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A Study to Mitigate Rural High-Speed Horizontal Curve Crashes in Kansas

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A Kansas Department of Transportation (KDOT) crash database of nine years (from 2004 to 2012) was used and counties with high number of crashes were selected. Eleven counties with high number of horizontal curve related crashes were selected, and implemented countermeasures at the selected curves were investigated and discussed. K-5 highway is one of the highways with high number of crashes in which the speed limit of a long distance of the roadway, including the problematic curves, reduced in June 2009 from 55 miles per hour (mph) to 50 mph. The effect of this speed limit reduction on crash occurrences of seven years, including 3.5 years before and 3.5 years after the speed limit reduction, was investigated using a statistical t-test method. In addition, various countermeasures to improve the traffic safety of these horizontal curves were discussed.

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Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Driving on horizontal curves is a more complicated task than on straight sections of a roadway, and poses more workload on drivers as well. While a small portion of roadways are made up of horizontal curve sections, approximately a quarter of all fatal crashes on highways occur at horizontal curve sections. Thus, studying the crashes at horizontal curves and the safety improvement at these sections is one of the most interesting topics in the transportation safety field. Safety improvement of horizontal curve sections of rural transportation networks can effectively and considerably contribute to crash severity and frequency reduction. Low-cost countermeasures to improve traffic safety of horizontal curve sections and their effectiveness were discussed.

A Kansas Department of Transportation (KDOT) crash database of nine years (from 2004 to 2012) was used and counties with high number of crashes were selected. Eleven counties with high number of horizontal curve related crashes were selected, and implemented countermeasures at the selected curves were investigated and discussed. K-5 highway is one of the highways with high number of crashes in which the speed limit of a long distance of the roadway, including the problematic curves, reduced in June 2009 from 55 miles per hour (mph) to 50 mph. The effect of this speed limit reduction on crash occurrences of seven years, including 3.5 years before and 3.5 years after the speed limit reduction, was investigated using a statistical t-test method. In addition, various countermeasures to improve the traffic safety of these horizontal curves were discussed.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Literature Review

1.1 Introduction

Thousands of people are killed annually due to automobile crashes on transportation networks in the United States. A majority of fatal crashes occur on rural roadways, and a considerable number of those fatal crashes occur on horizontal curves, especially on two-lane rural roads, even though horizontal curves constitute a very small portion of rural roads nationwide. Therefore, increasing the safety of horizontal curves could be beneficial and cost-effective. While improvements are implemented in short segments of roadways (horizontal curves), and probably with low budgets, greater reduction in fatal crashes and fatalities are needed. This chapter reviews relevant studies which have investigated effective countermeasures to diminish fatalities and serious injuries on horizontal curves.

1.2 Importance of Horizontal Curves

A horizontal curve is located wherever an alteration occurs in the horizontal alignment or direction of a road, consequently affecting vehicle movement by producing centrifugal force and causing altered driving conditions. According to National Cooperative Highway Research Program report (NCHRP 600 Second Edition), design aspects of a curve, such as lane width, degree of curvature, radius of curve, design superelevation, and design consistency, impact the workload of drivers. Therefore, an appropriate design will lessen the workload related to the geometry of the curve. In addition, drivers must be given advance notice of any change in roadway horizontal alignment, and, for horizontal curves, spirals, and appropriate superelevation changes are suggested treatments to inform and prepare drivers for transition into a curve. Driver visibility changes on curved segments of a road, causing most drivers to focus on tangent points, while on other road segments, including smooth curves, drivers focus on the horizon (Campbell et al., 2012).

According to NCHRP 600 Second Edition, navigating a curve within a safe speed is the most important factor affecting crash rates on curves. Drivers select their driving speed based on two definite parameters: expectations regarding a curve (affected by design consistency), and road signage and advisory speed. However, drivers' expectations typically outweigh the effect of road signage. A very noticeable issue is a combination of horizontal curve and sag vertical curve, in which the curve radius or apparent radius, as viewed from the driver's perspective, is greater than the actual radius of the curve, thus influencing driver judgment when selecting proper driving speed to negotiate the curve safely. The observed speeds might exceed the advisory speed due to poor judgment of the drivers. Such an adverse result is also expected wherever a combination of a horizontal curve and a crest vertical curve exists, since the apparent radius is less than the actual radius and the curve seems sharper than it is. As a result, speed reduction generally occurs. This speed reduction would be a positive result, but may not occur in all cases.

A two-level process model describes the task of steering control as "an open-loop anticipatory component (far view)" and "a closed-loop compensatory component (near view)" (Campbell et al., 2012). Drivers use "far view" to predict curvature and steering angle, and "near view" is applied when drivers attempt to correct a deviation from the desired path. However, all path-decision behaviors of drivers, such as curve-cutting, are not completely explained by this model. Although steering action should be dependent on direct visual feedback, drivers often rely on their estimation of vehicle characteristics and their previous experience navigating curves (Godthelp, 1986).

A driver chooses curve entry speed based on personal perception of curvature influenced by geometric alignment and delineation features of the curve segment. Drivers often enter a curve at an improper speed because of curvature misperception. In order to correct driving mistakes, drivers often take compensatory control ("near view") actions, especially in sharp curves (Godthelp, 1986; Simsek, Bittner, Levison, & Garness, 2000). In these cases, instead of following the ideal radius or the radius at the center of the lane, drivers often follow a trajectory with a larger radius.

Based on Fatality Analysis Reporting System (FARS) data from 2002, 38,309 fatal crashes caused 42,815 deaths on US highways and nearly 25% of fatal crashes occurred on curve segments. More than 75% of those crashes were single vehicle, run-off-road (ROR), and approximately 10% of them were head-on crashes (Campbell et al., 2012). In recent years, the number of fatal crashes on US highways has decreased; however, the percentage of curve-related fatalities has remained constant. In 2008, horizontal curve-related fatal crashes accounted for

27% of all nationwide fatal crashes, and approximately 80% of those crashes were road departure crashes (Cheung, 2010). Current most recent data from the FARS database verifies the same trend for fatal crashes and fatalities on horizontal curves in 2011. Twenty-eight percent of fatal crashes occurred on horizontal curves, and approximately 84% of those crashes were ROR crashes. An appropriate design, including consistency of a curve segment with other segments of the roadway, especially with close segments before and after the curve, proper curve radius, suitable spiral, superelevation, and lane width on the curve, can result in improvement of safety on the curve.

Other treatments can increase curve segment safety. Adequate treatment selection must be conducted according to expert judgment or/and empirical data (Campbell et al., 2012). Countermeasures for safety improvement of a curve are classified into three groups: low-cost, intermediate-cost, and high-cost treatments (Christiansen, 2011).

1.3 Low-Cost Countermeasures

Nine basic treatments were introduced as low-cost countermeasures by FHWA, classified as the following (McGee & Hanscom, 2006):

1. Centerline
2. Edge line
3. Horizontal alignment signs
4. Advisory speed plaque
5. One-direction large arrow sign
6. Combination horizontal alignment/advisory speed sign
7. Curve speed sign
8. Chevron alignment sign
9. Delineators

1.3.1 Centerline and Edge Line

A centerline is the minimum treatment for a horizontal curve. Use of a centerline and edge line depends on travel width and average daily traffic (ADT). Based on the Manual on Uniform Traffic Control Devices (MUTCD), the use of a centerline for roadways with travel width less than 16 ft requires engineering judgment. Edge lines are required when roadways with lane width of 20 ft or more have a minimum ADT of 6,000 vehicles per day (vpd). When a curve does not provide adequate sight distance on two-lane roadways, a solid yellow line is necessary for one or both directions, while edge lines are solid white lines along the right side of the road. The primary purpose of centerlines and edge lines is to provide a visual cue for drivers and impede encroachment into the opposite lane or edge line. Centerlines and edge lines provide a visual guide for drivers to follow the curve, and prevent drifting to the shoulder and probable ROR incidents or crashes. NCHRP 600 Second Edition states that pavement surface markings provide the strongest curvature guide (Campbell et al., 2012).

Various materials are utilized for pavement marking. One material commonly used is thermoplastic marking, which lasts longer than other materials, thus increasing its cost-effectiveness (McGee & Hanscom, 2006). Materials such as retro-reflective pavement materials (RPMs) and retro-reflective raised pavement materials (RRPMs) are also applicable, depending on roadway conditions. However, FHWA (2009) prohibits the use of raised pavement markings for edge lines. Various studies suggest that the combination of centerlines or edge lines with rumble strips improve curve safety (Bogenreif, 2011; Camacho, 2012).

Conventional width for a centerline or edge line is 4 to 6 inches; however, 8- to 12-inch widths are used by some states (Lord, Brewer, Fitzpatrick, Geedipally, & Peng, 2011). Using edge lines with 8-inch width was found an appropriate alternative for roadways with 12-foot wide lanes, unpaved shoulders, and an ADT of 2,000 to 5,000 vpd (Fitzpatrick, Balke, Harwood, & Anderson, 2000; Neuman et al., 2003). Hallmark, Hawkins, and Smadi (2012) summarized positive benefits, drivers' feedback, and improvements, including increased visibility particularly during nighttime conditions and especially for older drivers, peripheral vision stimulation, lane keeping, comfort of drivers, and aesthetics.

Material used or selected for centerline stripes significantly impacts cost, which varies by state. Lord et al. (2011) indicated that average costs for Type I, solid white edge line is $0.30 per linear foot for 4-inch markings, $0.66 for 6-inch markings, and $0.94 for 8-inch markings. The cost per linear foot for Type II, solid white edge line per linear foot for 4-inch, 6-inch, and 8-inch markings were estimated at $0.12, $0.25, and $0.35, respectively.

1.3.2 Horizontal Alignment Signs and Advisory Speed Signs

A variety of signs presented in the MUTCD are used in advance of a curve or a turn to warn drivers of an upcoming horizontal curve (FHWA, 2009). For a single curve, turn sign (W1-1), curve sign (W1-2), hairpin curve sign (W1-11) for 135 degrees change in alignment, and a 270-degree loop sign (W1-15) are applicable, as depicted in Figure 1.1. Similarly, two signs are used for two sequential curves or turns: reverse turns (W1-3) and reverse curves (W 1-4). For several sequential curves, the winding road sign (W1-5) is appropriate.

