambisan and Hallmark 2011)
- Roadside post-mounted delineators (Nambisan and Hallmark 2011)
- Vertical delineation (Hallmark et al. 2012)

- Dynamic curve warning systems/Dynamic speed feedback (Hallmark et al. 2012, Hallmark et al. 2015, Nambisan and Hallmark 2011)
- Raised pavement marking (Hallmark et al. 2013, Nambisan and Hallmark 2011)
- High-friction surface treatment (Hallmark et al. 2013, Nambisan and Hallmark 2011)
- Edge lines (Hallmark et al. 2015) and wider edge lines (Hallmark et al. 2013, Nambisan and Hallmark 2011)
- Transverse pavement marking bars (Hallmark et al. 2013, Hallmark et al. 2013, Nambisan and Hallmark 2011)
- Pavement legends (Nambisan and Hallmark 2011)
- On-pavement curve signs (Hallmark et al. 2012, Hallmark et al. 2013)
- Pavement insert lights (Hallmark et al. 2013)
- Profile thermoplastic markings (Lord et al. 2011)
- Clear zones (Lord et al. 2011).

Since this research focuses on countermeasures commonly used in Kansas, such as paved shoulders, rumble strips, chevrons and post-mounted delineators, median cable barriers, and safety edge treatments, the relevant literature has been summarized in this section.

2.1.1. Paved Shoulders

Paved shoulders have proven to be effective in reducing all crash types—head-on, run-off-road, and side-swipe crashes. A study conducted on rural two-lane highways in Kansas found that upgrading narrow unpaved shoulders to 3 ft composite shoulders reduced shoulder-related crashes up to 61%, and decreased fatal and injury crashes up to 31% (Zeng and Schrock 2012, Zeng et al. 2013). A study conducted using data from seven US states concluded that increasing paved shoulders by 2 ft for shoulder widths between zero and 12 ft could reduce shoulder-related crashes by 16% (Zegeer et al. 1988). A Texas study showed that increasing paved shoulder width from 2 ft to 10 ft has reduced run-off-road and single-vehicle fatal, serious, and minor injury vehicle crashes by 71% to 87% on rural two-lane undivided road segments (Peng et al. 2012). However, some literature yielded 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 (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 crash. Centerline rumble strips mainly focus on reducing head-on crashes, while shoulder rumble strips focus on reducing single-vehicle crashes. In some road segments, both shoulder and centerline rumble strips have been implemented to prevent crashes, especially on curved road segments.

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). However, some studies of implementing shoulder rumble strips showed mixed effects 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 et al. 2013b). Centerline rumble strips were shown to reduced 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 centerlines and shoulder rumble strips (Persaud et al. 2015). Another study showed a 63.3% decrease in lane departure crashes on rural two-lane undivided highways in Washington state due to centerline and shoulder rumble strips (Olson et al. 2013b). However, a North Dakota study showed mixed results for the combined treatment of centerline and shoulder rumble strips (Kubas et al. 2013). The same study showed that due to centerline and shoulder rumble strips, all crashes and fatal crashes tend to decrease by 2.1% and 44.7%, respectively, while injury crashes increased by 20.7% on rural roadways. Furthermore, the same study showed 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 used in horizontal curved road segments provide better direction and sharpness than any other traffic control devices (Hallmark et al. 2013, McGee and Hanscom 2006). A study conducted on the connecting roadway of Naples and Canosa, Italy showed that chevrons reduced total crashes by 2.6% while reducing run-off-road-type crashes by 10%. Also, it was found that chevrons were more effective in rainy periods, where their use reduced crashes by 59.4%. However, the same study found that the number of nighttime crashes could rise by 92% (Montella 2009). A 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” (FHWA 2009). The purpose of post delineation is to outline the edges of the roadway and accent critical locations. According to the Handbook of Road Safety Measures, post-mounted delineators have a 4% crash-increasing effect on serious and minor injuries for all crash types and lead to a 5% rise in property damage only for all crash types on rural two-lane undivided road segments (Elvik and Vaa 2004). A study conducted on Korean freeways showed that installing post-mounted delineators increased crashes of all severities and types by 19% (Choi et al. 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, they offer greater deflection potential, which lessens the force of impact on the vehicle (Ross Jr. et al. 1993).

Bahar et al. (2007) reported that the crash-reduction effects of median cable barriers on three-lane highways were 100% and 26% for fatal and injury crashes, respectively. Furthermore, this countermeasure had a 29% crash-reduction effect on injury severity for all crash types on multilane divided highways and a 92% crash-reduction effect on head-on fatal crashes on rural highways. However, it was reported that median cable barriers showed a 34% crash-increasing trend for crashes of all severities and types on three-lane highways (Bahar et al. 2007). An Oregon study reported that median cable barriers reduced potential cross-over crashes by 40%, and the fatal crash rate was cut to zero per year from 0.6 per year. However, injury crashes rose from 0.7 per year to 3.8 per year (Sposito and 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. The same study reported that annual serious-injury median rollover collisions and annual fatal median rollover collisions were reduced by 65% and 31%, respectively, due to median cable barriers (Olson et al. 2013a). In addition, a study conducted in North Carolina concluded that even though some crash types, such as run-off-road-left and hit-fixed-object, increased due to median cable barriers, overall roadway safety was improved by reducing serious and fatal crashes as well as head-on crashes (Hunter et al. 2001).

2.1.6. Safety Edge

According to the Federal Highway Administration (FHWA), an effective solution for lane departure-type crashes is a safety edge treatment, where the edge of the pavement is shaped by 30 degrees. A safety edge may help drivers return to the roadway when a pavement edge drop-off appears. If there is no safety edge, 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 adopted the safety edge treatment to reduce pavement drop-off-type crashes.

The states of Georgia and Indiana have seen a 5.7% to 9.5% crash-reduction effect for all crash types due to safety edge treatment. Furthermore, these two states experienced a 4.8% to 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, fatal and injury run-off-road-type crashes rose by 20% and 2.6%, respectively, due to safety edge treatments on two-lane roads with unpaved and combined shoulders (Graham et al. 2011).

2.2. Methods of Developing Crash Modification Factors

Existing methods of developing CMFs can be divided into two main categories, 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 to be gathered from treatment and non-treatment sites and dated before and after the crash time period (Hallmark et al. 2012). Cross-sectional studies require only after-crash data for treatment and non-treatment sites (Bonneson and Lord 2005, Dissanayake and Esfandabadi 2015, Gross and Jovanis 2007, Hallmark et al. 2012). However, results can vary depending on the methods used to evaluate safety effectiveness (Torbic 2009).

2.2.1. Before-and-After Studies

The following types of before-and-after studies have been used to evaluate the safety effectiveness of countermeasures:

- Naïve before-and-after study (Izadpanah at al. 2009)
- Before-and-after study with yoked comparison (Griffin and 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 and Ozbay 2010)

Data requirements for before-and-after studies are higher than for cross-sectional studies. For such studies, the crash frequencies during the before and after periods at a treated site and the crash frequencies during the before and after periods at a non-treatment site, or the safety performance function (SPF) of the treated sites, are required (AASHTO 2010). However, it may be difficult to identify a clear cut-off point between the before and after periods for a treatment because the implementation date of that treatment is not known or is difficult to determine. Also, it is necessary to collect the geometric data such as segment length, annual average 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 methods 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 the observed and expected number of crashes in the before-and-after period have been used to estimate the safety effectiveness of a countermeasure in the after period (Park and Abdel-Aty 2015). The strength of the EB method is that it overcomes the limitation of the Naïve and CG methods by accounting for the regression-to-the-mean effect (Park and Abdel-Aty 2015, Shen and Gan 2003). Furthermore, the EB method accounts for observed changes in crash frequencies during the before and after periods and AADT changes (Park and Abdel-Aty 2015). The strength of the EB method for evaluations of safety effectiveness of the countermeasures has led to its widespread use internationally.

Studies conducted in Idaho, California, Illinois, British Colombia/Canada, and Minnesota used the EB method to determine the safety effectiveness of shoulder rumble strips (Griffith 1999, Khan et al. 2015, Patel et al. 2007, Sayed et al. 2010). A study conducted using data collected from seven states—California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington—used the EB method to evaluate the safety effectiveness of centerline rumble strips (Persaud et al. 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 et al. 2008). Studies conducted in Connecticut and Washington to evaluate the 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 et al. 2011) used the EB method. The EB method was used for analysis during a study conducted in San Francisco, California, to evaluate the safety effectiveness of high-visibility school crosswalks (Feldman et al. 2010). Finally, some researchers have used the EB method to gauge the combined effects of multiple treatments, such as installing both shoulder rumble strips and widening shoulder widths on rural two-lane roadways in Florida (Park and Abdel-Aty 2015).

2.2.1.2. Before-and-After Full Bayesian

The before-and-after full Bayesian method is one of two commonly used methods in before-and-after studies. The main difference between the EB and full Bayesian (FB) methods is that the EB method calculates safety effectiveness by combining the accident record for the treatment site and the SPF, showing how different factors affect accident occurrence. In the FB method, a distribution of expected crash frequencies is estimated instead of using point estimates (as in the EB method), which allows more precise levels of uncertainty in 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 and Ozbay 2010).

The FB method has been found to be very useful and provide better estimates than the EB method when working with a small number of observations (Miranda-Moreno and Fu 2007). This is because the FB method uses one step to conduct the SPF and treatment estimation, while the EB method requires several steps. 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 has been used by many safety researchers. Among them are studies conducted in Iowa to estimate the safety effectiveness of the road diet (Pawlovich et al. 2006) and to convert roads from four lanes to three lanes (Li et al. 2008). Other instances of the use of the FB method include a Minnesota study to estimate the safety effectiveness of converting unsignalized intersections to signalized intersections (Aul and Davis 2006) and a study conducted in Michigan, California, Washington, and Illinois to estimate the safety performance functions for two-lane highways (Qin et al. 2005). Furthermore, studies 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 et al. 2008).

2.2.2. Cross-Sectional Studies

2.2.2.1. Studies Using the Cross-Sectional Method

The cross-sectional method is commonly used in transportation safety research to estimate the expected number of crashes (Gross and 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 and 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 and Jovanis 2007, Gross and Donnell 2011). The cross-sectional method has also been used to calculate CMFs to evaluate the safety effectiveness of composite shoulders, wide unpaved shoulders, and wide paved shoulders on rural two-lane undivided roadways in Kansas (Zeng et al. 2013).

This frequently used method has inherent strengths and weaknesses. Strengths of the cross-sectional method include its applicability when multiple treatments are used on corresponding road segments (Lee et al. 2015) and for sensitivity analysis to identify alternative highway improvements (Benekohal and Hashmi 1992). The cross-sectional method also does not require the date of implementation of the countermeasure (AASHTO 2010). A weakness of the cross-sectional method is that it does not capture the effects of the factors not included in the model (Benekohal and Hashmi 1992). This method also requires a relatively large sample size, and the accuracy of estimates often varies according to data quality (Gan et al. 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 et al. 2001).

2.2.2.2. Studies Using the Case-Control Method

The case-control method has been used for many safety studies in the transportation sector (Davis et al. 2006, Dissanayake and Esfandabadi 2015, Gross and Jovanis 2007, Gross and Donnell 2011, Zeng et al. 2013). Defining case and control is essential in employing 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 and Jovanis 2007, Gross and Donnell 2011). Although a few past studies have focused on the effects of geometric elements, 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 the safety effectiveness of lane and shoulder widths of rural two-lane undivided road segments (Gross and Jovanis 2007, Jovanis and Gross 2007). CMFs for bypass lanes at rural intersections in Kansas and the presence of lighting at intersections in Minnesota were also estimated using the case-control method (Dissanayake and Esfandabadi 2015, Gross and Donnell 2011).