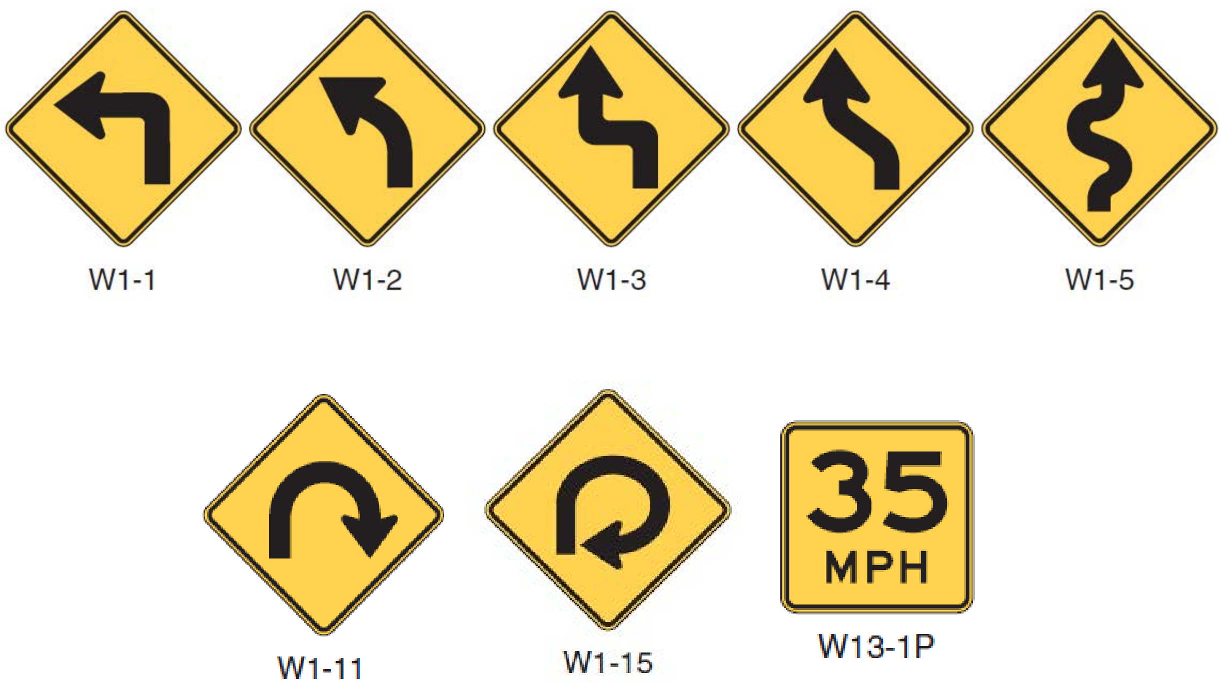


Figure 1.1: Advanced Warning Signs for Horizontal Curves
Source: FHWA, 2009

The Kansas Department of Transportation (KDOT) Handbook of Traffic Control Practices for Low Volume Rural Roads (KDOT, 1991) suggests a turn sign when the advisory speed is equal to or less than 30 miles per hour (mph) and a curve sign for speeds greater than 30 mph. An advisory speed plaque (W1-13) can also be added to curve-related signs. The advisory speed sign should be placed below the horizontal alignment sign. McGee and Hanscom (2006) emphasize that advisory speed is not the legal speed limit, but an advised speed to drivers.

NCHRP 600 Second Edition states that, although researchers agree about the use of warning signs in advance of a curve, disagreement exists regarding the use of symbols or text messages (Campbell et al., 2012).

Placement of a highway curve sign is related to the curve's advisory speed and posted speed, or 85th percentile speed of the tangent section of road prior to the curve. McGee and Hanscom (2006) provide guidelines for warning signs placement in advance of highway curves in accordance with approach speed.

Table 1.1: Guidelines for Advance Placement of Curve Warning Signs

Posted or 85th percentile speed (mph)	Advance placement distance (feet) for advisory speed of the curve (mph) of						
	10	**20**	**30**	**40**	**50**	**60**	**70**
20	n/a[1]	-	-	-	-	-	-
25	n/a[1]	n/a[1]	-	-	-	-	-
30	n/a[1]	n/a[1]	-	-	-	-	-
35	n/a[1]	n/a[1]	n/a[1]	-	-	-	-
40	100[2]	100[2]	n/a[1]	-	-	-	-
45	125	100[2]	100[2]	n/a[1]	-	-	-
50	200	175	125	100[2]	-	-	-
55	275	225	200	125	n/a[1]	-	-
60	350	325	275	200	100[2]	-	-
65	450	400	350	275	200	100[2]	-
70	525	500	450	375	275	150	-
75	625	600	550	475	375	250	100[2]

Source: FHWA, 2009

[1] No suggested distances are provided for these speeds, as the placement location depends on site conditions and other signing to provide an adequate advance warning for the driver.

[2] The minimum advance placement distance is listed as 100 feet to provide adequate spacing between signs.

As described in McGee and Hanscom (2006), all signs must be comprised of retro-reflective sheeting for increased night visibility and low-light conditions. The lower edge of the sign must be at least 5 feet above the pavement surface, and the closest edge of the sign to the road must be at least 6 feet from the outer edge of the shoulder.

Srinivasan et al. (2009) studied the effectiveness of improvement of delineation of some curve-related signs, including chevrons and one-arrow direction signs on horizontal curves on two-lane rural roads in Connecticut. Results indicated a reduction of 18% in all crashes, a 25% reduction in injury and fatal non-intersection crashes, and a 35% reduction in crashes during dark conditions. A few studies achieved varying results when relating the effectiveness of horizontal curve signs. Studies showed a reduction in crash occurrence with the use of advance curve warning signs; however, crash reduction percentages varied from a 10% to a 30% reduction in all crashes. In 2011, the average cost for each aluminum advisory sign made in Texas was $300 (Lord et al., 2011).

1.3.2.1 Larger Signs and Doubling Up Signs

McGee and Hanscom (2006) state that increase in the size of horizontal curve signs is permitted by the MUTCD whenever the volume, speed, or other conditions of a roadway require emphasis on sign readability. FHWA (2009) provided Table 1.2 for sign sizes on various roadways.

Table 1.2: Sizes of Warning Signs in Inches

Description		Conventional Road		Expressway	Freeway	Minimum	Oversized
Shape	Sign Series	Single-Lane	Multi-Lane				
Diamond	W1-1, 2, 3, 4, 5	30×30	36×36	36×36	36×36	–	48×48
	W1-1a, W1-2a	36×36	36×36	48×48	48×48	–	48×48
	W1-11, W1-15	30×30	30×30	36×36	48×48	–	48×48
Rectangular	W1-6	48×24	48×24	60×30	60×30	–	60×30
	W1-8	18×24	18×24	30×36	36×48	–	24×30
	W13-1P	18×18	18×18	24×24	30×30	–	30×30

Source: FHWA, 2009

Doubling up signs is another method of providing additional opportunities for roadway users to see the warning signs, consequently improving horizontal curve safety. A second similar sign is used on the left side of the roadway.

1.3.2.2 High Retro-Reflective Intensity and Fluorescent Yellow Sheeting

Various types of retro-reflective materials are listed by MUTCD which are used in the construction of roadway signs. Increasing the retro-reflectivity of signs (measured in candela per lux per meter squared [$cd/lx/m^2$]) can increase the sign visibility. For example, instead of utilizing engineering grade (Type I), high intensity grade (Type III) and micro-prismatic sheeting (Type V) can increase sign visibility. A study in 2006 estimated a 2.4% cost increase to upgrading material from Type III to Type V. Higher visibility allows earlier drivers responses to changes in roadway alignment, thus improving road safety (McGee & Hanscom, 2006).

1.3.3 Combination Horizontal Alignment Signs/Advisory Speed Signs

Combination horizontal alignment/advisory speed signs, referred to as supplementary signs, could be used on curves with high number of crashes and great differences between posted speeds and curves advisory speeds. The W1-1a sign is used as a combination of a turn sign and advisory speed sign, and the W1-2a is used as a combination of a curve sign and an advisory speed sign. The purpose of these signs is to motivate drivers to reduce driving speed when navigating a curve. The W1-1a and W1-2a signs are used at the beginning point of the curve. When distance between the alignment sign and the beginning point of a curve is less than 200 feet, it is better not to use a W1-1a or W1-2a sign. However, Campbell et al. (2012) suggest that, because of higher visual demands of drivers on curves, “conspicuous non-verbal information,” such as chevrons, is more effective than advisory speed signs.

W1-1a W1-2a

Figure 1.2: Combination Curve Alignment Sign/Advisory Speed Sign
Source: FHWA, 2009

1.3.4 Chevrons and One-Direction Arrow Sign

The W1-6 (one direction arrow sign) and the W1-8 (chevron) communicate an alteration in horizontal alignment. Both signs are also used with horizontal alignment signs, specifically when a sharp curve is present in the road. These signs must be placed on the outside of the curve at an approximate right angle with approaching traffic. One W1-6 sign is sufficient for each direction. If additional delineation is required, chevrons are appropriate alternatives, in which case at least two of them should always be in the driver's sight when navigating the curve (Lord et al., 2011). Campbell et al. (2012) suggest that chevrons are the "strongest guidance cues for long-range guidance (anticipatory control)." Srinivasan et al. (2009) classified W1-6 and W1-8 signs as curve delineation signs.

Figure 1.3: Curve Delineation Signs
Source: FHWA, 2009

The KDOT Highway Sign Manual (KDOT, 2007) recommends chevrons when the difference between the posted speed and curve advisory speed is 15 mph or more. According to FHWA (2009), chevrons must be installed at least 4 feet above the travel way, and McGee and Hanscom (2006) recommend that chevrons be posted 5 feet above the surface of the roadway in rural areas. In urban areas, chevron height is increased to 7 feet. McGee and Hanscom point out that MUTCD (FHWA, 2003) does not specify spacing for chevrons; therefore, McGee and Hanscom use two states' spacing guidelines. The latest edition of MUTCD (FHWA, 2009), however, determines a guide for chevron spacing, as shown in Table 1.3.

Table 1.3: Typical Spacing of Chevron Alignment Signs on Horizontal Curves

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

Note: The relationship between the curve radius and the advisory speed shown in this table should not be used to determine the advisory speed.

Source: FHWA, 2009

Iowa's traffic safety analysis manual (McDonald, 2012) recommends chevrons for curves with degree of curvature greater than or equal to 6 degrees, and post-mounted delineators (PMDs) are recommended for curves with degree of curvature less than 6 degrees. However, it also recommends using chevrons occasionally for curves with degree of curvature less than 6 degrees in case of sight distance reduction caused by vegetation or a combination of horizontal and vertical curves, or whenever crash history indicates delineation improvement is needed.

Srinivasan et al. (2009) reported a 20% reduction in crashes during dark conditions and a 20% reduction in departure crashes during dark conditions because of chevrons installed on horizontal curves in Washington State; however, a variety of reduction percentages of crash occurrences were reported in other studies (Lord et al., 2011). McGee and Hanscom (2006) state where the degree of curvature is more than 7 degrees, chevrons can significantly reduce centerline encroachment.