The case-control method, however, also 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 and 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 and Donnell 2011). In addition, the traditional case-control method cannot distinguish whether the segment experienced a single crash or multiple crashes (Gross Jr. 2006). Even though the matched case-control method can control confounding variables, it increases the complexity of data collection and sample selection, especially if there are many matching variables to be considered (Gross and Donnell 2011).

3. METHODOLOGY AND DATA

3.1. Methodology

After reviewing the available methods, a methodology was selected to estimate CMFs for identified countermeasures related to lane departure crashes. Also, consideration was given to data availability for the road segments where the countermeasures had been implemented. The following sections describe how the CMFs were estimated, using a different method for each countermeasure considered.

3.1.1. Methods of Developing CMFs for Each Countermeasure

This section summarizes three methods of developing CMFs for lane departure countermeasures in Kansas. Cross-sectional and case-control methods based on cross-sectional data were used to develop CMFs where the date of implementation of the countermeasure was not known. The EB method was selected to develop CMFs where the date of implementation was known.

3.1.1.1. Cross-Sectional Method

A commonly used approach to estimate CMFs using the cross-sectional method is to develop linear regression models, assuming negative binomial error distribution. Here, the considered lane departure countermeasures are used as independent variables with other road geometric and traffic-related characteristics. Next, 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 independent variables before using them in the model (Kutner et al. 2004). Therefore, correlation matrices were developed for the independent variables used in developing models for tangent and curved segments. This allowed the researchers to identify multi-collinearity and then select statistically significant independent variables. Even though several different values were used as a cut-off level to identify the multi-collinearity, the most commonly used value (0.5) in previous traffic-related research was used as a cut-off level in this study (Dissanayake and Kotikalapudi 2012, Oh et al. 2005).

Before developing the models, the total dataset was randomly divided into two parts: two-thirds and one-third of the total dataset were to be treated as a model-developing dataset and a validation dataset, respectively. A model-developing dataset was used to develop the models, and a validation dataset was used to validate the accuracy of the developed models. The negative binomial log linear model is commonly used in the cross-sectional method to develop a crash-frequency model (Gross and Donnell 2011, Shankar et al.1995, Tarko et al. 1998, Vogt and Bared 1998). Equation 1 shows the general form of the negative binomial regression model, which is modified for the crash-frequency modeling (Montgomery et al. 2015, Poch and Mannering 1996).

$$\ln y = x\beta + \varepsilon_i \tag{1}$$

where

y = n×1 observations of crashes
β = p×1 vector of estimated regression parameters corresponding to geometric design and traffic-volume-related independent variables
x = n×p known independent model matrix of geometric design and traffic volume-related variables
ε_i = n×1 random vector variables (error)

The mean-variance relationship of a negative binomial distribution can be expressed as shown in Equation 2 (Poch and Mannering 1996).

$$Var\ (y) = E(y) + k\ E(y)^2 \tag{2}$$

where

$Var\ (y)$ = variance of observed crashes
$E(y) = \mu$ = expected crash frequency
k = overdispersion parameter

The maximum likelihood method estimates the coefficients in the linear regression model, as described in Equation 3 (Montgomery et al. 2015).

$$\mathrm{L}(\mathrm{y}, \mathrm{x}, \beta, \sigma^2) = \frac{1}{(2\pi\sigma^2)^{n/2}} \exp[-\frac{1}{2\sigma^2} \sum_{i=1}^{n} (y - \mu)^2] \tag{3}$$

Before developing models, outliers should be identified because they could affect the model fitness. In some cases, if the model fitness is not satisfactory or many variables become insignificant, outliers should be treated to enhance the model's 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 the one case 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 dependent variable (the number of crashes per year on road segments) for outlier analysis. The stepwise method of selecting significant variables from the candidate variables was used to develop the models. The number of crashes per year per segment was chosen as the dependent variable, and previously selected variables were considered as independent variables to develop regression models according to Equation 1.

Model validation was carried out using two commonly used criteria, the mean of the residuals and mean square error (MSE), after fitting the estimated model using a validation dataset. If the mean of the residuals is approximately equal to zero and the MSE calculated using the validation dataset is approximately equal to the model MSE, the model is deemed to be a good model for predicting lane departure crashes on considered road segments.

3.1.1.2. Case-Control Method

The commonly used method of matched case-control design calls for development of a conditional logistic regression model to investigate the relationship between the outcome and risk factor (Gross and Donnell 2011, Jovanis and Gross 2007, Woodward 2013). This makes it easy to identify whether having a specific lane departure countermeasure can reduce crashes. Another advantage of employing a matched case-control design is that it directly controls confounding variables, which have a hidden effect on the dependent variable (Gross and Jovanis 2007). Also, confounding variables will provide erroneous results by suggesting a relationship between some independent variables and the dependent variable when no relationship exists. 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 4 (Montgomery et al. 2015).

$$E(y_i) = \pi_i = \frac{\exp(X_i^{'}\beta)}{1+\exp(X_i^{'}\beta)} \quad (4)$$

where

$E(y_i)$ = expected crashes at location *i*
β_i = estimated coefficients for independent variables
x_i = unmatched independent variables associated with road geometry

The dependent variable of the extracted dataset must be modified so that if the number of crashes is equal to or greater than 1, then 1 must be assigned to the crash column of the corresponding road segment, otherwise zero is used. The same dataset used in the cross-sectional method was used for the model development by modifying the dependent variable as noted earlier. 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 5.

$$L(y_1, y_1, \ldots y_1, \beta) = \prod_{i=1}^{n} \pi_i^{y_i} (1-\pi_i^{y_i})^{1-y_i} \quad (5)$$

The 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 refer to the proportion of events (crash segments) correctly predicted to the total number of crash segments and the proportion of non-events (no crash segments) correctly predicted to the total number of no crash segments, respectively.

3.1.1.3. Empirical Bayes Method

The empirical Bayes method is used when the date of implementation of the respective countermeasure is known. Safety edge treatment was the only countermeasures with the desired date of implementation available for this study. Therefore, the EB method was selected to estimate CMFs for safety edge treatment. 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 SPF. Generalized linear regression models, assuming negative binomial error structure, were used to develop SPFs using the form shown in Equation 6.

$$\hat{E}(k_{iy}) = AADT \times L_i \times e^{(\beta X_i)} \quad (6)$$

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)
β	=	$p\times1$ vector of estimated regression parameters corresponding to geometric design and traffic-volume-related independent variables
x	=	$n\times p$ known independent model matrix of geometric design and traffic volume-related variables

Equation 7 and Equation 8 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.

$$P_i = \sum_{y=1}^{3} \hat{E}(k_{iy}) \quad (7)$$

$$Q_i = \sum_{y=5}^{7} \hat{E}(k_{iy}) \quad (8)$$

Also, the ratio of the SPF estimates before and after safety edge implementation for segment i can be calculated using Equation 9.

$$C_i = \frac{\sum_{y=5}^{7} \hat{E}(k_{iy})}{\sum_{y=1}^{3} \hat{E}(k_{iy})} = \frac{Q_i}{P_i} \quad (9)$$

Step 2.

The expected number of crashes, M_i, before safety edge implementation can be estimated using Equation 10.

$$M_i = w_i \, P_i + (1 - w_i) \, K_i \tag{10}$$

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

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

where

K_i = total crash counts during the before period at site i
w_i = weight factor
k = overdispersion parameter

Overdispersion is one of the issues that need to be addressed when estimating CMFs using the EB method. Also, it has been found that the overdispersion parameter is a function of a roadway segment's length (Sun et al. 2014). A statistically more reliable SPF will have an overdispersion parameter closer to zero.

Equation 11 can be used to estimate the variance of M_i. Equation 12 and Equation 13 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 $\widehat{M}$.

$$\text{Var}(M_i) = (1 - w_i) \, M_i \tag{11}$$

Thus,

$$\widehat{M} = \sum_{i=1}^{I} M_i \tag{12}$$

$$\widehat{var}(\widehat{M}) = \sum_{i=1}^{I} var\,(M_i) \tag{13}$$

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 14 and 15.

$$\hat{\pi}_i = C_i \; M_i \tag{14}$$

$$\widehat{var}(\pi_i) = C_i^2 \, \widehat{var}(M_i) = C_i^2 (1 - w_i) \, M_i \tag{15}$$

where

$\widehat{var}(\pi_i)$	=	the variance of the estimate of EB-predicted crashes
$\hat{\pi}$	=	$\sum_{i=1}^{I} \pi_i$
$\widehat{var}(\hat{\pi}_\iota)$	=	$\sum_{i=1}^{I} var(\hat{\pi}_i)$

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 16 and Equation 17.

$$\hat{\theta} = \frac{L}{\hat{\pi} \left[1 + \frac{\widehat{var}(\hat{\pi}_\iota)}{\hat{\pi}^2}\right]} \tag{16}$$

$$\sigma(\hat{\theta}) = \frac{\hat{\theta} \times \sqrt{\frac{1}{L} + \frac{\widehat{var}(\hat{\pi}_\iota)}{\hat{\pi}^2}}}{1 + \frac{\widehat{var}(\hat{\pi}_\iota)}{\hat{\pi}^2}} \tag{17}$$

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.

3.2. Data and Model Variables

3.2.1. Data Availability

Data were collected after identifying commonly used lane departure countermeasures and potential methods for estimating CMFs based on data requirements. Two data sources were used: the Kansas Crash and Analysis Reporting System (KCARS) and the Control Section Analysis System (CANSYS). A brief description of each database is given below.

3.2.1.1. KCARS

The KCARS database provides a wide range of crash attributes, such as crash severity, number of people involved by their injury 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, the data can be exported into Excel and used in ArcGIS to map the crashes on the 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 the beginning and end of the road segment. These data can be used in ArcGIS and combined with the KCARS data to divide the road network into homogeneous segments with respect to the traffic and geometric characteristics of the roads.

Data obtained from CANSYS and KCARS were divided into three main categories: road geometry data, traffic-related data, and date of implementation. Methods of estimating CMFs were finalized after considering the available data for each countermeasure. Table 3 shows the availability of data fields for each countermeasure considered for this research and the proposed method of estimating CMFs for each countermeasure.

Table 3. 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 two-lane/four-lane divided road segments)	Available	Available	Not Available	Cross-Sectional Method
Centerline rumble strip (rural two-lane road segments)	Available	Available	Not Available	Cross-Sectional Method
Shoulder rumble strips (rural two-lane/four-lane divided road segments)	Available	Available	Not Available	Cross-Sectional Method
Chevrons (rural two-lane road segments)	Available	Available	Not Available	Cross - Sectional Method
Post-mounted delineators (rural two-lane road segments)	Available	Available	Not Available	Cross-Sectional Method
Median cable barriers (four-lane road segments)	Available	Available	Not Available	Cross-Sectional Method
Safety edges (two-lane and four-lane road segments)	Available	Available	Available	Before-and-After EB Method

Based on Table 3, it is seen that the dates of implementation of the paved shoulders and shoulder rumble strips on rural two-lane and four-lane road segments, centerline rumble strips, chevrons and post-mounted delineators on rural roads, and median cable barriers on four-lane road segments were not readily available. Therefore, the cross-sectional or case-control methods should be employed to estimate their CMFs. Since safety edge treatments have the date of implementation, the EB method can be used to estimate CMFs for the safety edge treatment.

3.2.2. Data

The dependent variable for the cross-sectional method is crashes per segment per year. For the case-control method, the dependent variable is whether the considered segment is the location of a crash site. Therefore, the number of crashes in each segment was extracted and combined with the geometric and traffic-related characteristics of the road. This section summarizes the data extracted for each countermeasure on different road segments using information from KCARS and CANSYS.

3.2.2.1. Rumble Strips and Paved Shoulders on Rural and Four-Lane Divided Road Segments

Step 1:

The KCARS database was used to extract details on lane departure crashes in Kansas from the beginning of 2009 through the end of 2014. Fatal and injury crashes and lane departure crashes of all severities 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 Figure 3.

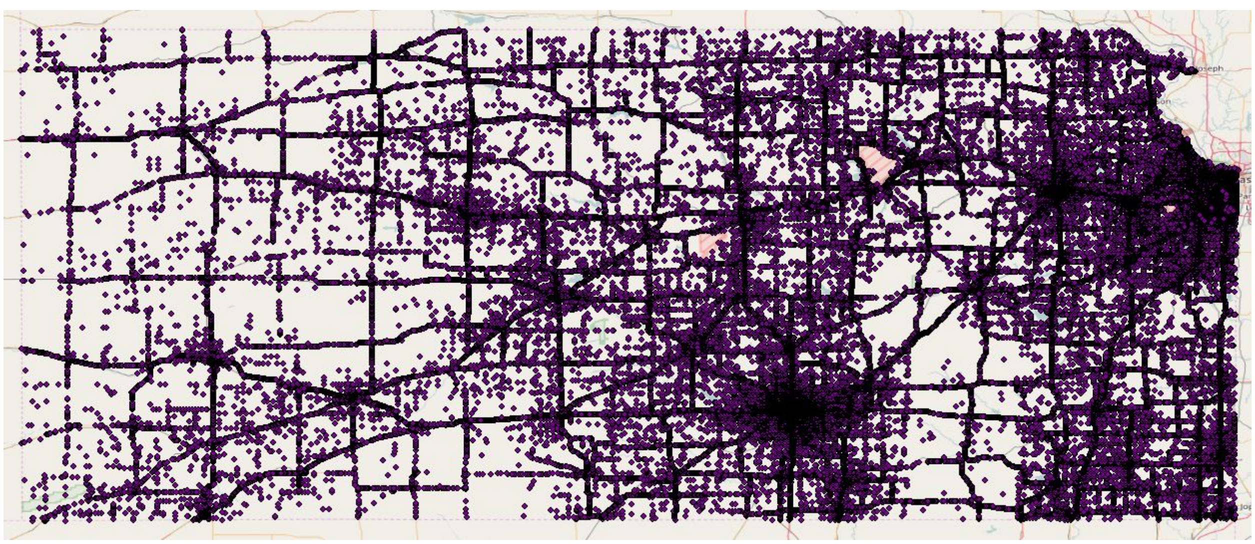


Figure 3. Lane departure crashes on Kansas roadways from the beginning of 2009 through the end of 2014

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.

Step 3:

Using number of lanes, the road network was divided into several groups, such as two-lane highways and four-lane highways. Next, separate buffer zones were created 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 4.

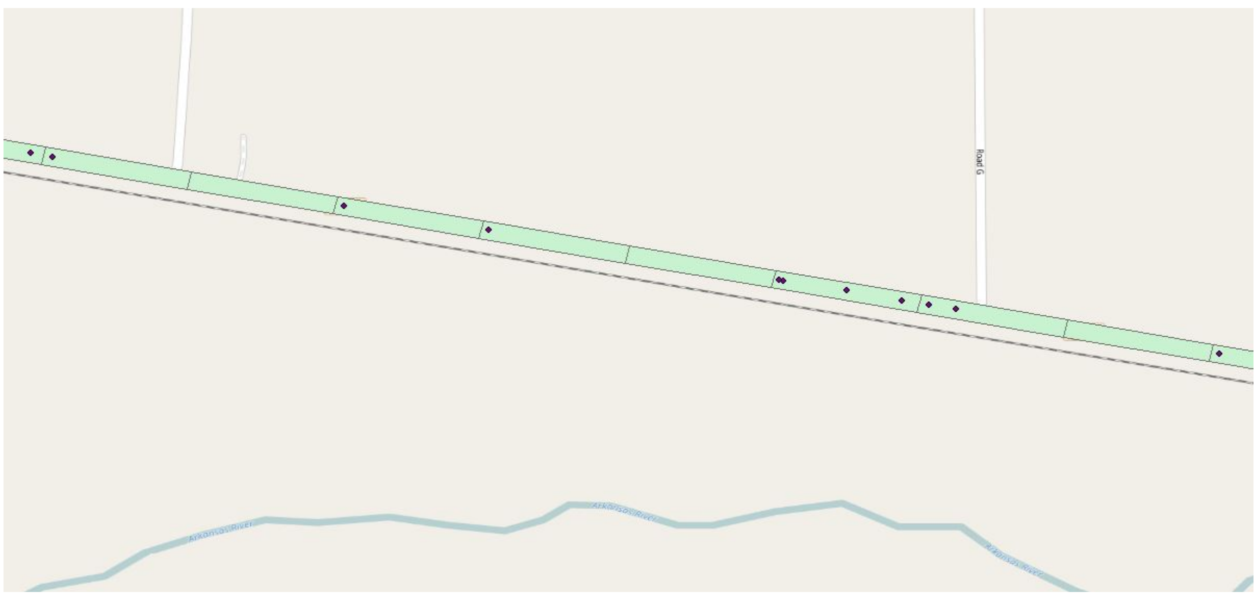


Figure 4. Lane departure crashes in buffered road segments of the Kansas road network

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 and to identify their geometric and traffic-related characteristics. The output was exported into Excel so that it could be used in SAS to develop the models. Finally, segment lengths were calculated using the beginning and ending mileposts of the road segments. However, the Highway Safety Manual (HSM) guideline for the minimum segment length is 0.1 miles (AASHTO 2010). Therefore, before developing models, segments of less than 0.1 miles were removed from the dataset.

3.2.2.2. Chevrons and Post-Mounted Delineators on Two-Lane Road Segments

Data on chevrons and post-mounted delineators were not included in the CANSYS database. Also, inventories of chevrons and post-mounted delineators could not be found. Therefore, it was decided to extract the data manually, as described below.

Step 1:

Google Street View was used to locate curves with and without chevrons and post-mounted delineators. The curves then were plotted on Google Earth as shown in Figure 5.

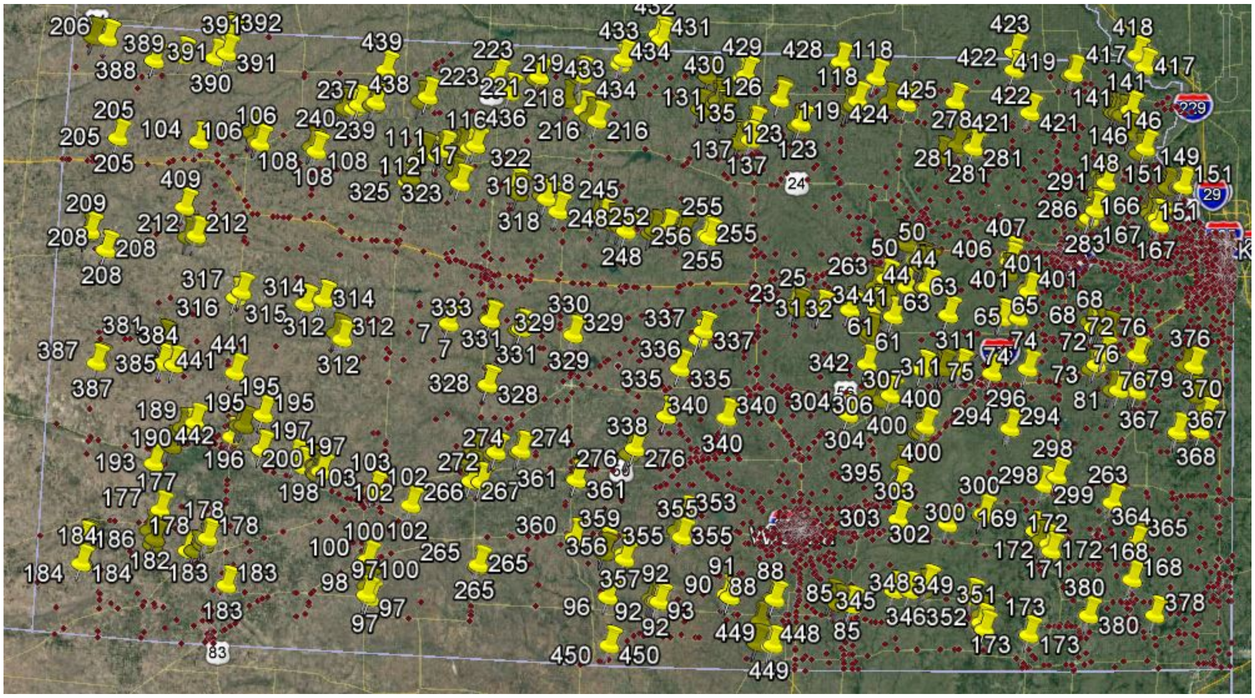


Image © Google 2015

Figure 5. Selected locations of chevrons and post-mounted delineators on Kansas two-lane roadways

Step 2:

Identified points were saved as a KML file, which was imported into ArcGIS 10.1. The road network shape file with its attributes, lane departure all-severity crashes, and lane departure fatal and injury severity crashes were then imported into ArcGIS 10.1 as shown in Figure 6.

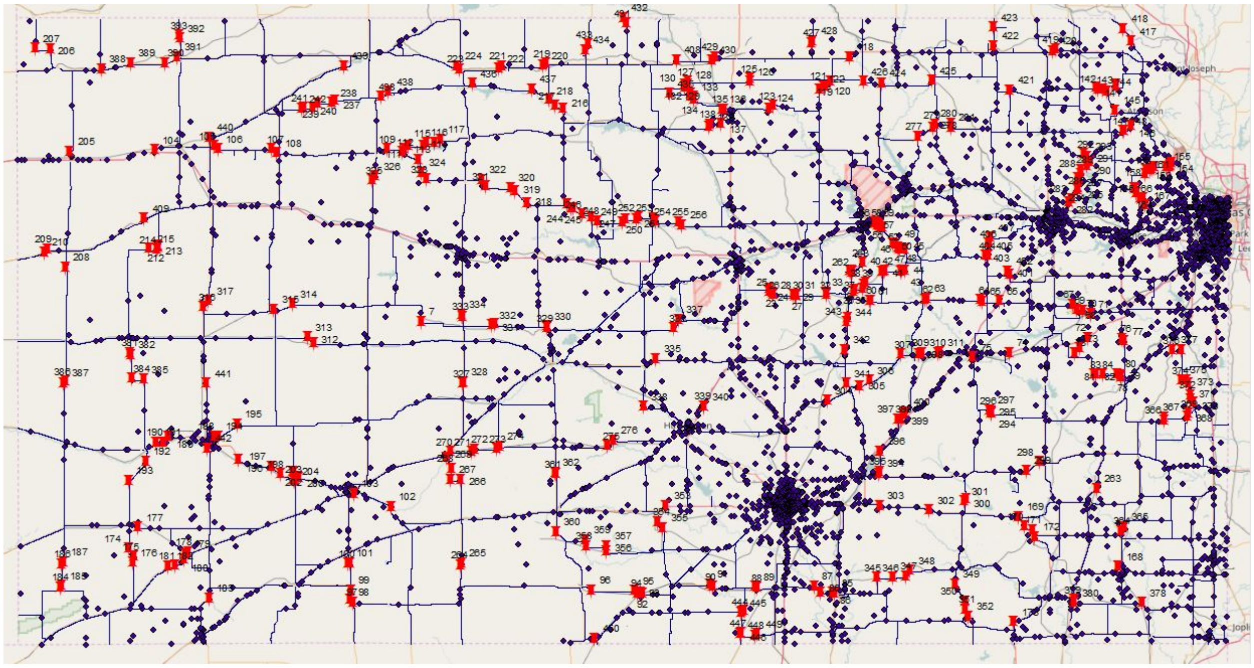


Figure 6. Location map of chevrons and post-mounted delineators (in red) and crashes (purple) on Kansas two-lane roadways

Next, 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.