McGee and Hanscom (2006) approximate $500 for the installation of 10 chevrons, and Srinivasan et al. (2009) estimated $100 for the installation of each chevron on two-lane rural roads in Washington State. A recent study reported an average cost of $433 for the installation of one chevron in Texas (Lord et al., 2011).

1.3.5 Delineators

Delineators are retro-reflective devices mounted above the roadway surface, parallel to the roadway segment, in order to guide drivers through alignment changes at horizontal curves. PMDs are not warning signs, but they provide guidance information, as shown in Figure 1.4.

Selecting chevron alignment signs or PMDs are determined based on two different criteria. The KDOT Highway Sign Manual (KDOT, 2007) recommends using delineators where the difference between posted speed and advisory speed is 10 mph or less. McGee and Hanscom (2006) recommend PMDs for curves smaller than or equal to 7 degrees.

Figure 1.4: Post-Mounted Delineators
Source: McGee & Hanscom, 2006

Hallmark et al. (2012) reported that PMDs and chevrons with retro-reflectorized posts are better guides for drivers to recognize the curve sharpness compared to standard PMDs and chevrons.

FHWA (2009) states that delineators must be posted approximately 4 feet above the road surface and must be placed 2 to 8 feet from the outer edge of the shoulder. The delineator color should be identical to the adjacent edge line. FHWA (2009) also determines suitable spacing for delineators in accordance with the radius of the curve, as shown in Table 1.4.

Table 1.4: Recommended Spacing for Delineators at Horizontal Curves

Radius (R) of Curve	Approximate Spacing (S) on Curve
50 feet	20 feet
115 feet	25 feet
180 feet	35 feet
250 feet	40 feet
300 feet	50 feet
400 feet	55 feet
500 feet	65 feet
600 feet	70 feet
700 feet	75 feet
800 feet	80 feet
900 feet	85 feet
1,000 feet	90 feet

Notes:
1. Spacing for specific radii may be interpolated from table.
2. The minimum spacing should be 20 feet.
3. The spacing on curves should not exceed 300 feet.
4. In advance of or beyond a curve, and proceeding away from the end of the curve, the spacing of the first delineator is 2S, the second 3S, and the third 6S, but not to exceed 300 feet.
5. S refers to the delineator spacing for specific radii computed from the formula $S=3\sqrt{R-50}$.
6. The distances for S shown in the table above were rounded to the nearest 5 feet.

Source: FHWA, 2009

A study of installed PMDs on horizontal curves revealed a 25% reduction in all types of crashes at horizontal curves (Gan, Shen, & Rodriguez, 2005); however, unique reduction percentage is not anticipated for crashes on horizontal curves, according to another study (Lord et al., 2011). Moreover, Lord et al. estimated that the average cost of installing each delineator in Texas is approximately $31.40.

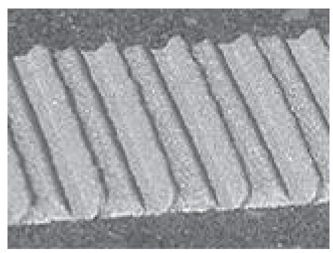
Other low-cost treatments are available, but they are not classified as basic treatments by McGee and Hanscom (2006). These low-cost countermeasures are discussed on the following pages.

1.3.6 Profile Thermoplastic Markings and Raised Pavement Markings

Profile thermoplastic markings and raised pavement markings (RPMs) produce a rumble effect and auditory warning which may increase safety. Profile thermoplastic markings and retro-reflective raised pavements markings (RRPMs) increase visibility, in contrast to RPMs with non-retro-reflective features. These two marking types typically are not appropriate for snowy regions because snow plows often damage them; however, design changes may make them compatible with snow plowing. According to FHWA, RRPMs are suitable for smooth curves (less than 3.5 degrees) and relatively high traffic volume (more than 5,000 vpd) since on sharper curves, they may create an unrealistic feeling of safety for drivers, consequently causing drivers to negotiate a sharp curve faster than usual because of increased curve visibility (McGee & Hanscom, 2006).

Campbell et al. (2012) suggest that a combination of RRPMs with centerlines and edge lines increases curve safety. For very sharp curves (more than 12 degrees), the report recommends the use of RRPMs pairs on the outside edges of the centerline, placed 800.5 feet (244 meters) in advance of every curve; spacing intervals should be 131.2 feet (40 meters) for sharp curves and 262.5 feet (80 meters) for smooth curves (Campbell et al., 2012). Another study recommends the utilization of snow-plowable RPMs for curves that cause ROR crashes (McDonald, 2012).

Raised Profile Thermoplastic Markers



Inverted Profile Thermoplastic Markers

Figure 1.5: Profile Thermoplastic Markings
Source: McGee & Hanscom, 2006

Standard RPM - for Centerline

Snow-Plowable RPM

Figure 1.6: Raised Pavement Markings
Source: McGee & Hanscom, 2006

Lord et al. (2011) estimated an average cost of $0.93/ft^2 for profile thermoplastic marking in Texas. The study also compared costs of pavement markings for various materials, as shown in Table 1.5.

Table 1.5: Estimated Cost of Pavement Markings

Pavement Marking Material	Cost ($/mile)
Paint	1,056
Thermoplastic	1,584
Tape	3,960
Buttons	2,233

Source: Lord et al., 2011

1.3.7 Reflective Barrier Delineation

Reflective sheeting panels installed on concrete barriers or guardrail improve visibility of horizontal curves, particularly during nighttime. Reflectors should be mounted on guardrail perpendicular to approaching headlights, as shown in Figure 1.7. The color of reflective sheeting or mounted reflectors must match the adjacent edge line color. Eighteen to 36-inch spacing is typically used for panels and reflectors.

Figure 1.7: Reflective Panels and Mounted Reflectors
Source: McGee & Hanscom, 2006

McGee and Hanscom (2006) estimated that each reflector costs $3 to install and almost $2.33 per linear foot of 4-inch wide reflective panels. Lord et al. (2011) estimated each reflector cost as $3.42 and each linear foot of reflective panel with 4-inch, 6-inch, and 8-inch width as $0.30, $0.66, and $0.94, respectively.

As described in McGee and Hanscom (2006), reflective sheeting can be implemented on obstructions near the edge of roadways and in the clear zone, but it is potentially hazardous for ROR crashes. Reflective tape with a 6-inch width is typically applied on the object, as illustrated in Figure 1.8. When the distance between the object and shoulder is 8 feet or less, the marker should be placed at least 4 feet above the pavement surface, otherwise the 4-foot height should be measured from the ground. Yellow reflective materials are commonly used unless aesthetic consideration requires a brown color.

Figure 1.8: Reflective Tape on Object Close to the Road
Source: McGee & Hanscom, 2006

1.3.8 Speed Limit Advisory Marking

Speed limit markings can be used as a supplemental warning in advance of a curve with a common horizontal alignment sign. Use of an arrow sign and "SLOW" text on the pavement has a similar effect (McGee & Hanscom, 2006; Lord et al., 2011). Campbell et al. (2012) suggest that an arrow sign and text should be placed 230 feet (70 meters) in advance of the curve in high hazard areas or at sharp curves. However, McGee and Hanscom state that sign distance placement depends on approach speed and curve design speed. According to several studies (McGee & Hanscom, 2006; Lord et al., 2011; Campbell et al., 2012), speed reduction is expected when this kind of treatment is used. Lord et al. (2011) reported that speed limit advisory pavement markings cost $116 on average.

Figure 1.9: Speed Limit Advisory Pavement Marking
Source: McGee & Hanscom, 2006

Figure 1.10: PennDOT Curve Advance Marking
Source: McGee & Hanscom, 2006

One study recommends placing on-pavement curve signs where advisory sign placements are recommended. In a study conducted by Charlton (2007) in New Zealand, on-pavement curve signs were determined to be more effective than chevrons at low speeds (28 mph [45 km/hr]; Hallmark et al., 2012).

1.3.9 Optical Speed Bars

Thermoplastic painted stripes, or transverse stripes, are implemented perpendicular to roadway alignment in advance of the curve and on the curve (Campbell et al., 2012), as shown in Figure 1.11. The primary objective of this treatment is to give drivers the illusion of increased speed by decreasing the distance between stripes, thus causing drivers to slow their driving speed. Based on McGee and Hanscom (2006), these white stripes are typically 18 inches long and 12 inches wide. Their effectiveness is attributed to spaces between the stripes which gradually decrease closer to the curve. No clear conclusion confirms effectiveness of this treatment since various studies indicate occasional reduction in speed, sometimes no reduction in speed, or a slight increase in speed (Campbell et al., 2012). McGee and Hanscom (2006) estimated a $2,000 cost for the implementation of optical bars on two directions of a curve in Virginia by the Virginia Department of Transportation (VDOT) in 2006. Campbell et al. (2012) suggest that a combination of rumble strips and transverse stripes would be more effective.

Figure 1.11: Optical Speed Bars
Source: McGee & Hanscom, 2006

Hallmark et al. (2012) categorized optical speed bars as “transverse pavement markings,” “on-pavement chevrons,” and “herringbone.” On-pavement chevrons are shown in Figure 1.12. According to their study, on-pavement chevrons are typically applied on freeway ramps, in advance of curves, and as entrance treatment to rural communities. Anticipated results of on-pavement chevron applications include a decrease in mean speed or 85th percentile speed at horizontal curves (Hallmark et al., 2012).

Figure 1.12: Application of On-Pavement Chevrons
Source: Hallmark et al., 2012

1.3.10 Rumble Strips

Rumble strips are grooved or raised elements installed on the pavement surface. Four types of rumble strips are used: milled, rolled, formed, and raised rumble strips. Bogenreif (2011) reported that one-third of Iowa safety funding was allocated for the installation of shoulder and edge line rumble strips. Rumble strips placed near or on curve sections of roads cause noise and vibration to alert drivers of their lateral placement on the curve. Rumble strips on a horizontal curve can be utilized three ways: 1) centerline rumble strips (CLRS) prevent drivers from encroaching into the opposite lane, 2) edge line or shoulder rumble strips warn drivers of ROR crashes, and 3) transverse rumble strips that encourage drivers to reduce their driving speed. KDOT practice only allows transverse rumble strips in advance of a stop condition.