Step 3:

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, with their geometric and traffic-related characteristics. The output was exported into Excel to be used in SAS to develop the models. Finally, the segment lengths were calculated using the beginning and ending mileposts of the road segments. However, the HSM guideline for minimum segment length is 0.1 miles (AASHTO 2010). Therefore, before developing the models, segments of less than 0.1 miles were removed from the dataset.

3.2.2.3. Cable Median Barriers on Four-Lane Divided Road Segments

The dataset was prepared with the raw dataset used to develop models for rumble strips and paved shoulders on four-lane road segments. 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 the data for developing models for cable median barriers.

Step 1:

Filter the dataset used to develop models for four-lane roadways to identify four-lane roadways with median cable barriers, depressed medians, and rigid and semi-rigid median barriers.

Step 2:

To aid the model development, the dataset was narrowed down. The entire dataset was filtered using median widths of 30 to 39 ft, 40 to 49 ft, and 50 to 60 ft, lane widths equal to 12 ft, posted speed limits of 60 mph and 70 mph, area type urban, shoulder rumble strips, and paved shoulders. Also, road segments of less than 0.1 mile were removed as specified in the HSM.

3.2.2.4. Safety Edge Treatments on Rural, Two-Lane, Undivided Road Segments

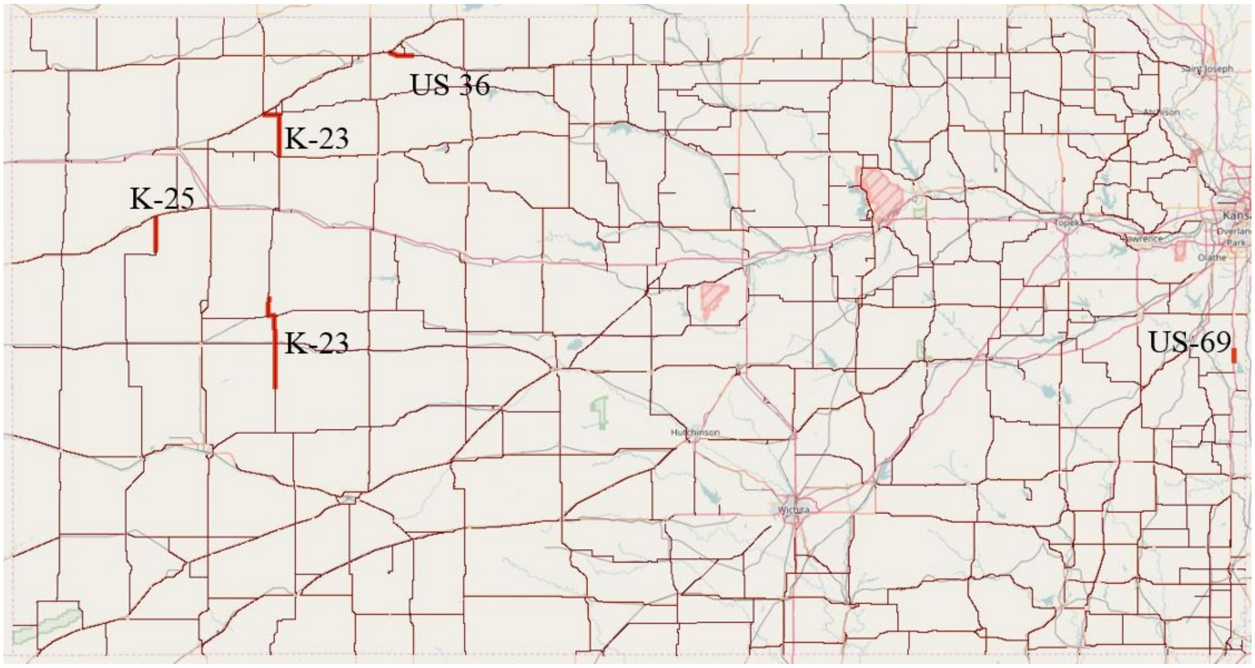
Information on road segments with safety edge treatments was obtained by contacting KDOT district engineers. Five locations cited below were identified with their dates of implementation and other treatments within the analysis period:

1. US 69 Miami/Linn County line north 4.68 miles in 2015
2. US 36 from east US 36/K-383 Junction to the Phillips County in 2011
3. K- 23 from the Lane County line to 0.5 miles south of Grove in 2010
4. K- 25 from Russell Spring to US 40 in 2012
5. K- 23 from Hoxie to the US 83/K-383 junction in 2012

Since the implementation date for the safety edge treatment is known, it was decided to employ before-and-after EB to estimate CMFs. However, the US 69 road segment had to be excluded since the after-crash data were not available. The following steps were taken when extracting the data to evaluate the effectiveness of the safety edge treatments.

Step 1:

Identify the road segments with safety edge treatments and map them on Google Earth. Save the location as a KML file to import into ArcGIS 10.1. Figure 7 shows the locations with the safety edge treatments after being mapped in ArcGIS 10.1.

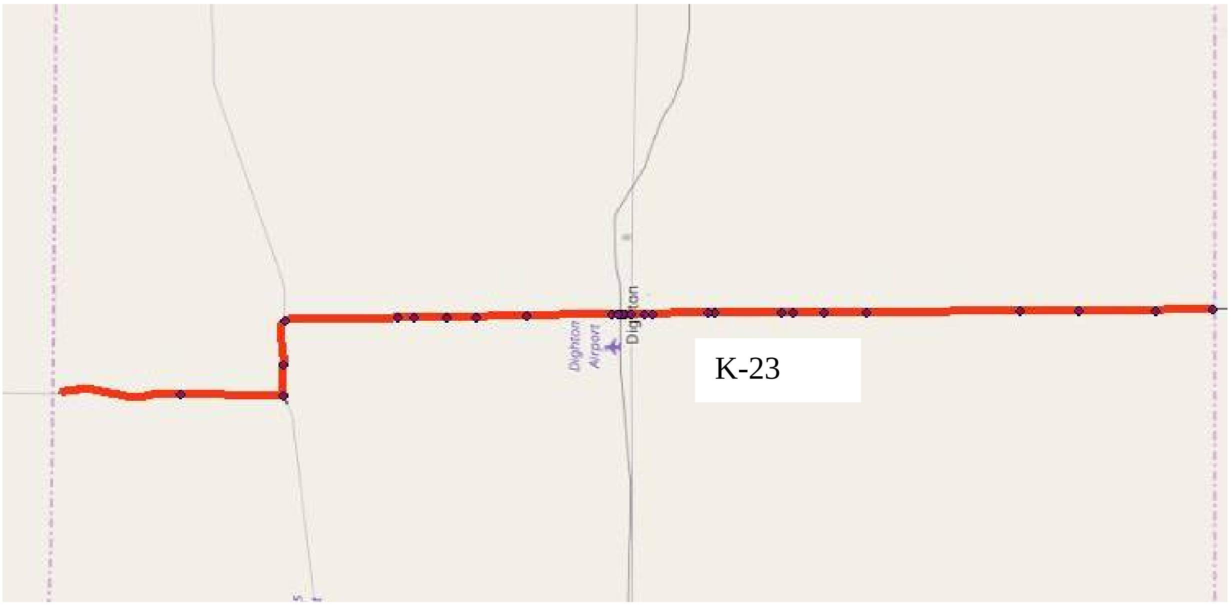


Map © Google 2015

Figure 7. Road segments with safety edge treatments

Step 2:

Lane departure crashes were mapped with the year the crash occurred using data from the KCARS database. Also, geometric and traffic characteristics in the CANSYS database were used to divide long road stretches with safety edge treatments into homogeneous road segments. Figure 8 shows the mapped crashes on K-23 from the Lane County line to 0.5 miles south of Grove.



Map © Google 2015

Figure 8. Mapped crashes on K-23 from Lane County line to 0.5 miles south of Grove

Step 3:

All lane departure crashes and fatal and injury lane departure crashes from 2007 to 2015 were counted separately for each homogeneous road segment; the output was exported into an Excel spreadsheet. However, the HSM guideline for the minimum segment length is 0.1 miles (AASHTO 2010). Therefore, before developing the models, segments of less than 0.1 miles were removed from the dataset.

Step 4:

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.

3.2.3. Model Variables

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

3.2.3.1. Rumble Strips and Paved Shoulders on Two-Lane Road Segments

A correlation matrix was developed for the independent variables considered for two-lane rural road segments. Results showed that AADT correlated with AADT of medium trucks (0.706) and AADT of heavy trucks (0.729) for tangent and curved road segments, respectively. 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 ft, 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.

3.2.3.2. Rumble Strips and Paved Shoulders on Four-Lane Divided Road Segments

Before developing the models, multi-collinearity was checked among independent variables. A correlation matrix was developed for the independent variables considered for four-lane divided road segments. Results showed that 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, including 8 categorical and 4 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 subsequently by considering the crashes per year per segment from 2009 to 2014 as a dependent variable. Before developing the models, the entire dataset was divided into one-third and two-thirds sections for model building and validation. Data for all crash severities on tangent and curved road segments were used to develop the model without treating for any outliers. However, the dataset extracted using fatal and injury crashes for tangent and curved road segments contained many outliers. Therefore, Cook’s distance was used to remove the outliers from the model-building dataset. Reference levels for categorical variables were set as no no-passing, painted median, area type urban, average lane width equal to or less than 12 ft, 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.

3.2.3.3. Chevrons and Post-Mounted Delineators on Two-Lane Road Segments

Before developing the models, the independent variables were checked for multi-collinearity. A correlation matrix was developed for the independent variables considered for two-lane road segments. Results showed that 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 9 categorical and 4 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. Next, models were developed by considering the crashes per year per segment from 2009 to 2014 as a dependent 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 ft, 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 sections of one-third and two-thirds for model building and validation.

3.2.3.4. Cable Median Barriers on Four-Lane Divided Road Segments

Since the sample size was not large enough to develop models for the curved road segments, the models were developed only 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 independent variables. A correlation matrix was developed for the independent variables considered for four-lane divided road segments. Posted speed limits were correlated with terrain type (-0.535) and median width of 40 to 49 in. (-0.586). Therefore, posted speed limit was removed from the dataset. The final dataset contained 7 variables including 3 categorical and 4 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 dependent variable. Before developing the models, the entire dataset was divided into sections of one-third and two-thirds for model building and validation. Reference levels of the categorical variables were set as terrain type rolling, median width of 30 to 39 in., and depressed median for categorical variables of terrain type, median width, and barrier type.

3.2.3.5. Safety Edge Treatments on Rural Two-Lane Undivided Road Segments

Since it was decided to develop SPFs for all lane departure crashes and fatal and injury lane departure crashes using a generalized linear regression model as shown in Equation 6, explanatory variables were selected and checked for the multi-collinearity effect. No multi-collinearity effect was found among the considered independent variables. The final dataset contained 8 variables, namely AADT, segment length, passing restrictions, lane width, speed limit, percentage of commercial vehicles, paved shoulders, and horizontal curvature.

4. RESULTS AND MODEL VALIDATION

This section summarizes results for the different methods used to estimate CMFs and methods of validating 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 a large 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 for developing models. Tables 4 and 5 show descriptive statistics of continuous and categorical variables identified as potential independent variables to develop models for rumble strips and paved shoulders on two-lane road segments.

Table 4. 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 5. 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

When developing the models, some levels of independent variables were combined to create samples of sufficient size. One example was the merger of the 10 ft lane and 11 ft lane and its inclusion as a lane width of less than 12 ft, as shown in Table 5.

4.1.2. Results

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 6 shows the parameters estimated for the final models, which were developed using the cross-sectional method with the standard deviation and *p*-value of the estimates.

Table 6. 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)

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)
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

Even though the centerline rumble strips and both centerline and shoulder rumble strips were insignificant in some models, those variables remained in the models, as had been done in previous research using the cross-sectional method (Gross and Jovanis 2007, Gross and Donnell 2011). The major reason for retaining these insignificant variables was that those were the countermeasures to be evaluated where parameter estimates were used to estimate CMFs. Therefore, entry and exit values were increased when using the stepwise method to develop models that give 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 that 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; results are shown in Table 7.

Table 7. CMFs for paved shoulders and rumble strips using the cross-sectional method for rural two-lane road segments

	All lane departure crashes		**Fatal and injury lane departure crashes**	
	Tangent Road Segments	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
Countermeasures	**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 the results of the cross-sectional method, centerline and shoulder rumble strips can be identified together as the most effective countermeasure among the four considered for 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 CMFs includes 1.

4.1.2.2. Case-Control Method

Two models each 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 8. Odds ratios were calculated using estimated parameters.

Table 8. Parameter estimates of the model developed using the case-control method for rural two-lane road segments

	All Lane Departure Crashes				Fatal and Injury Lane Departure Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
Variables	**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 9, with maximum and minimum values for the CMF. As shown by the cross-sectional method, some important variables needed to be in the model to estimate the CMFs when respective countermeasures were insignificant. To keep them in the model, entry and exist values were increased in the stepwise method when developing models so that every variable had an equal chance. As a result, AADT in one model became insignificant (p-value = 0.26) in one of the developed models.

Table 9. CMFs for paved shoulders and rumble strips using the case-control method for rural two-lane road segments

	All lane departure crashes		Fatal and injury lane departure crashes	
	Tangent Road Segments	Curved Road Segments	Tangent Road Segments	Curved Road Segments
Countermeasures	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 in Table 9 show that centerline and shoulder rumble strips, and 2 ft paved shoulders have a 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 effects 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 categories of lane departure crashes on curved road segments.

4.1.3. Model Validation

4.1.3.1. Cross-Sectional Method

Model validation was carried out using two commonly used criteria; the mean of the residuals and MSE were checked after fitting the estimated model using the validation dataset, as mentioned in the description of the methodology. Table 10 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 10, it can be clearly seen that in all models, the mean of the residuals is close to zero, and the MSE of the validation dataset is approximately equal to the model MSE. Therefore, the developed models using the cross-sectional method are accurate enough to predict lane departure crashes on two-lane-rural highways; hence, the estimated CMFs based on estimated regression parameters were accurate.

Table 10. Model validation for models developed using the cross-sectional method for two-lane rural road segments

	All Lane Departure Crashes				Fatal and Injury Lane Departure Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
Validation Statistics	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 Residuals	-	0.176	-	0.193	-	0.100	-	0.271

4.1.3.2. Case-Control Method

A ROC was used to evaluate the predictive power of the models for a binary outcome. Classification tables were used to implement this method, as mentioned in the methodology. Table 11 shows the calculated accuracy, sensitivity, and specificity for the developed models using the case-control method. Based on these results, the developed models predict the outcome with close to 90% accuracy and predict no crashes with greater than 90% accuracy. Furthermore, the developed models predict crash events with 50% accuracy, which is reasonable for such models.

Table 11. Model validation for models developed using the case-control method for two-lane rural road segments

	All Lane Departure Crashes		Fatal and Injury Lane Departure Crashes	
Validation Statistics	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 lengths of 2,316 miles and 597 miles, respectively, considered for developing the models. Some levels of categorical variables had small sample sizes and were therefore combined for use as categorical variables for the model. Table 12 shows the categorical variables used in the model after combining some levels, and Table 13 shows the descriptive statistics of continuous variables.

Table 12. 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 < 60 mph	1,251	176	7.61	416	45	7.59
Speed Limit 60_65 mph	2,026	364	15.73	772	102	17.09
Speed Limit 70_75 mph	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 13. 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 14 shows parameter estimates for the final models developed using the cross-sectional method with the standard deviations and *p*-values of the estimates.

Table 14. 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

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 significance level in some models. However, it is necessary that the models include the variable to estimate CMFs of shoulder rumble strips and paved shoulders ≥2_ft. Therefore, entry and exit levels were increased when using the stepwise 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 the p-values of those variables were higher.

After the models were developed, CMFs were estimated using the expression, CMF = exp (β), where β is the estimated regression parameter for the corresponding variable. Table 15 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 in the case of all lane departure crashes on tangent road segments.

Table 15. CMFs for paved shoulders and rumble strips using the cross-sectional method

	All lane departure crashes		**Fatal and injury lane departure crashes**	
	Tangent Road Segments	**Curved Road Segments**	**Tangent Road Segments**	**Curved Road Segments**
Countermeasures	**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 16. 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 appear in the models to estimate the CMFs, entry and exist values of the stepwise 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.

Odds ratios were calculated using estimated parameters. Since no paved shoulder was set as the 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 17 with the maximum and minimum values for the CMFs.

Table 16. Parameter estimates of the model developed using the case-control method of shoulder rumble strips and paved shoulders on four-lane divided road segments

	All Lane Departure Crashes				Fatal and Injury Lane Departure Crashes			
	Tangent Road Segments		Curved Road Segments		Tangent Road Segments		Curved Road Segments	
Variables	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)

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)**
% 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

Table 17. Estimated CMFs for paved shoulders and rumble strips on four-lane roadways using the case-control method

	All lane departure crashes		Fatal and injury lane departure crashes	
	Tangent Road Segments	Curved Road Segments	Tangent Road Segments	Curved Road Segments
Countermeasures	**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 as well as fatal and injury lane departure crashes. Furthermore, paved shoulders without rumble strips ≥2_ft were shown to be 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-increasing effect on some road segments.

4.2.3. Model Validation

4.2.3.1. Cross-Sectional Method

Table 18 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 the results in Table 18, it is clear that in all models the mean of the residuals is close to zero and the MSE of the validation datasets is approximately equal to the model MSE. Therefore, the 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.

Table 18. 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 Residuals	–	0.006	–	0.022	–	-0.392	–	0.673

4.2.3.2. Case-Control Method

Table 19 shows the calculated accuracy, sensitivity, and specificity for the developed models using the case-control method.

Table 19. 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

These results suggest that the developed models using all lane departure crashes predict the outcome with an accuracy close to 70%, while fatal and injury lane departure crashes are predicted with an accuracy greater 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 greater than 95%. Finally, the developed models predict crash events with an accuracy closer to 50%, except for the model developed for tangent road segments using fatal and injury lane departure crashes.

4.3. Chevrons and Post-Mounted Delineators on Two-Lane Road Segments

4.3.1. Descriptive Statistics of the Site Selected

A total of 527 curved road segments, with a total length of 210.6 miles, were considered for developing models. Some levels of these categorical variables had small sample sizes and were combined for use as categorical variables for the model. Table 20 shows the descriptive statistics of the categorical variables. Table 21 shows continuous variables used in the models after combining some levels.

Table 20. Descriptive statistics of categorical variables used to develop models for chevrons and post-mounted delineators on two-lane road segments

Variables	Description	Number of Segments	Total Length of Segments (miles)	% to Total Length
Passing Restrictions	No-Passing	1,918	107.10	50.85
	No No-Passing	1,328	103.51	49.15
Area Type	Rural	3.193	206.91	98.24
	Urban	53	3.70	1.76
Lane Width	<12_ft	272	14.94	7.09
	≥12_ft	2,974	195.67	92.91
Speed Limit	≤60mph	2,198	54.11	25.69
	>60mph	1,048	156.50	74.31
Rumble Strips	Centerline	273	21.24	10.08
	Shoulder	404	27.29	12.96
	Centerline and Shoulder	139	11.20	5.32
	No Rumble Strips	2,430	150.88	71.64
Paved Shoulders	2 ft Paved Shoulders	1,650	119.06	56.53
	No Paved Shoulders	1,596	91.55	43.47
Terrain Type	Flat	1,513	105.73	50.20
	Rolling	1,733	104.88	49.80
Target Countermeasures	Chevrons	739	42.32	20.09
	Post-Mounted Delineators	606	38.34	18.20
	Without Chevrons and Post-Mounted Delineators	1,901	129.95	61.70

Table 21. Descriptive statistics of continuous variables used to develop models for chevrons and post-mounted delineators on two-lane road segments

Variables	Mean	Standard Deviation	Minimum	Median	Maximum
AADT (vehicles/day)	1580.3	1399.9	115	1050	8230
Segment Length (miles)	0.10	0.02	0.10	0.10	0.61
Percent Heavy Vehicle	20.48	10.61	3.70	19.33	63.71
Horizontal Curvature (degree of curvature)	2.62	4.21	0.18	1.56	62.28

4.3.2. Results

4.3.2.1. Cross-Sectional Method

Table 22 shows the regression parameters estimated for the model developed using the cross-sectional method to estimate CMFs of chevrons and post-mounted delineators on rural two-lane roadways, with their standard deviations and p-values.

Table 22. Parameter estimates of models developed to estimate CMFs of chevrons and post-mounted delineators on two-lane road segments using the cross-sectional method

	All Lane Departure Crashes		Fatal and Injury Lane Departure Crashes	
Variables	**Parameter Estimates**	**Standard Error (p-value)**	**Parameter Estimates**	**Standard Error (p-value)**
Intercepts	-4.170	0.349 (<.0001)	-5.626	0.262 (<.0001)
No Passing Restrictions	0.079	0.085 (0.35)	0.117	0.064 (0.07)
Area Type Rural	-1.121	0.300 (0.0002)	-0.404	0.225 (0.07)
Terrain Type Flat	-0.106	0.081 (0.19)	-0.060	0.061 (0.32)
% Heavy Commercial Vehicles	*ns**	*ns**	-0.005	0.003 (0.13)
Horizontal curvature	0.033	0.010 (0.0006)	0.027	0.007 (0.0002)
Ln (segment length)	0.291	0.039 (<.0001)	0.165	0.029 (<.0001)
Ln (AADT)	0.472	0.057 (<.0001)	0.201	0.043 (<.0001)
Centerline Rumble Strips	-0.283	0.140 (0.043)	-0.160	0.105 (0.12)
Shoulder Rumble Strips	-0.451	0.132 (0.0006)	-0.101	0.099 (0.30)
Both Centerline and Shoulder Rumble Strips	-0.423	0.196 (0.22)	-0.170	0.147 (0.24)
Chevrons	-0.122	0.100 (0.10)	-0.125	0.075 (0.09)
Post-Mounted Delineators	-0.161	0.100 (0.15)	-0.107	0.075 (0.15)

ns* = not significant for the developed model

All lane departure crashes and fatal and injury lane departure crashes on curved road segments were considered when developing the models. Estimated regression parameters were then converted to CMFs using the expression CMF=exp (β), where β is the estimated regression parameter. Results are shown in Table 23.

Table 23. Estimated CMFs for chevrons and post-mounted delineators on two-lane road segments using the cross-sectional method

Countermeasures	All Lane-Departure Crashes CMF (CMF_{min}, CMF_{max})	Fatal and Injury Lane Departure Crashes CMF (CMF_{min}, CMF_{max})
Chevrons	0.89 (0.80,0.98)	0.88 (0.82,0.95)
Post-Mounted Delineators	0.85 (0.77,0.94)	0.90 (0.83,0.97)

4.3.2.2. Case-Control Method

Case-control models were developed using the same variables and datasets employed to create cross-sectional models for chevrons and post-mounted delineators. Table 24 shows the estimated parameters using the case-control method with their standard deviations and p-values.