1.3.11 Centerline Rumble Strips

In general, milled rumble strips are used for CLRS, and they are installed at or near the centerline. Several factors, such as operating condition, cross section characteristics, and potential road users affect optimum dimensions for milled centerline rumble strips (Lord et al., 2011). Common dimensions discussed in McGee and Hanscom (2006) are 12-inch to 16-inch length (vertical to the centerline), 7-inch width, and 0.5-inch depth (or height). Russell and Rys (2006) recommended milled rumble strips with 12-inch to 16-inch length (perpendicular to the centerline), 7-inch width (along the centerline), 0.5-inch depth, with a 12-inch continuous apart or alternating pairs 12-inches apart with the pairs 24-inches apart. In a recent study by Karkle, Rys, and Russell (2011) the most typical CLRS are milled strips with 16-inch length, 7-inch width, 0.5-inch depth, and 12-inch continuous spacing.

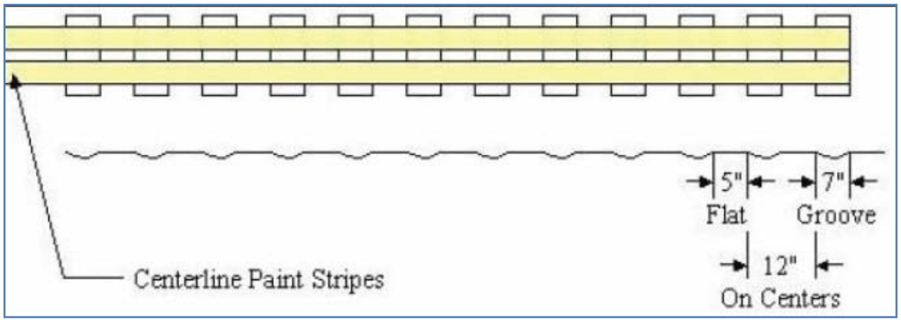


Figure 1.13: Illustration of a Pattern of CLRS
Source: McGee & Hanscom, 2006

McGee and Hanscom (2006) estimated the cost of CLRS to be approximately $0.40 per linear foot, and Lord et al. (2011) reported CLRS to cost approximately $8.63 per linear foot in Texas.

Figure 1.14: Example of CLRS
Source: AASHTO, n.d.

1.3.12 Edge Line or Shoulder Rumble Strips/Stripes

Shoulder rumble strips (SRS) are used when sufficient width of shoulder is present in the roadway; the SRS can be applied on the edge line (commonly called rumble stripes) or shoulder, depending on shoulder width, as shown in Figure 1.15. Lord et al. (2011) suggested 4-inch to 12-inch offset distance from edge line when an 8-foot clear shoulder width is available after installation. McGee and Hanscom (2006) recommend a 7.1-inch longitudinal width and 15.8-inch transverse width with a repeating pattern of approximately 5.1 inches. Implementation cost has been estimated at $8.63 per linear foot in Texas (Lord et al., 2011).

Hallmark et al. (2012) introduced edge line rumble stripes as an innovative combination of rumble strips and edge line markings in order to improve visibility during wet conditions. McDonald (2012) also recommended rumble stripes or milled-in wet-weather visibility pavement markings through curves with a run-off-road crash history.

Figure 1.15: Example of SRS
Source: McGee & Hanscom, 2006

1.3.13 Roadway Rumble Strips

Transverse rumble strips are grooved or raised stripes across the road pavement used to remind drivers to reduce speed or increase caution when negotiating a curve section. The maximum height or depth should not exceed 0.5 inch and, in advance of this treatment, a warning “RUMBLE STRIPS AHEAD” sign is recommended to be used to warn motorists, bicyclists, and motorcyclists. Maintenance concerns should be considered, especially when raised rumble strips are implemented in snowy regions. To prevent motorists from using the opposite lane when they encounter transverse rumble strips, a discontinuous pattern design such as gaps in the bars or grooves across the pavement is recommended.

Figure 1.16: Example of Roadway Rumble Strip
Source: McGee & Hanscom, 2006

1.4 Intermediate- and High-Cost Treatments

1.4.1 Flashing Beacons

Flashing beacons are used as a supplementary treatment when conventional safety improvement countermeasures have not remedied a safety problem (McGee & Hanscom, 2006). A typical circular yellow section from a standard traffic signal is used for flashing beacons. This treatment attracts driver attention to existing signs. Flashing beacons are commonly installed above the signs, and at least 12 inches from the nearest edge of the signs. Lord et al. (2011) estimated the cost of a traditional unit as $2,300 and a solar powered unit as $4,900 in Texas.

Figure 1.17: Use of Flashing Beacons with a Sign
Source: Stein & Neuman, 2007

Similar to flashing beacons, Light-Emitting Diodes (LEDs) are used in traffic signs such as chevrons, as illustrated in Figure 1.18. This treatment advantageously directs driver attention to the sign.

Figure 1.18: Chevron Enhanced with LEDs
Source: Christiansen, 2011

Another application for LEDs is their use in pavement markers to enhance delineation, particularly during low visibility conditions. LEDs can be used in RPMs or markers (solar or hardwired) with the level of pavement, and are snowplow-safe and bike-safe (FHWA, 2009). The cost of a photocell-powered LED RPM is approximately $50, including material and installation (Ibarra & Rice, 2009). The cost of 20 embedded LED markers connected by wire and installed at 20-foot spacing on a curve section is estimated to be $48,000 for a 110 VAC power system and $55,000 for a solar power source (Everard, 2013).

Figure 1.19: Example of Using In-Pavement LED Markers
Source: TAPCO, n.d.

1.4.2 Dynamic Curve Warning System

Dynamic Curve Warning System (DCWS) includes a system that detects an approaching vehicle and measures its speed, and a warning variable message and/or beacons activate whenever the vehicle navigates the curve faster than a safe speed. The detection and measuring system consists of loop detectors or radar. Various designs have been suggested for this system, but the simplest design includes a constant message sign enhanced with flashing beacons on the corner of the sign. When a vehicle with excessive speed approaches the curve, the detection system activates the beacons to warn the driver. Because of their high cost, DCWSs are suggested for curves in which common treatments have not improved curve safety. A wide diversity of design options influences DCWS implementation cost. McGee and Hanscom (2006) reported a $61,000 system installation cost in California, while in Texas a system was estimated to cost $18,000. However, a 44% reduction in total crashes was reported by the California Department of Transportation (Caltrans) in the first year after installation of DCWS (McGee & Hanscom, 2006).

Figure 1.20: Dynamic Curve Warning System in Texas
Source: Lord et al., 2011

Figure 1.21: DCWS
Source: Britton, 2009

The Traffic & Parking Control Company (TAPCO) recently introduced a Sequential Dynamic Curve Warning System (SDCWS), consisting of chevrons enhanced with LEDs and solar power sources combined with a radar detector and activator or controller. When the radar detector senses a speeding vehicle, it triggers the controller and the controller wirelessly activates LEDs on the chevrons to flash sequentially or synchronously at a desired rate. According to the TAPCO, a wireless, vehicle activated, 5-sign system with solar 30-inch by 36-inch signs would cost $14,000. This system was studied in five states: Colorado, Missouri, Texas, Washington, and Wisconsin. The results of the study have not been published yet.

Figure 1.22: Chevrons Enhanced with LEDs
Source: FHWA, 2011
Note: Beneficially using chevrons equipped with LEDs, solar power source, and radar for activation of LEDs for curve safety improvement.

1.4.3 Paved Shoulders and Widening Shoulders

Paved shoulders provide extra space for drivers to escape in the event of vehicle approaching head-on, thus increasing the safety of curve segments on a roadway. Removing material from the old shoulder, recompacting the shoulder, and replacing it with new appropriate asphalt constitutes construction activity. Various aggregates and colors can be used to distinguish the shoulder and travel lane for drivers in the event that they leave the travel lane while driving. Widening paved or stabilized shoulders provides additional space for drivers and increases curve safety.

Figure 1.23: Example of Inside Shoulder Widening
Source: McGee & Hanscom, 2006

McGee and Hanscom (2006) estimated a $1/yd^2 cost for seal-coating a gravel shoulder. Another study reported asphalt to cost approximately $3.80 per gallon and aggregates to cost $72 per cubic yard (Lord et al., 2011).

1.4.4 Shoulder Drop-Off Mitigation (Safety Edge)

Horizontal curves often contain drop-offs because unstabilized pavement edges erode, resulting in a height difference and causing drop-offs (McGee & Hanscom, 2006; Lord et al., 2011). McGee and Hanscom (2006) recommend a 45-degree angle fillet of asphalt on each side of the roadway, and Lord et al. (2011) recommend a formed slope with a 30-degree angle. Fillet or slope-formed shoulders enable drivers who leave the travel-lane to return their vehicles to the roadway with less hazard or risk. FHWA states that the treatment is cost-effective because it requires less than 1% of the asphalt required for a new surfacing project (McGee & Hanscom, 2006).

Figure 1.24: Examples of Safety Edges
Source: McGee & Hanscom, 2006

New safety edge guidelines at KDOT, effective since January 18, 2013, recommend 1.7H: 1V for asphalt and concrete shoulders with 0 to 3 feet width, 1/4H: 1V for asphalt shoulders wider than 3 feet, and vertical edges for concrete shoulders greater than 3 feet.

1.4.5 Installation or Improvement of Lighting

Installation of new lighting or improvement of old lighting can increase the visibility of a curve section of roadway. Lighting is particularly beneficial at nighttime and in adverse weather conditions. However, the installation of new lighting is expensive and should be considered only if economically justifiable. Lord et al. (2011) reported the average cost of lighting to be $2,336 for each of the installed lighting in Texas.

Figure 1.25: Using Lighting to Improve Visibility on a Curve
Source: Lord et al., 2011

1.4.6 Skid Resistant Pavement Surface

The use of special aggregates such as calcined bauxite can increase the friction coefficient of a pavement surface. During resurfacing activities, this treatment can be applied on horizontal curves to increase curve safety, especially when surfaces are wet. This treatment can be obtained by overlaying existing asphalt with appropriate asphalt or applying grooving on the pavement surface. Moreover, the pavement surface must be well drained to meet the purpose. To obtain a proper asphalt overlay, voids should be present on the surface to help drainage and improve skid resistance. Voids can be formed using aggregate which lacks particular particle gradations. Longitudinal or transversal grooving provides drainage and increases friction (Lord et al., 2011).

Investigating the safety effectiveness of a skid resistive overlay in New York showed a 50% reduction in wet condition crashes and a 20% reduction in total crashes (McGee & Hanscom, 2006). Results indicated that grooved pavement demonstrates better performance in wet weather conditions comparing to the other. McGee and Hanscom reported a 72% reduction in wet condition crashes in California, but dry pavement crashes were reduced by only 7% in those curves. McGee and Hanscom also reported the cost of a 2-mile overlay in California to be $200,000 in the year 1996.