Table 24. Parameter estimates of models developed to estimate CMFs of chevrons and post-mounted delineators on two-lane 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	-2.795	0.533 (<.0001)	-4.011	0.725 (<.0001)
No No-Passing	0.135	0.141 (0.37)	0.337	0.190 (0.07)
Paved Shoulders	-0.438	0.176 (0.012)	-0.436	0.236 (0.06)
Area Type Rural	*ns**	*ns**	-0.270	0.457 (0.10)
Average Lane Width >12_ft	0.250	0.263 (0.15)	0.567	0.403 (0.34)
Terrain Type Flat	0.049	0.134 (0.83)	0.037	0.180 (0.71)
Percent Heavy Commercial Vehicles	-0.007	0.007 (0.06)	-0.019	0.010 (0.30)
Horizontal Curvature	0.041	0.013 (0.0003)	0.058	0.016 (0.002)
Segment Length	8.970	1.357 (<.0001)	8.515	1.574 (<.0001)
AADT	0.348	0.049 (<.0001)	0.275	0.063 (<.0001)
Chevrons	-0.308	0.178 (0.01)	-0.644	0.257 (0.08)
Post-Mounted Delineators	-0.366	0.176 (0.10)	-0.383	0.238 (0.03)

ns*- = not significant for the developed model

Since road segments without chevrons or post-mounted delineators were designated as the reference level, the estimated odds ratio for the respective countermeasures can be considered as the CMF. Results are shown in Table 25.

Table 25. Estimated CMFs for chevrons and post-mounted delineators on two-lane road segments using the case-control method

Countermeasures	All Crash Severities CMF (CMF_{min}, CMF_{max})	Fatal and Injury Crash Severities CMF (CMF_{min}, CMF_{max})
Chevrons	0.73 (0.62,0.88)	0.53 (0.41,0.68)
Post-Mounted Delineators	0.69 (0.58,0.83)	0.68 (0.54,0.87)

4.3.3. Model Validation

4.3.3.1. Cross-Sectional Method

Model validation was carried out using the MSE and mean of the residuals for the cross-sectional method. Table 26 shows the validation statistics calculated using the model validation dataset and the estimated MSE from the developed model.

Table 26. 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	2.06	0.15	1.55	0.05
Mean of Residuals	-	-0.12	-	0.07

Based on results in Table 26, it is apparent that in all models, the mean residuals are close to zero and the MSE of the validation datasets are less than the model MSE. Therefore, the 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.

4.3.3.2. Case-Control Method

After developing the models, validation was carried out using classification tables. Table 27 shows validation statistics calculated using the model validation dataset.

Table 27. 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	92	99
Sensitivity	90	95
Specificity	72	80

According to the results in Table 27, the developed models can predict crashes or no crashes with an accuracy close to 90% while predicting no crash events with greater than 90% accuracy. Furthermore, the developed models using all lane departure crashes and fatal and injury lane departure crashes can predict crash events with accuracy levels of 72% and 80%, respectively.

4.4. Cable Median Barriers

4.4.1. Descriptive Statistics of Sites Selected

A total of 1,545 tangent segments, with a total length 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 generate an unbiased dataset for developing models, stratified sampling was used to select 150 data points covering 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 28 shows the descriptive statistics of the categorical variables. Table 29 shows descriptive statistics of continuous variables of the whole dataset, which contained 1,545 road segments, and the sample selected using stratified sampling, which contained 150 road segments.

Table 28. 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 65 mph	711	103	39.89	65	8.7	33.59
Posted Speed Limit 70 mph	834	155.2	60.11	85	17.2	66.41
Median Width 30 to 39 ft	123	24.2	9.37	18	2.7	10.42
Median Width 40 to 49 ft	181	26.1	10.11	42	6.3	24.32
Median Width 50 to 60 ft	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

Table 29. 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

4.4.2. Results

4.4.2.1. Cross-Sectional Method

Table 30 shows the 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.

Table 30. Parameter estimates of the model developed to estimate CMFs of cable median barriers on four-lane divided road segments using the cross-sectional method

	All Lane Departure Crashes		Fatal and Injury Lane Departure Crashes	
Variables	**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 in.	-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

All lane departure crashes, and fatal and injury lane departure crashes on tangent road segments were considered when developing the models. Estimated regression parameters were converted to CMFs using the expression CMF = exp (β), where β is the estimated regression parameter. Results are shown in Table 31.

Table 31. 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

Case-control models were developed using the same variables and datasets employed to develop cross-sectional models for cable median barriers. Table 32 shows estimated parameters using the case-control method with their standard deviations and p-values.

Table 32. Parameter estimates of the model developed to estimate CMFs for cable median barriers on four-lane divided road segments using the case-control method

	All Lane Departure Crashes		Fatal and Injury Lane Departure Crashes	
Variables	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 ft	-2.262	1.192 (0.0578)	-1.237	1.061 (0.243)
Median Width 50 to 60 ft	-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

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. Results are shown in Table 33.

Table 33. Estimated CMFs for cable median barriers on four-lane divided road segments using the case-control method

Countermeasure	All Lane Departure Crashes CMF (CMF_{min}, CMF_{max})	Fatal and Injury Lane Departure Crashes 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 was carried out using MSE and mean of the residuals for the cross-sectional method. Table 34 shows validation statistics calculated using the model validation dataset and estimated MSE from the developed model.

Table 34. Model validation for the model developed using cable median barriers on four-lane divided road segments for the cross-sectional method

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

The results in Table 34 show that in all models, the mean residuals are close to zero and the MSE value of the validation datasets is approximately equal to the model MSE. Therefore, the models developed 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 35 shows validation statistics calculated using the model validation dataset.

Table 35. 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	86.00	90.24
Sensitivity	50.00	53.85
Specificity	97.37	97.10

The results in Table 35 show that the developed models can predict crashes or no crashes with an accuracy close to 90%, while predicting no crash events with an accuracy above 97%. Furthermore, the developed models using all crash severities, and fatal and injury crash severities predict crash events with an accuracy greater than 50%.

4.5. Safety Edge Treatment on Rural Two-Lane Undivided Road Segments

4.5.1. Descriptive Statistics of the Site Selected

Four roadways with safety edge treatment were selected for the analysis. Using geometric and traffic characteristics in the CANSYS database, road segments were further divided into homogeneous segments. This study covered a total of 74 sites. The selected sites had 58 lane departure crashes, including 10 fatal and injury lane departure crashes in the before period. Furthermore, those sites had 57 lane departure crashes and 13 fatal and injury lane departure crashes in the after period. Descriptive statistics for the main characteristics of the four selected road segments are shown in Table 36.

Since the SPF given in the HSM is taken from studies done in another state, it was decided to develop a Kansas-specific SPF. Crashes per year per site served as the dependent variable, and independent variables (mentioned in Section 3.2.3.5) were used to develop a generalized linear regression model, assuming a negative binomial error structure. Reference sites were used to estimate regression parameters to predict crashes on each site with a safety edge treatment. Results are shown in Table 37.

Table 36. Descriptive statistics of road geometric/traffic and crash characteristics of road segments with safety edge treatments

Characteristics	Description	US 36(1) Before	US 36(1) After	K-23(2) Before	K-23(2) After	K-25(3) Before	K-25(3) After	K-23(4) Before	K-23(4) After
AADT	Mean	971	1,049	825.5	883.8	199.8	233.6	639.5	632.4
	St Dev	275.7	286.3	501.1	638.6	27.77	18.65	253.4	281.3
	Minimum	115	125	355	395	170	215	45	50
	Median	985	1,130	630	670	185	245	655	585
	Maximum	1,230	1,240	2,250	3,130	285	260	1,130	1,040
Lane Departure Crashes	All	14	28	26	20	4	2	14	7
	Fatal and injury	3	6	4	6	1	0	2	0
Segment Length	Mean	1.00		1.02		1.66		1.582	
	St Dev	0.775		1.745		3.2		2.32	
	Minimum	0.1		0.1		0.1		0.1	
	Median	0.82		0.25		0.22		0.855	
	Maximum	2.51		7.92		8.82		7.965	

Name of the Road Segment: US 36[1], K-23[2], K-25[3], K-23[4]

1. US 36 from east US 36/K-383 junction to the Phillips County Line
2. K-23 from the Lane County line to 0.5 miles south of Grove
3. K-25 from Russell Spring to US 40
4. K-23 from Hoxie to the US 83/K-383 junction

Table 37. Estimated regression parameters for SPFs

Variables	All Lane Departure Crashes			Fatal and Injury Lane Departure Crashes		
	Parameter Estimates	Standard Error	Pr > |t|	Parameter Estimates	Standard Error	Pr > |t|
Intercepts	-3.732	0.142	<.0001	0.666	0.050	<.0001
No Passing (both sides)	ns*	ns*	ns*	-0.418	0.051	<.0001
No Passing (single side)	ns*	ns*	ns*	-0.226	0.038	<.0001
Lane Width (<12_ft)	0.808	0.112	<.0001	ns*	ns*	ns*
Paved Shoulders	-0.513	0.140	0.0002	ns*	ns*	ns*
Ln (segment length)	1.164	0.068	<.0001	0.267	0.019	<.0001
Ln (AADT)	0.305	0.078	<.0001	0.056	0.022	0.0107

ns* = not significant for the developed model

4.5.2. Results

Using the developed SPF, EB estimates of the crashes in the after time period were calculated. Next, CMFs were calculated for all lane departure crashes as well as fatal and injury lane departure crashes. Results are shown in Table 38.

Table 38. Estimated CMFs for safety edge treatments

Crash Severity	Crashes in the After Period		CMF	Standard Error	Safety Effectiveness
	Observed	EB estimates			
All Lane Departure Crashes	57	55	0.892	0.149	10.8
Fatal and Injury Lane Departure Crashes	13	19	0.648	0.195	35.2

After estimating the CMFs, the ratio between safety effectiveness and the standard error of the safety effectiveness was calculated to check the significance of the developed CMFs (AASHTO 2010). If the value is less than 1.7, the developed CMF is not significant at a 90% confidence level; if it is greater than 1.7 and less than 2, the CMF is significant at a 90% confidence level; and if it is greater than or equal to 2, the CMF is significant at a 95% confidence level. However, the ratio between safety effectiveness and the standard error of the safety effectiveness is 0.73 for all lane departure crashes and 1.8 for fatal and injury lane departure crashes. This implies that the safety edge treatment is more reliable in reducing fatal and injury lane departure crashes.

5. CONCLUSIONS

This study employed cross-sectional, case-control, and before-and-after EB methods to estimate the safety effectiveness of lane departure countermeasures using CMFs. Cross-sectional and case-control methods were used to estimate CMFs for paved shoulders, and shoulder rumble strips on rural two-lane undivided and four-lane divided road segments; centerline rumble strips on rural two-lane road segments; cable median barriers on four-lane divided road segments; and chevrons and post-mounted delineators on two-lane road segments. The before-and-after EB method was used to estimate CMFs for safety edge treatments on rural two-lane undivided road segments.

Estimated CMFs from both the cross-sectional and case-control methods showed that the combination of both centerline and shoulder rumble strips was the most effective countermeasure to reduce all lane departure crashes on rural two-lane tangent (14% to 33% reduction) and curved road (11% to 24% reduction) segments. However, shoulder rumble strips were shown to have a statistically positive relationship with all lane departure crashes on rural two-lane road segments, which implied that they might have a crash-increasing effect of 2% to 26%. 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 on tangent road segments, with a 9% to 20% crash-reduction effect. For the curved road segments, paved shoulders ≥2 ft were shown to be most effective, reducing crashes by 16% to 26%. For fatal and injury crashes on four-lane, divided tangent and curved segments, shoulder rumble strips with paved shoulders ≥2 ft showed significant crash-reduction effects of 50% to 68% and 69% to 70%, respectively. Models developed to estimate the safety effectiveness of cable median barriers on four-lane divided road segments showed that cable median barriers reduced 50% to 65% of all lane departure crashes while reducing 18% to 61% of fatal and injury lane departure crashes. Models developed for chevrons and post-mounted delineators on rural two-lane curved road segments showed that the presence of chevrons led to a safety effectiveness of 10% to 27% for all lane departure crashes and 12% to 47% for fatal and injury lane departure crashes. Post-mounted delineators showed a safety effectiveness of 15% to 31% for all lane departure crashes and 10% to 32% for fatal and injury crashes. Even though the models were developed to estimate CMFs, they accurately predicted crashes on respective road segments. To check the predictive power of the model validation methods, cross-sectional and case-control methods were employed.

Since the generalized linear regression assuming negative binomial error structure was used to develop models for the cross-sectional method, the mean of the residuals and MSE were used as validation statistics. For the case-control method, accuracy, sensitivity, and specificity were used to check the predictive power of the developed logistic regression models. The validation statistics calculated for cross-sectional models showed that the mean of the residuals of each model was closer to zero. The MSE calculated for the validation dataset for each model was approximately close to the model MSE, which implied the developed models could accurately predict lane departure crashes. Hence, the estimated CMFs are accurate. For the case-control method, the accuracy and specificity of all models were more than 80%, while sensitivity was closer to or more than 50%, which implied that the developed models have greater predictive power. Therefore, the estimated CMFs using those models are accurate. However, it was seen that the models developed using the case-control method had a higher standard error; hence, they showed a larger percent range of crash-reduction effects than the models developed using the cross-sectional method. The higher range for the estimated CMFs using the case-control method occurred primarily because it assumed all road segments to have one or more crashes on an equal basis, so crashes might have been under-predicted. This suggests that the case-control method is more suitable for developing models for road segments where there are fewer crashes or fewer variations in crashes, while the cross-sectional method is more appropriate for developing models for road segments where there is a larger range in the number of crashes. Furthermore, these two approaches are useful to estimate CMFs for those countermeasures where the date of implementation is not known.

Since the implementation dates of safety edge treatments are known, the before-and-after EB method was used to estimate CMFs. Since the SPF was not known, a generalized linear regression assuming a negative binomial error structure was used to estimate regression parameters for the SPF. Then, the EB estimates were calculated for all lane departure crashes and fatal and injury lane departure crashes. Safety edge treatments on rural two-lane undivided road segments have a safety effectiveness of 10.8% for all lane departure crashes and 35.5% for fatal and injury lane departure crashes. The safety effectiveness of safety edge treatments for all lane departure crashes was shown to be not significant at the 90% confidence level. However, it was found that the safety effectiveness of safety edge treatments is significant at the 90% confidence level.

Since the safety effectiveness of the countermeasures considered is based on data from the Kansas road network, the results can be used as a decision-making tool when implementing lane departure countermeasures on similar roadways in Kansas.

REFERENCES

AASHTO. 2010. *Highway Safety Manual (HSM) 2010*. American Association of State Highway and Transportation Officials, Washington, DC.

Allison, P. D. 2012. *Logistic Regression Using SAS: Theory and application*. SAS Institute, Cary, NC.

Appiah, J., B. Naik, R. Wojtal, and L. Rilet. 2011. Safety Effectiveness of Actuated Advance Warning Systems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2250, pp. 19–24.

Aul, N. and G. Davis. 2006. Use of Propensity Score Matching Method and Hybrid Bayesian Method to Estimate Crash Modification Factors of Signal Installation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1950, pp. 17–23.

Bahar, G., M. Masliah, R. Wolff, and P. Park. 2007. *Desktop Reference for Crash Reduction Factors*. FHWA-SA-07-015. Federal Highway Administration, Office of Safety, Washington, DC.

Benekohal, R. F. and A. M. Hashmi. 1992. Procedures for Estimating Accident Reductions on Two-Lane Highways. *Journal of Transportation Engineering*, Vol. 118, No. 1, pp. 111–129.

Bonneson, J. A., and D. Lord. 2005. *Role and Application of Accident Modification Factors in the Highway Design Process.* Texas A&M Transportation Institute, Texas A&M University System, College Station, TX.

Bonneson, J. A., K. Zimmerman, and M. A. Brewer. 2002. *Engineering Countermeasures to Reduce Red-Light Running (RLR).* Texas A&M Transportation Institute, Texas A&M University System, College Station, TX.

Choi, Y., S. Kho, C. Lee, and D. Kim. 2015. Development of Crash Modification Factors of Alignment Elements and Safety Countermeasures for Korean Freeways. Paper presented at the Transportation Research Board 94th Annual Meeting, January 11–15, Washington, DC.

Council, F. M., D. W. Reinfurt, B. Campbell, F. L. Roediger, C. L. Carroll, A. K. Dutt, and J. R. Dunham. 1980. *Accident Research Manual*. FHWA-RD-80-016. Federal Highway Administration, Washington DC.

Davis, G. A., S. Davuluri, and J. Pei. 2006. Speed as a Risk Factor in Serious Run-Off-Road Crashes: Bayesian Case-Control Analysis with Case Speed Uncertainty. *Journal of Transportation and Statistics*, Vol. 9, No. 1.

Dissanayake, S. and A. S. Esfandabadi. 2015. *Evaluation of Bypass Lane Safety, Operations, and Design in Kansas.* Kansas State University Transportation Center, Manhattan, KS.

Dissanayake, S. and S. Kotikalapudi. 2012. *Characteristics and Contributory Causes Related to Large-Truck Crashes (Phase II)–All Crashes.* Mid-America Transportation Center, Lincoln, NE.

Dwyer-Lindgren L, A. Bertozzi-Villa, R. W. Stubbs, C. Morozoff, M. J. Kutz, C. Huynh, R. M. Barber, K. A. Shackelford, J. P. Mackenbach, F. J. van Lenthe, A. D. Flaxman, M. Naghavi, A. H. Mokdad, and C. J. L. Murray. 2016. County-Level Trends in Mortality Rates for Major Causes of Death, 1980–2014. *Journal of the American Medical Association*, Vol. 316, No. 22, pp. 2385–2401.

Elvik, R. and T. Vaa, ed. 2004. *The Handbook of Road Safety Measures*. Elsevier Science, Oxford, UK.

Elvik, R., T. Vaa, A. Erke, and M. Sorensen. 2009. *The Handbook of Road Safety Measures.* Emerald Group Publishing, Bingley, UK.

Feldman, M., J. Manzi, and M. Mitman. 2010. Empirical Bayesian Evaluation of Safety Effects of High-Visibility School (Yellow) Crosswalks in San Francisco, California. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2198, pp. 8–14.

FHWA. 2013. *FHWA Roadway Departure Strategic Plan*. Federal Highway Administration, Office of Safety, Washington, DC.

FHWA. 2009. *Manual on Uniform Traffic Control Devices (MUTCD)*. Federal Highway Administration, Office of Transportation Operations, Washington, DC.

Fitzpatrick, K., D. Lord, and B. Park. 2008. Accident Modification Factors for Medians on Freeways and Multilane Rural Highways in Texas. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2083, pp. 62–71.

Gan, A., J. Shen, and A. Rodriguez. 2005. *Update of Florida Crash Reduction Factors and Countermeasures to Improve the Development of District Safety Improvement Projects.* Florida Department of Transportation, Tallahassee, FL.

Graham, J., K. Richard, M. O'Laughlin, and D. Harwood. 2011. *Safety Evaluation of the Safety Edge Treatment.* Federal Highway Administration, Turner-Fairbank Research Center, McLean, VA.

Griffin, L. I. and R. J. Flowers. 1997. *A Discussion of Six Procedures for Evaluating Highway Safety Projects.* Federal Highway Administration, Washington, DC.

Griffith, M. 1999. Safety Evaluation of Rolled-In Continuous Shoulder Rumble Strips Installed on Freeways. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1665, pp. 28–34.

Gross Jr., F. 2006. *Alternative Methods for Estimating Safety Effectiveness on Rural, Two-Lane Highways: Case-Control and Cohort Methods.* PhD Dissertation. Pennsylvania State University, University Park, PA.

Gross, F. and E. T. Donnell. 2011. Case-Control and Cross-Sectional Methods for Estimating Crash Modification Factors: Comparisons from Roadway Lighting and Lane and Shoulder Width Safety Effect Studies. *Journal of Safety Research,* Vol. 42, No. 2, pp. 117–129.

Gross, F. and P. P. Jovanis. 2007. Estimation of the Safety Effectiveness of Lane and Shoulder Width: Case-Control Approach. *Journal of Transportation Engineering,* Vol. 133, No. 6, pp. 362–369.

Gross, F., B. Persaud, and C. Lyon. 2010. *A Guide to Developing Quality Crash Modification Factors.* FHWA-SA-10-032. Federal Highway Administration, Office of Safety, Washington, DC.

Hallmark, S. L., L. N. Boyle, and Y. Qiu. 2012. *Relationship between Lane Departure Events and Roadway Characteristics.* Midwest Transportation Consortium, Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L., A. Goswamy, and M. D. Pawlovich. 2016. *Safety Edge Crash Modification Factors.* Tech Brief. Center for Transportation Research and Education, Midwest Transportation Center, Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L. and N. R. Hawkins. 2014. *Chevrons and Oversized Chevrons*. Tech Transfer Summary. Center for Transportation Research and Education, Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L., N. R. Hawkins, and O. G. Smadi. 2013. *Toolbox of Countermeasures for Rural Two-Lane Curves.* Center for Transportation Research and Education, Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L., N. Hawkins, and O. Smadi. 2012. *Evaluation of Low-Cost Treatments on Rural Two-Lane Curves*. Midwest Transportation Consortium, Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L., N. Hawkins, and O. Smadi. 2015. *Evaluation of Dynamic Speed Feedback Signs on Curves: A National Demonstration Project*. Federal Highway Administration, Turner-Fairbank Research Center, McLean, VA.

Hallmark, S. L., S. Knickerbocker, and N. R. Hawkins. 2013. *Transverse* Speed *Bars for Rural Traffic Calming.* Tech Brief. Center for Transportation Research and Education, Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L., T. McDonald, and R. Sperry. 2009. *Evaluation of Rumble Stripes on Low-Volume Rural Roads in Iowa—Phase I.* Institute for Transportation, Iowa State University, Ames, IA.

Hallmark, S. L., Y. Qiu, N. Hawkins, and O. Smadi. 2015. Crash Modification Factors for Dynamic Speed Feedback Signs on Rural Curves. *Journal of Transportation Technologies*, Vol. 5, No. 1, pp. 9.

Hallmark, S. L., D. Veneziano, T. McDonald, J. Graham, K. M. Bauer, R. Patel, and F. M. Council. 2006. *Safety Impacts of Pavement Edge Drop-Offs.* AAA Foundation for Traffic Safety, Washington, DC.

Hallmark, S., T. McDonald, B. Sperry, and E. Vencil. 2011. *Evaluation of Safety Edge Benefits in Iowa.* Institute for Transportation, Iowa State University, Ames, IA.

Harwood, Douglas, et al. 2003. Safety Effectiveness of Intersection Left-and Right-Turn Lanes. *Transportation Research Record: Journal of the Transportation Research Board*, No.1840, pp.131–139.

Hauer, E. 1997. *Observational Before-After Studies in Road Safety: Estimating: The Effect of Highway and Traffic Engineering Measures on Road Safety.* Pegamon, Tarrytown, NY.

Hunter, W., J. Stewart, K. Eccles, H. Huang, F. Council, and D. Harkey. 2001. Three-Strand Cable Median Barrier in North Carolina: In-Service Evaluation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1743, pp. 97–103.