Figure 1.26: Application of Skid Resistant Material on a Curve
Source: McGee & Hanscom, 2006

1.5 Conclusions

A variety of countermeasures have been proposed to improve the safety of horizontal curves. Some countermeasures are primary treatments, including centerline, edge line, and curve warning signs, and must initially be considered. For example, pavement markings, including centerline and edge lines, should be implemented when roadway lane width allows centerline or/and edge line markings use. Horizontal alignment signs in advance of the curve are also primary countermeasures that inform drivers of an upcoming change in roadway alignment. Delineators and chevrons are two common and effective treatments which are beneficial for guiding drivers through gentle and sharp curves, respectively. Another advantageous countermeasure is the use of rumble strips on centerlines and edge lines and they are commonly applied in some states, but thermoplastic and RPMs are effective alternatives to rumble strips because they provide visual clues and vibrating effects. Widening the lane and/or paved shoulder may occasionally improve horizontal curves and provide sufficient space for other treatments, such as markings or rumble strips. In addition, shoulder drop-off mitigation is usable when resurfacing is implemented.

The use of supplementary countermeasures on curves continuously experiencing safety issues should be helpful in order to reduce crashes at horizontal curve sections. These treatments include:

- Larger signs and doubling up signs (Section 1.3.2.1);
- Reflective barrier delineation (Section 1.3.7);
- Speed limit advisory marking (Section 1.3.8);
- Optical speed bars (Section 1.3.9);
- Flashing beacons (Section 1.4.1).

Additional treatments can be considered to enhance curve safety; however, they may be too costly or more applicable in new construction. Expensive alternative countermeasures include DCWS and lighting of all horizontal curves.

1.6 Chapter Summary

This chapter discussed general countermeasures and treatments used to improve horizontal curve safety, including several attributes of horizontal curves which identify why curves are very important for road safety. In addition, countermeasures described in this chapter were divided into two classifications: 1) low-cost and 2) intermediate- and high-cost countermeasures. Two recent studies conducted in Iowa in 2012 provided important study conclusions and guidelines for the application of existing countermeasures. These include using wider edge lines, combining rumble strips and pavement markings (rumble stripes), and combining existing signs with LEDs and solar power sources with radar detectors to increase visibility for road users. This is especially helpful during wet weather conditions and for those drivers who exceed the posted or advisory speed. The use of simple innovative methods, such as retro-reflective materials on posts of reflectorized chevrons and PMDs to provide increased visibility, are also described in these two studies. Each countermeasure was discussed individually and information regarding their effectiveness and costs was presented if available. Table 1.6 and Table 1.7 in this report summarize the low-cost and intermediate- and high-cost countermeasures, their use in Kansas (common or tried), their effectiveness, and findings through literature review for each of the countermeasures, respectively.

Table 1.6: Low-Cost Treatment Effectiveness and Usage in Kansas

Treatment	Kansas		Nationwide	
	Common	Tried	Effectiveness	Findings
Centerline	Yes	Yes	High	McGee and Hanscom (2006) reported a 35% reduction in crash occurrence on entire roadway in 1996.
Edge Line	Yes	Yes	High	A 5% reduction in total number of crashes and a 17% reduction in fixed object crashes were reported (McGee & Hanscom, 2006). A 30% reduction was reported in ROR crashes in all types of roadways in Florida (Gan et al., 2005).
Horizontal Alignment Sign	Yes	Yes	High	Evaluation of curve signs showed an 18% reduction in crashes in 1968 (McGee & Hanscom, 2006). Also, Highway Safety Manual reported a 30% crash reduction due to implementing advanced signs (AASHTO, 2010). For curves with safety issues, using <u>larger signs</u> or signs made with <u>high retro-reflective materials</u> are recommended. <u>Identical sign</u> on the left side of the roadway is recommended for the horizontal curve section in which the right side sign is not visible enough (McGee & Hanscom, 2006).
Advisory Speed Plaque	Yes	Yes	Medium	FHWA (2009) recommends a 16-degree ball bank indicator reading for speeds of 20 mph and lower, a 14-degree for speeds of 25 and 30 mph, and a 12-degree for speeds of 35 mph or higher.
Chevron	Yes	Yes	High	Are recommended for curves greater than 7 degrees (McGee & Hanscom, 2006). An 18% reduction in all crashes, a 25% reduction in injury and fatal crashes, and a 35% reduction in crashes during nighttime were reported on two-lane roadways in Connecticut (Srinivasan et al., 2009).
One-Direction Arrow Sign	Yes	Yes	Medium	This sign may be used as a supplement or an alternative to chevron alignment signs (FHWA, 2009).
Post Mounted Delineators	Yes	Yes	High	PMDs reduced ROR crashes by 15% on two-lane roadway in 1966 (McGee & Hanscom, 2006). A 25% reduction in total number of crashes on tangent and curve section was reported (Gan et al., 2005). Are recommended for curves less than or equal to 7 degrees.
Profile Thermoplastic Markings & Raised Pavement Markings	Yes	Yes	Medium	RPMs have better performance on curves less than 3.5 degrees (McGee & Hanscom, 2006) and ADTs greater than 5,000 vpd.

Table 1.6: Low-Cost Treatment Effectiveness and Usage in Kansas (Continued)

Treatment	Kansas		Nationwide	
	Common	Tried	Effectiveness	Findings
Reflective Barrier Delineation	Yes[1]	Yes[2]	Medium	An 8% reduction for fatal and injury crashes was reported (Montella, 2005).
Speed Limit Advisory Markings	No	No	Medium	Pennsylvania Department of Transportation reported 6% to 7% reduction in vehicular speeds (Lord et al., 2011).
Optical Speed Bars	No	No	Not Clear	Reduction and increase in 85th percentile speed were considered in different studies through using this treatment (Campbell et al., 2012).
Centerline Rumble Strips	Yes	Yes	High	CLRS are recommended for roadways that experience considerable number of cross-centerline crashes. A 36% decrease was reported for centerline crossing fatal and injury crashes (Kar & Weeks, 2009). Colorado Department of Transportation reported a 34% reduction in head on crashes and a 36.5% reduction in opposite side swipe crashes (Hallmark et al., 2012). **Kansas:** A study showed 96% of surveyed road users of US-50 highways between towns of Newton and Hutchinson had positive opinion about CLRS and their effect on crash reduction (Russell & Rys, 2005). CLRS are recommended for roadways with AADTs less than 5,750 vpd (Rys, Karkle, & Russell, 2012).
Shoulder Rumble Strips and Edge Line Rumble stripes	Yes[3]	Yes[4]	High	A 65% to 70% reduction in ROR crashes was observed through using shoulder rumble stripes by New York State Department of Transportation in 1997, and a 25% reduction in ROR crashes was reported due to using edge line rumble stripes by Mississippi Department of Transportation in 2006 (Hallmark et al., 2012). **Kansas:** SRSs are recommended for narrow shoulders. For AADTs greater than 3,000 vpd both configurations are recommended (Rys, Karkle, & Russell, 2012).
Transverse Rumble Strips	No	No	Medium	Mostly recommended for sections with high number of rear-end crashes and a sharp curve after a long tangent section (Villwock-Witte & Veneziano, 2013).

[1]- The only use of reflective materials, as reflective barrier delineation, is on guardrail in Kansas.
[2]- The only use of reflective materials, as reflective barrier delineation, is on guardrail in Kansas.
[3]- Only SRS is used in Kansas.
[4]- Only SRS is used in Kansas.

Table 1.7: Intermediate- and High-Cost Treatment Effectiveness and Usage in Kansas

Treatment	Kansas		Nationwide	
	Common	Tried	Effectiveness	Findings
Flashing Beacons	Yes	Yes	Medium	A crash reduction factor (CRF) of 39 was reported for curve warning sign equipped with flash beacons in conjunction with chevrons (FHWA, 2009).
Chevrons Enhanced with LEDs	No	No	Not Determined	A system manufactured by Traffic and Parking Control Co. (TAPCO) is under study in five states: Colorado, Missouri, Iowa, Washington, and Texas. Results of the study have not yet been published.
Pavement LED Markers	No	Yes	Not Determined	In pavement lighting increases visibility of RPMs. A few studies investigated the pedestrian crosswalk application of in pavement markers. There are issues with maintenance and resurfacing (Carson, Tydlacka, Gray, & Voigt, 2008).
Dynamic Curve Warning Systems	No	No	High	Due to their cost, DCWS is recommended for problematic curves in which conventional treatments are not effective. A 44% reduction in all crashes was reported by Caltrans (McGee & Hanscom, 2006).
Paved Shoulders and Widening Shoulders	Yes	Yes	Medium	An 8.3% reduction in all crashes was reported for paved shoulders. A 4.4% reduction in total crashes and a 7.8% in ROR crashes were reported for every foot of shoulder widening (Hallmark, McDonald, Tian, & Andersen, 2009).
Shoulder Drop-Off Mitigation	Yes	Yes	Medium	Safety edge can be implemented in conjunction with resurfacing. A 7% reduction in total crashes was reported (Graham, Richard, O'Laughlin, & Harwood, 2011).
Installation or Improvement of Lighting	Yes	Yes	Medium	A CRF of 20 was reported for rural roadways illumination for all road types (Elvik & Vaa, 2004).
Skid Resistant Pavement Surface	No	Yes	High	For rural roadways, a CRF of 31.6 for all crashes and a CRF of 65.4 for wet-road crashes were reported (Lyon & Persaud, 2008).

Chapter 2: Identifying Curves with a High Number of Crashes

2.1 Introduction

In Chapter 1, recommended treatments and countermeasures for horizontal curve sections from the literature were discussed. In this chapter, countermeasures applied on horizontal curves with a high number of crashes in selected counties of Kansas are investigated. Two methods are used to classify curves according to recommended criteria for applying countermeasures and defining hazardous horizontal curves. The first criterion is based on the degree of curvature being 7 degrees as a threshold for applying chevrons and PMDs (McGee & Hanscom, 2006). The second criterion is based on studies which suggest that a majority of severe crashes occur on horizontal curves with radii less than 1500 feet (Preston, 2009). Countermeasures are considered for each classified groups of curves.

2.2 Data Selection

The state of Kansas is divided into 105 counties. To conduct this study, 11 counties (approximately 10% of total counties) were selected as having a high number of crashes at horizontal curves on rural highways. A database of crashes at horizontal curves provided by KDOT contained 3,855 horizontal curve-related crashes during the nine years from 2004 to 2012, including crashes on Interstate and state highways. This database was used to determine counties with the highest numbers of crashes. According to the database, the selected counties had 996 crashes, excluding Interstate crashes, comprising approximately 25.8% of crashes. Since the purpose of this study was to investigate crashes at horizontal curve sections in rural highways, all 996 crashes were located on Google Maps by latitude and longitude of the crash points from KDOT crash database, and crashes that occurred on tangent sections, at intersections, or in urban or residential areas were excluded. After verifying each crash on Google Maps, 725 crashes which occurred on 318 horizontal curves were selected for this study. Selected counties, number of horizontal curve-related crashes, and number of horizontal curves where crashes occurred are presented in Table 2.1.

Table 2.1: Selected Counties and Related Crash Information from the 725 Selected Crashes

No	County Name	Number of Crashes from Database	Number of Crashes on Horizontal Curves	Number of Curves
1	Douglas	145	111	29
2	Geary	76	54	32
3	Leavenworth	248	209	68
4	Lyon	121	75	40
5	Marshall	35	23	12
6	Morris	35	24	12
7	Pottawatomie	51	39	26
8	Riley	80	54	21
9	Shawnee	51	41	23
10	Wabaunsee	71	39	26
11	Wyandotte	83	56	32
Total		996	725	318

Each county was considered individually, and curves with a high number of crashes were selected for each county according to a comparison between curves of that county; in other words, curves with three crashes were selected because they had a higher number of crashes in that county's data set, while another county recorded 16 crashes on one curve. Considering all 11 counties, 43 horizontal curves were selected with high numbers of crashes. Although the selected horizontal curves (43 out of 318) constituted 13.5% of the total number of curves in the selected counties, 206 crashes (28.4%) occurred on these curves. Various countermeasures of horizontal curves, such as chevrons and PMDs, were assigned in accordance with the degree of curvature according to McGee and Hanscom (2006). Only a few curves in the KDOT database contained degree of curvature information; therefore, the degree of curvature of horizontal curves was determined with AutoCAD and images of horizontal curves from Google Maps, as explained in the section below.

2.3 Degree of Curvature of Horizontal Curves

To determine the degree of curvature of each horizontal curve, a plan view of the horizontal curve was imported into an AutoCAD software package from Google Maps. All curves were assumed to be circular. The point of tangent (PI) was determined by extending two lines drawn on tangent sections of the roadway preceding and following the curve section. Next, the point of curvature (PC) and point of tangency (PT) were estimated in the AutoCAD environment and the long chord of the curve was drawn to determine the vertex of the curve by connecting the PI to the chord with a perpendicular line, so the external distance (E) and middle ordinate (MO) could be measured. Other important characteristics of the curve, including central angle (Δ), radius (R), and degree of curvature (D), could then be estimated based on standard, curve-related equations shown below.

$$\frac{\Delta}{2} = tg^{-1}\left(\frac{E + MO}{\left(\frac{LC}{2}\right)}\right) \qquad \text{Equation 2.1}$$

Where:
Δ: is the central angle,
E: is external distance,
MO: is the middle ordinate, and
LC: is the length of chord.

$$R = \frac{LC}{2sin\left(\frac{\Delta}{2}\right)} \qquad \text{Equation 2.2}$$

Where:
R: is the radius of the curve,
LC: is the length of chord, and
Δ: is the central angle.

The degree of curvature (D) can be calculated according to the following equation:

$$D = \frac{5279.58}{R}$$ Equation 2.3

Where:
5279.58: is the conversion value from mile to foot,
D: is the degree of curvature, and
R: is the radius of the curve.

The length of curve (L) and radius (R) were obtained from AutoCAD software for each curve, and the degree of curvature was calculated from Equation 2.3. A typical circular curve is shown in the Figure 2.1, including features of a horizontal curve.

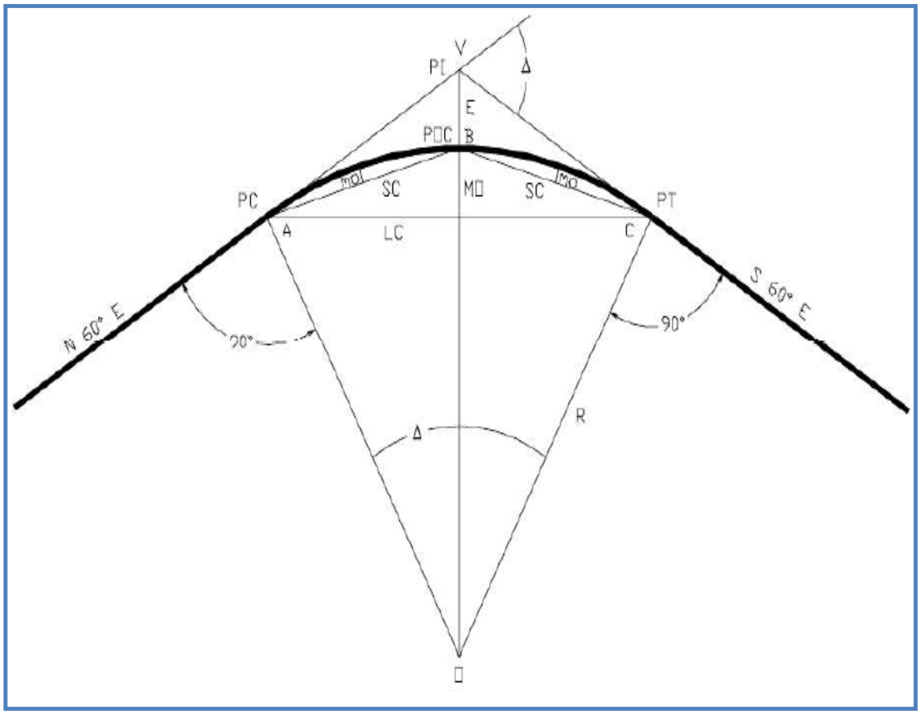


Figure 2.1: Typical Horizontal Curve
Note: O: center of the curve; Δ: central angle; R: radius; PC: point of curvature; PI: point of tangent intersection; PT: point of tangent; LC: long chord; E: external distance; and MO: middle ordinate.

The above method was applied to all 43 curves selected with a high number of crashes for the selected 11 counties, and radius, length of curve, and degree of curvature were calculated for all the curves. Figure 2.2 illustrates the major characteristics of a typical curve using Google Maps and AutoCAD software package.

Figure 2.2: Determining Characteristics of a Curve Using Google Maps and AutoCAD
Source: Google, n.d.

2.4 Classification of Curves

Two classification methods were applied to categorize the studied horizontal curves. The first method classified curves into three groups based on recommended countermeasures by McGee and Hanscom (2006). Since chevrons are suggested for curves with a degree of curvature of 7 degrees or more and PMDs are recommended for curves with less than 7 degrees of curvature according to McGee and Hanscom, then three groups of curves were determined. The first group contained curves with degree of curvature less than 1 degree, the second group included curves with degree of curvature equal to or greater than 1 degree and less than or equal to 7 degrees, and the third group included curves with degree of curvature greater than 7 degrees.

To provide a better perception of crash severity in this study, equivalent property damage only (EPDO) crashes were used.

$$EPDO = PDO + 15 \times (I + F) \quad \text{Equation 2.4}$$

Where:
EPDO: number of equivalent property damage only crashes,
PDO: number of property damage only crashes,
15: coefficient representing equivalent PDO crashes for injury and fatal crashes for Kansas,
I: number of injury crashes, and
F: number of fatal crashes.

Numbers of Property Damage Only (PDO), injury, fatal, total, and EPDO crashes are presented in Table 2.2 for each curve groups of this method.

Table 2.2: Data of Curves Classification, Method 1

No	Degree of Curvature	Number of Curves	Number of PDO Crashes	Number of Injury Crashes	Number of Fatal Crashes	Total	Number of EPDO Crashes
1	$D < 1$	6	12	8	0	20	132
2	$1 \leq D \leq 7$	29	81	41	6	128	786
3	$D > 7$	8	41	17	0	58	296
Total		43	134	66	6	206	1214

More than half of the studied curves (67.44%) exhibited curvature between 1 and 7 degrees, and more than half of total crashes (62.14%) occurred on these curves. All fatal crashes, 62.12% of injury crashes, and 60.45% of property damage only (PDO) crashes occurred on curves with degree of curvature between 1 and 7 degrees. Curves with degree of curvature less than 1 degree constituted 13.95% of studied curves; 8.96% of PDO crashes, 12.12% of injury crashes, and no fatal crashes occurred in this group. 18.60% of curves had degree of curvature greater than 7 degrees, and 30.60% of PDO crashes, 25.76% of injury crashes, and 0% of fatal crashes occurred on these curves.

Preston (2009) reported that horizontal curves with radii less than 1500 feet (corresponding to 3.5 degree of curvature) had more injury and fatal crashes. In the second classification method, horizontal curves were categorized into two groups. The first group consisted of horizontal curves with degree of curvature less than or equal to 3.5 degrees, corresponding to radius of 1500 feet, and the second group contained curves with degree of curvature greater than 3.5 degrees. Numbers of PDO, injury, fatal, total, and EPDO crashes are presented in Table 2.3 for each curve groups of the second method.

Table 2.3: Data of Curves Classification, Method 2

No	Degree of Curvature	Number of Curves	Number of PDO Crashes	Number of Injury Crashes	Number of Fatal Crashes	Total	Number of EPDO Crashes
1	$D \leq 3.5$	21	54	25	4	83	489
2	$D > 3.5$	22	80	41	2	123	725
Total		43	134	66	6	206	1214

Figure 2.3 illustrates two curve groups based on the second method used for curve classification.

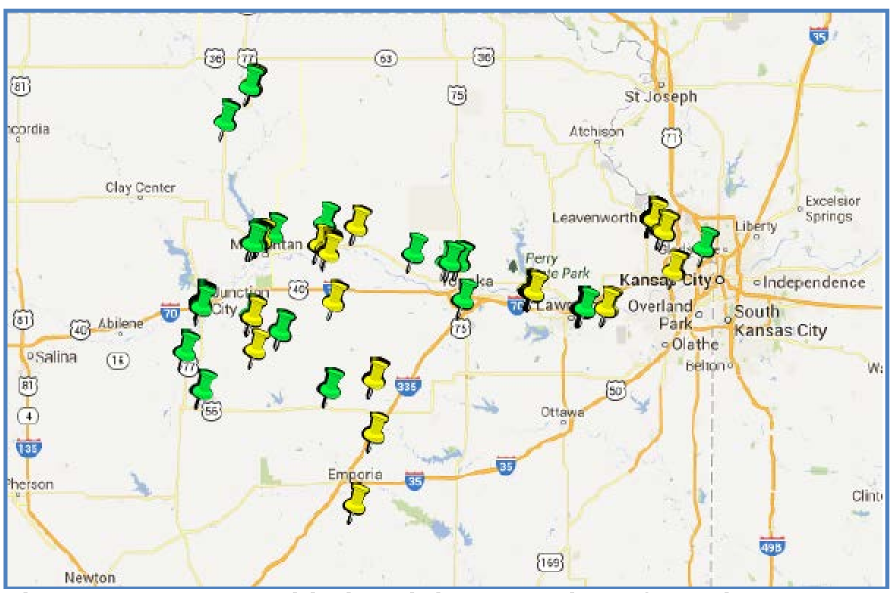


Figure 2.3: Curves with the Highest Number of Crashes
Source: Google, n.d.
Note: Yellow indicators show curves with degree of curvature greater than 3.5 degrees and green indicators depict curves with degree of curvature less than or equal to 3.5 degrees.