Insurance Institute for Highway Safety Highway Loss Data Institute. 2015. *Saving Lives: Improved Vehicle Designs Bring Down Death Rates.* Status Report 50. Arlington, VA.

Izadpanah, P., A. Hadayeghi, and H. Zarei. 2009. *Before-and-After Study Technical Brief.* Transportation Safety Council, Institute of Transportation Engineers, Washington, DC.

Jovanis, P. and F. Gross. 2007. Estimation of Safety Effectiveness of Changes in Shoulder Width with Case Control and Cohort Methods. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2019, pp. 237–245.

KDOT. 2015. *Kansas Strategic Highway Safety Plan.* Kansas Department of Transportation. Retrieved from www.ksdot.org/bureaus/burTrafficSaf/reports/kshsPlan2015.asp.

Kay, J., P. T. Savolainen, T. J. Gates, T. K. Datta, J. Finkelman, and B. Hamadeh. 2015. Safety Impacts of a Statewide Centerline Rumble Strip Installation Program. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2515, pp. 34–40.

Khan, M., A. Abdel-Rahim, and C. J. Williams. 2015. Potential Crash Reduction Benefits of Shoulder Rumble Strips in Two-Lane Rural Highways. *Accident Analysis and Prevention*, Vol. 75, pp. 35–42.

Kubas, A., P. Kayabas, K. Vachal, and M. Berwick. 2013. *Rumble Strips in North Dakota: A Comparison of Road Segments, Safety, and Crash Patterns.* Upper Great Plains Transportation Institute, North Dakota State University, Fargo, ND.

Kutner, M. H., C. Nachtsheim, and J. Neter. 2004. *Applied Linear Regression Models.* McGraw-Hill/Irwin, New York, NY.

Lan, B., B. Persaud, C. Lyon, and R. Bhim. 2009. Validation of a Full Bayes Methodology for Observational Before-After Road Safety Studies and Application to Evaluation of Rural Signal Conversions. *Accident Analysis and Prevention*, Vol. 41, No. 3, pp. 574–580.

Lee, C., M. Abdel-Aty, J. Park, and J. Wang. 2015. Development of Crash Modification Factors for Changing Lane Width on Roadway Segments Using Generalized Nonlinear Models. *Accident Analysis and Prevention*, Vol. 76, pp. 83–91.

Li, W., A. Carriquiry, M. Pawlovich, and T. Welch. 2008. The Choice of Statistical Models in Road Safety Countermeasure Effectiveness Studies in Iowa. *Accident Analysis and Prevention*, Vol. 40, No. 4, pp. 1531–1542.

Li, Z., K. Kepaptsoglou, Y. Lee, H. Patel, Y. Liu, and H. G. Kim. 2013. Safety Effects of Shoulder Paving for Rural and Urban Interstate, Multilane, and Two-Lane Highways. *Journal of Transportation Engineering*, Vol. 139, No. 10, pp. 1010–1019.

Lord, D., and J. Bonneson. 2007. Development of Accident Modification Factors for Rural Frontage Road Segments in Texas. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2023, pp. 20–27.

Lord, D., M. A. Brewer, K. Fitzpatrick, S. R. Geedipally, and Y. Peng. 2011. *Analysis of Roadway Departure Crashes on Two-Lane Rural Roads in Texas.* Texas Department of Transportation, Austin, TX.

Ma, J., K. M. Kockelman, and P. Damien. 2008. A Multivariate Poisson-Lognormal Regression Model for Prediction of Crash Counts by Severity, Using Bayesian Methods. *Accident Analysis and Prevention*, Vol. 40, No. 3, pp. 964–975.

McGee, H. W. and F. R. Hanscom. 2006. *Low-Cost Treatments for Horizontal Curve Safety.* FHWA-SA-07-002. Federal Highway Administration, Office of Safety, Washington, DC.

Miranda-Moreno, L. F. and L. Fu. 2007. Traffic Safety Study: Empirical Bayes or Full Bayes? Paper presented at the Transportation Research Board 86th Annual Meeting, January 21–25, Washington, DC.

Montella, A. 2009. Safety Evaluation of Curve Delineation Improvements: Empirical Bayes Observational Before-and-After Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2103, pp. 69–79.

Montgomery, D. C., E. A. Peck, and G. G. Vining. 2015. *Introduction to Linear Regression Analysis*. John Wiley and Sons, Hoboken, NJ.

Nambisan, S. and S. L. Hallmark. 2011. *Lane Departure Safety Countermeasures: Strategic Action Plan for the Iowa Department of Transportation*. Institute for Transportation, Iowa State University, Ames, IA.

National Highway Transportation Safety Administration. 2016. *Fatality Analysis Reporting System*. Retrieved from www-fars.nhtsa.dot.gov/Main/index.aspx.

Oh, C., Y. Kang, B. Kim, and W. Kim. 2005. Analysis of Pedestrian-Vehicle Crashes in Korea. Paper presented at the 84th Annual Meeting of the Transportation Research Board. January 9–13, Washington, DC.

Olson, D., M. Sujka, and B. Manchas. 2013a. *Cable Median Barrier Program in Washington State*. Washington State Department of Transportation, Olympia, WA.

Olson, D., M. Sujka, and B. Manchas. 2013b. *Performance Analysis Of Centerline And Shoulder Rumble Strips Installed in Combination in Washington State*. Washington State Department of Transportation, Olympia, WA.

Park, J. and M. Abdel-Aty. 2015. Development of Adjustment Functions to Assess Combined Safety Effects of Multiple Treatments on Rural Two-Lane Roadways. *Accident Analysis and Prevention*, Vol. 75, pp. 310–319.

Patel, R., F. Council, and M. Griffith. 2007. Estimating Safety Benefits of Shoulder Rumble Strips on Two-Lane Rural Highways in Minnesota: Empirical Bayes Observational Before-and-After Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2019, pp. 205–211.

Pawlovich, M., W. Li, A. Carriquiry, and T. Welch. 2006. Iowa's Experience with Road Diet Measures: Use of Bayesian Approach to Assess Impacts on Crash Frequencies and Crash Rates. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1953, pp. 163–171.

Peng, Y., S. Geedipally, and D. Lord. 2012. Effect of Roadside Features on Single-Vehicle Roadway Departure Crashes on Rural Two-Lane Roads. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2309, pp. 21–29.

Persaud, B., C. Lyon, K. Eccles, and J. Soika. 2015. Safety Evaluation of Centerline Plus Shoulder Rumble Strips. Paper presented at the Transportation Research Board 94th Annual Meeting, January 11–15, Washington, DC.

Persaud, B. N., R. A. Retting, and C. A. Lyon. 2004. Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads. *Accident Analysis and Prevention*, Vol. 36, No. 6, pp. 1073–1079.

Poch, M. and F. Mannering. 1996. Negative Binomial Analysis of Intersection-Accident Frequencies. *Journal of Transportation Engineering*, 122, No. 2, pp. 105–113.

Qin, X., J. N. Ivan, N. Ravishanker, and J. Liu. 2005. Hierarchical Bayesian Estimation of Safety Performance Functions for Two-Lane Highways using Markov Chain Monte Carlo Modeling. *Journal of Transportation Engineering*, Vol. 131, No. 5, pp. 345–351.

Retting, R. A., S. A. Ferguson, and A. T. McCartt. 2003. A Review of Evidence-Based Traffic Engineering Measures Designed to Reduce Pedestrian-Motor Vehicle Crashes. *American Journal of Public Health*, Vol. 93, No. 9, pp. 1456–1463.

Ross Jr, H., D. Sicking, R. A. Zimmer, and J. D. Michie. 1993. *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.* National Cooperative Highway Research Program, Washington, DC. onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_350-a.pdf.

SAS Institute. 2014. *SAS 9.4 Output Delivery System: User's Guide SAS Institute.* support.sas.com/documentation/cdl/en/odsgs/66634/PDF/default/odsgs.pdf.

Sayed, T., P. deLeur, and J. Pump. 2010. Impact of Rumble Strips on Collision Reduction on Highways in British Columbia, Canada: Comprehensive Before-and-After Safety Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2148, pp. 9–15.

Shankar, V., F. Mannering, and W. Barfield. 1995. Effect of Roadway Geometrics and Environmental Factors on Rural Freeway Accident Frequencies. *Accident Analysis and Prevention*, Vol. 27, No. 3, pp. 371–389.

Shen, J. and A. Gan. 2003. Development of Crash Reduction Factors: Methods, Problems, and Research Needs. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1840, pp. 50–56.

Sposito, B. and S. Johnston. 1998. *Three-Cable Median Barrier Final Report*. Oregon Department of Transportation Research Unit, Salem, OR.

Srinivasan, R., J. Baek, D. Carter, B. Persaud, C. Lyon, K.A. Eccles, F. Gross, and N. X. Lefler. 2009. *Safety Evaluation of Improved Curve Delineation.* FHWA-HRT-09-045. Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, VA.

Strathman, J. G., K. Dueker, J. Zhang, and T. Williams. 2001. *Analysis of Design Attributes and Crashes on the Oregon Highway System*. Center for Urban Studies, Portland State University, Portland, OR.

Sun, X., S. Das, Z. Zhang, F. Wang, and C. Leboeuf. 2014. Investigating Safety Impact of Edgelines on Narrow, Rural Two-Lane Highways by Empirical Bayes Method. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2433, pp.121–128.

Tarko, A., S. Eranky, and K. Sinha. 1998. Methodological Considerations in the Development and Use of Crash Reduction Factors. Paper presented at the 77th Annual Meeting of the Transportation Research Board, January 11–15, Washington, DC.

Torbic, D. J. 2009. *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.* National Cooperative Highway Research Program, Washington, DC. www.cmfclearinghouse.org/studydocs/nchrp_rpt_641-GuidanceRumbleStrips.pdf.

Vogt, A. and J. Bared. 1998. Accident Models for Two-Lane Rural Segments and Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1635, pp. 18–29.

Woodward, M. 2013. *Epidemiology: Study Design and Data Analysis*. CRC Press, Boca Raton, FL.

World Health Organization. 2015. *Global Status Report on Road Safety 2015*. ISBN 978 92 4 156506 6. World Health Organization, Geneva, Switzerland.

Yanmaz-Tuzel, O. and K. Ozbay. 2010. A Comparative Full Bayesian Before-and-After Analysis and Application to Urban Road Safety Countermeasures in New Jersey. *Accident Analysis and Prevention*, Vol. 42, No. 6, pp. 2099–2107.

Zegeer, C. V., D. W. Reinfurt, J. Hummer, L. Herf, and W. Hunter. 1988. Safety Effects of Cross-Section Design for Two-Lane Roads. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1195, pp. 20–32.

Zeng, H. and S. Schrock. 2012. Estimation of Safety Effectiveness of Composite Shoulders on Rural Two-Lane Highways. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2279, pp. 99–107.

Zeng, H., S. D. Schrock, and T. Mulinazzi. 2013. *Evaluation of Safety Effectiveness of Composite Shoulders, Wide Unpaved Shoulders, and Wide Paved Shoulders in Kansas*. Kansas Department of Transportation, Topeka, KS.

THE INSTITUTE FOR TRANSPORTATION IS THE FOCAL POINT FOR TRANSPORTATION AT IOWA STATE UNIVERSITY.

InTrans centers and programs perform transportation research and provide technology transfer services for government agencies and private companies;

InTrans manages its own education program for transportation students and provides K-12 resources; and

InTrans conducts local, regional, and national transportation services and continuing education programs.

INSTITUTE FOR TRANSPORTATION IOWA STATE UNIVERSITY

Visit www.InTrans.iastate.edu for color pdfs of this and other research reports.