Both groups, curves with equal to or less than 3.5 degrees and curves with degree of curvature greater than 3.5 degrees, had approximately equal number of curves, but most crashes occurred in the group with degree of curvature greater than 3.5 degrees. However, 66.67% of fatal crashes occurred at curve sections with degree of curvature equal to or less than 3.5 degrees. For horizontal curves with degree of curvature greater than 3.5 degrees, 59.70%, 62.12%, 33.33%, and 59.71% of PDO crashes, injury crashes, fatal crashes, and total number of crashes occurred, respectively.

2.5 Crash Rate

Since horizontal curve sections were considered in this study, the usual crash rate equation was applied:

$$R = \frac{A \times 1{,}000{,}000}{L \times V \times 365} \qquad \text{Equation 2.5}$$

Where:
R: crash rate of the study roadway (number of crashes per million vehicle-mile travel),
A: average number of crashes along the study section per year,
L: length of the section (miles), and
V: annual average daily traffic volume along the study section.

To calculate crash rates of the studied curves, annual average daily traffic (AADT) for curves was obtained from traffic maps of counties provided by KDOT. The average of AADTs of nine years, 2004 to 2012, was obtained from the KDOT database. AADTs vary from 374 vpd to 28,888 vpd. Likewise, among 43 studied curve sections, the length of each section obtained from AutoCAD software, varied from 173 feet to 5325 feet.

Crash rates and EPDO crash rates were calculated for each curve section and, due to considerable variation in section length and AADTs, they varied between 0.07 and 73.10 crashes/Million Vehicle Miles Traveled (MVMT). EPDO crash rates varied between 0.14 and 511.73 EPDO crashes/MVMT.

Table 2.4 to Table 2.8 show the ranks of curves based on crash rates and EPDO crash rates for each group of the two discussed classification methods. Table 2.9 and Table 2.10 rank all studied curves according to crash rates and EPDO crash rates, respectively.

Table 2.4: Ranks of Curves for Group 1 of Method 1 Classification Based on Crash Rates and EPDO Crash Rates

Curve Number	County	Road Name	Number of Crashes	AADT	Crash rate Crashes/ (MVMT)	Rank (crash rate)	EPDO crash rate Crashes/ (MVMT)	Rank (EPDO crash rate)
86	Geary	U077	5	3,424	0.44	4	4.14	4
126	Lyon	U056	5	1,450	1.89	1	7.18	1
270	Shawnee	U024	2	4,733	0.73	2	0.73	6
271	Shawnee	U024	3	7,635	0.42	5	4.30	2
278	Shawnee	U075	3	14,001	0.15	6	0.85	5
293	Wyandotte	K05	2	7,394	0.53	3	4.25	3

Table 2.5: Ranks of Curves for Group 2 of Method 1 Classification Based on Crash Rates and EPDO Crash Rates

Curve Number	County	Road Name	Number of Crashes	AADT	Crash rate Crashes/ (MVMT)	Rank (crash rate)	EPDO crash rate Crashes/ (MVMT)	Rank (EPDO crash rate)
6	Riley	K018	4	18,963	0.110	27	0.496	25
7	Riley	K018	8	18,963	0.226	23	0.622	24
9	Riley	K018	5	23,825	0.474	22	1.803	21
25	Marshall	U077	3	1,395	2.198	12	2.198	20
26	Marshall	U077	3	2,874	0.657	20	6.784	17
27	Marshall	U077	4	2,310	1.515	15	1.515	22
45	Pottawatomi	K099	3	3,048	0.852	19	4.829	18
52	Pottawatomi	U024	3	22,575	0.069	29	0.392	27
77	Geary	057	4	374	11.833	3	53.246	4
78	Geary	K057	4	374	24.545	1	368.175	1
87	Geary	U077	4	3,424	0.954	17	10.971	13
115	Lyon	K099	5	2,830	3.969	8	26.193	8
122	Lyon	K099	6	579	22.257	2	74.190	2
146	Wabaunsee	K099	3	841	8.375	4	8.375	15
155	Wabaunsee	K099	4	2,833	4.475	7	35.804	6
156	Wabaunsee	K099	3	2,833	3.595	9	20.369	9
236-A	Douglas	K010	5	28,888	0.109	28	0.416	26
236-B	Douglas	K010	9	27,138	0.193	24	1.093	23
238	Douglas	K010	6	27,250	0.138	26	0.138	29
245	Douglas	U040	5	3,889	2.011	13	13.270	12
246	Douglas	U040	8	3,889	3.052	10	35.098	7
247	Douglas	U040	7	3,889	5.108	6	56.189	3
282	Shawnee	U075	4	28,575	0.142	25	0.142	28
294-A	Wyandotte	K005	3	1,804	6.979	5	39.549	5
301	Wyandotte	K032	2	11,013	0.561	21	4.491	19
374	Morris	K177	2	1,616	1.771	14	14.168	11
376	Morris	U056	2	1,002	2.502	11	20.019	10
380	Morris	U077	5	2,218	1.119	16	7.384	16
381	Morris	U077	4	2,253	0.938	18	10.783	14

Table 2.6: Ranks of Curves for Group 3 of Method 1 Classification Based on Crash Rates and EPDO Crash Rates

Curve Number	County	Road Name	Number of Crashes	AADT	Crash rate Crashes/ (MVMT)	Rank (crash rate)	EPDO crash rate Crashes/ (MVMT)	Rank (EPDO crash rate)
59	Pottawatomi	U024	3	4,339	6.43	8	66.40	5
121	Lyon	K099	5	933	37.15	4	349.21	2
135	Wabaunsee	K018	3	569	35.32	5	35.32	6
166	Leavenworth	K005	16	1,730	69.04	2	310.70	3
167	Leavenworth	K005	12	1,730	45.79	3	152.64	4
168	Leavenworth	K005	14	1,730	73.10	1	511.73	1
295	Wyandotte	K005	3	1,804	12.62	7	12.62	8
371	Morris	K004	2	458	20.64	6	20.64	7

Table 2.7: Ranks of Curves for Group 1 of Method 2 Classification Based on Crash Rates and EPDO Crash Rates

Curve Number	County	Road Name	Number of Crashes	AADT	Crash rate Crashes/ (MVMT)	Rank (crash rate)	EPDO crash rate Crashes/ (MVMT)	Rank (EPDO crash rate)
6	Riley	K018	4	18,963	0.110	19	0.496	18
7	Riley	K018	8	18,963	0.226	15	0.622	17
25	Marshall	U077	3	1,395	2.198	3	2.198	13
26	Marshall	U077	3	2,874	0.657	11	6.784	8
45	Pottawatomi	K099	3	3,048	0.852	9	4.829	9
52	Pottawatomi	U024	3	22,575	0.069	21	0.392	20
77	Geary	K057	4	374	11.831	1	53.241	1
86	Geary	U077	5	3,424	0.441	13	4.143	12
87	Geary	U077	4	3,424	0.954	7	10.971	4
126	Lyon	U056	5	1,450	1.890	4	7.180	7
236-A	Douglas	K010	5	28,888	0.109	20	0.416	19
236-B	Douglas	K010	9	27,138	0.193	16	1.093	14
270	Shawnee	U024	2	4,733	0.728	10	0.728	16
271	Shawnee	U024	3	7,635	0.416	14	4.301	10
278	Shawnee	U075	3	14,001	0.149	17	0.847	15
282	Shawnee	U075	4	28,575	0.142	18	0.142	21
293	Wyandotte	K05	2	7,394	0.532	12	4.254	11
374	Morris	K177	2	1,616	1.771	5	14.168	3
376	Morris	U056	2	1,002	2.502	2	20.019	2
380	Morris	U077	5	2,218	1.119	6	7.384	6
381	Morris	U077	4	2,253	0.938	8	10.783	5

Table 2.8: Ranks of Curves for Group 2 of Method 2 Classification Based on Crash Rates and EPDO Crash Rates

Curve Number	County	Road Name	Number of Crashes	AADT	Crash rate Crashes/ (MVMT)	Rank (crash rate)	EPDO crash rate Crashes/ (MVMT)	Rank (EPDO crash rate)
9	Riley	K018	5	23,835	0.47	21	1.80	20
27	Marshall	U077	4	2,310	1.51	19	1.51	21
59	Pottawatomi	U024	3	4,339	6.43	12	66.40	7
78	Geary	K057	4	374	24.55	6	323.99	3
115	Lyon	K099	5	2,830	3.97	15	26.19	13
121	Lyon	K099	5	933	37.15	4	349.21	2
122	Lyon	K099	6	579	22.26	7	74.19	6
135	Wabaunsee	K018	3	569	35.32	5	35.32	11
146	Wabaunsee	K099	3	841	8.38	10	8.38	18
155	Wabaunsee	K099	4	2,833	4.48	14	35.80	10
156	Wabaunsee	K099	3	2,833	3.59	16	20.37	15
166	Leavenworth	K005	16	1,730	69.04	2	310.70	4
167	Leavenworth	K005	12	1,730	45.79	3	152.64	5
168	Leavenworth	K005	14	1,730	73.10	1	511.73	1
238	Douglas	K010	6	27,250	0.14	22	0.14	22
245	Douglas	U040	5	3,889	2.01	18	13.27	16
246	Douglas	U040	8	3,889	3.05	17	35.10	12
247	Douglas	U040	7	3,889	5.11	13	56.19	8
294-A	Wyandotte	K005	3	1,804	6.98	11	39.55	9
295	Wyandotte	K005	3	1,804	12.62	9	12.62	17
301	Wyandotte	K032	2	11,013	0.56	20	4.49	19
371	Morris	K004	2	458	20.64	8	20.64	14

Table 2.9: Ranks of Curves Based on Crash Rates

Rank	Number of Curve	Crash rate	Rank	Number of Curve	Crash rate	Rank	Number of Curve	Crash rate
1	168	72.103	16	115	3.969	31	301	0.561
2	166	69.044	17	156	3.595	32	293	0.532
3	167	45.792	18	246	3.052	33	9	0.474
4	121	37.150	19	376	2.502	34	86	0.441
5	135	35.317	20	25	2.198	35	271	0.416
6	78	24.545	21	245	2.011	36	7	0.226
7	122	22.257	22	126	1.890	37	236-B	0.193
8	371	20.643	23	374	1.771	38	278	0.149
9	295	12.622	24	27	1.24	39	282	0.142
10	77	11.831	25	380	1.119	40	238	0.138
11	146	8.375	26	87	0.954	41	6	0.110
12	294-A	6.979	27	381	0.938	42	236-A	0.109
13	59	6.426	28	45	0.852	43	52	0.069
14	247	5.108	29	270	0.728			
15	155	4.475	30	26	0.657			

Table 2.10: Ranks of Curves Based on EPDO Crash Rates

Rank	Number of Curve	EPDO Crash rate	Rank	Number of Curve	EPDO Crash rate	Rank	Number of Curve	EPDO Crash rate
1	168	511.731	16	156	20.369	31	86	4.143
2	121	349.207	17	376	20.019	32	25	2.198
3	78	323.994	18	374	14.167	33	9	1.802
4	166	310.697	19	245	13.270	34	27	1.515
5	167	152.640	20	295	12.622	35	236-B	1.093
6	122	74.190	21	87	10.971	36	278	0.847
7	59	66.398	22	381	10.783	37	270	0.728
8	247	56.189	23	146	8.375	38	7	0.622
9	77	53.241	24	380	7.384	39	6	0.496
10	294-A	39.549	25	126	7.180	40	236-A	0.416
11	155	35.804	26	26	6.784	41	52	0.392
12	135	35.317	27	45	4.829	42	282	0.142
13	246	35.098	28	301	4.491	43	238	0.138
14	115	26.193	29	271	4.301			
15	371	20.644	30	293	4.254			

2.6 Countermeasures

To determine which countermeasure treatments existed on the studied horizontal curve sections, all curves were investigated using Google Maps, and countermeasures were recorded according to available photos from Google Maps. Countermeasures determined from existing images of the studied sections include: edge line and centerline, horizontal curve alignment signs (including curve or turn sign, reverse curve or turn sign, and winding road sign), advisory speed plate, chevrons, PMDs, one-arrow direction sign, CLRS, and SRS, which are common curve countermeasures in Kansas.

Applied countermeasures were recorded for groups organized from each classification method.

Table 2.11: Countermeasures Used for Classification Method 1 Group 1, Relevant Crashes, and Their Portions

D*<1			Countermeasures**									
			CL	**EL**	**WS**	**ASP**	**ODAS**	**PMDs**	**Ch**	**NPZS**	**CLRS**	**SRS**
Curve		#	6	6	0	0	0	0	0	0	1	1
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**17.00**	**17.00**
Crashes	**PDO**	#	12	12	0	0	0	0	0	0	2	1
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**16.67**	**8.33**
	Injury	#	8	8	0	0	0	0	0	0	1	1
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**12.50**	**12.50**
	Fatal	#	0	0	0	0	0	0	0	0	0	0
		%	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	Total	#	20	20	0	0	0	0	0	0	3	2
		%	**100**	**100**	**100**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**15.00**	**10.00**
	EPDO	#	60	60	0	0	0	0	0	0	8	7
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**13.33**	**11.67**

*Degree of curvature
**CL: Centerline; EL: Edge Line; WS: Advance Warning Sign; ASP: Advisory Speed Plaques; ODAS: One-Direction Large Arrow Sign; PMDs: Post Mounted Delineators; Ch: Chevrons; NPZS: No-Passing Zone Sign; CLRS: Centerline Rumble Strips; SRS: Shoulder Rumble Strips.

Table 2.12: Countermeasures Used for Classification Method 1 Group 2, Relevant Crashes, and Their Portions

$1 \leq D^* \leq 7$			Countermeasures**									
			CL	EL	WS	ASP	ODAS	PMDs	Ch	NPZS	CLRS	SRS
Curve		#	29	29	8	8	0	5	8	6	2	2
		%	100	100	27.59	27.59	0.00	17.24	27.59	20.69	6.90	6.90
Crashes	PDO	#	81	81	21	21	0	19	23	15	4	5
		%	100	100	25.93	25.93	0.00	23.46	28.40	18.52	4.94	6.17
	Injury	#	41	41	16	16	0	5	15	15	10	1
		%	100	100	39.02	39.02	0.00	12.20	36.59	36.59	24.39	2.44
	Fatal	#	6	6	2	2	0	1	2	1	1	0
		%	100	100	33.33	33.33	0.00	16.67	33.33	16.67	16.67	0.00
	Total	#	128	128	39	39	0	25	40	31	15	6
		%	100	100	30.47	30.47	0.00	19.53	31.25	24.22	11.72	4.69
	EPDO	#	363	363	129	129	0	55	125	111	70	11
		%	100	100	35.54	35.54	0.00	15.15	34.44	30.58	19.28	3.03

*Degree of curvature
**CL: Centerline; EL: Edge Line; WS: Advance Warning Sign; ASP: Advisory Speed Plaques; ODAS: One-Direction Large Arrow Sign; PMDs: Post Mounted Delineators; Ch: Chevrons; NPZS: No-Passing Zone Sign; CLRS: Centerline Rumble Strips; SRS: Shoulder Rumble Strips.

Table 2.13: Countermeasures Used for Classification Method 1 Group 3, Relevant Crashes, and Their Portions

D*>7			Countermeasures**									
			CL	EL	WS	ASP	ODAS	PMDs	Ch	NPZS	CLRS	SRS
Curve		#	8	8	7	7	2	0	8	1	0	0
		%	100	100	87.50	87.50	25.00	0.00	100	12.50	0.00	0.00
Crashes	PDO	#	41	41	40	40	15	0	41	2	0	0
		%	100	100	97.56	97.56	36.59	0.00	100	4.88	0.00	0.00
	Injury	#	17	17	15	15	4	0	17	0	0	0
		%	100	100	88.24	88.24	23.53	0.00	100	0.00	0.00	0.00
	Fatal	#	0	0	0	0	0	0	0	0	0	0
		%	-	-	-	-	-	-	-	-	-	-
	Total	#	58	58	55	55	19	0	58	2	0	0
		%	100	100	94.83	94.83	32.76	0.00	100	3.45	0.00	0.00
	EPDO	#	143	143	130	130	39	0	143	2	0	0
		%	100	100	90.91	90.91	27.27	0.00	100	1.40	0.00	0.00

*Degree of curvature
**CL: Centerline; EL: Edge Line; WS: Advance Warning Sign; ASP: Advisory Speed Plaques; ODAS: One-Direction Large Arrow Sign; PMDs: Post Mounted Delineators; Ch: Chevrons; NPZS: No-Passing Zone Sign; CLRS: Centerline Rumble Strips; SRS: Shoulder Rumble Strips.

Table 2.14: Countermeasures Used for Classification Method 2 Group 1, Relevant Crashes, and Their Portions

D*<3.5			Countermeasures**									
			CL	**EL**	**WS**	**ASP**	**ODAS**	**PMDs**	**Ch**	**NPZS**	**CLRS**	**SRS**
Curve		#	21	21	0	0	0	3	0	2	1	2
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**14.29**	**0.00**	**9.52**	**4.76**	**9.52**
Crashes	**PDO**	#	54	54	0	0	0	11	0	4	2	5
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**20.37**	**0.00**	**7.41**	**3.70**	**9.26**
	Injury	#	25	25	0	0	0	4	0	3	1	1
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**16.00**	**0.00**	**12.00**	**4.00**	**4.00**
	Fatal	#	4	4	0	0	0	1	0	0	0	0
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**25.00**	**0.00**	**0.00**	**0.00**	**0.00**
	Total	#	83	83	0	0	0	16	0	7	3	6
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**19.28**	**0.00**	**8.43**	**3.61**	**7.23**
	EPDO	#	228	228	0	0	0	41	0	22	8	22
		%	**100**	**100**	**0.00**	**0.00**	**0.00**	**17.98**	**0.00**	**9.65**	**3.51**	**4.82**

*Degree of curvature
**CL: Centerline; EL: Edge Line; WS: Advance Warning Sign; ASP: Advisory Speed Plaques; ODAS: One-Direction Large Arrow Sign; PMDs: Post Mounted Delineators; Ch: Chevrons; NPZS: No-Passing Zone Sign; CLRS: Centerline Rumble Strips; SRS: Shoulder Rumble Strips.

Table 2.15: Countermeasures Used for Classification Method 2 Group 2, Relevant Crashes, and Their Portions

D*>3.5 Degrees			Countermeasures**									
			CL	**EL**	**WS**	**ASP**	**ODAS**	**PMDs**	**Ch**	**NPZS**	**CLRS**	**SRS**
Curve		#	22	22	15	15	2	2	16	5	2	1
		%	**100**	**100**	**68.18**	**68.18**	**9.09**	**9.09**	**72.73**	**22.73**	**9.09**	**4.55**
Crashes	**PDO**	#	80	80	61	61	15	8	64	13	4	1
		%	**100**	**100**	**76.25**	**76.25**	**18.75**	**10.00**	**80.00**	**16.25**	**5.00**	**1.25**
	Injury	#	41	41	31	31	4	1	32	12	10	1
		%	**100**	**100**	**75.61**	**75.61**	**9.76**	**2.44**	**78.05**	**29.27**	**24.39**	**2.44**
	Fatal	#	2	2	2	2	0	0	2	1	1	0
		%	**100**	**100**	**100**	**100**	**0.00**	**0.00**	**100**	**50.00**	**50.00**	**0.00**
	Total	#	123	123	94	94	19	9	98	26	15	2
		%	**100**	**100**	**76.42**	**76.42**	**15.45**	**7.32**	**79.67**	**21.14**	**12.20**	**1.63**
	EPDO	#	338	338	259	259	39	14	268	91	70	7
		%	**100**	**100**	**76.63**	**76.63**	**11.54**	**4.14**	**79.29**	**26.92**	**20.71**	**2.07**

*Degree of curvature
**CL: Centerline; EL: Edge Line; WS: Advance Warning Sign; ASP: Advisory Speed Plaques; ODAS: One-Direction Large Arrow Sign; PMDs: Post Mounted Delineators; Ch: Chevrons; NPZS: No-Passing Zone Sign; CLRS: Centerline Rumble Strips; SRS: Shoulder Rumble Strips.

Regardless of classifications and group, edge line and centerline were used as basic treatments on all studied curves. For the first classification method, only two out of six curves with degree of curvature less than 1 had one additional treatment. For example, one curve contained CLRS while the other curve utilized SRS. Among 29 curves in the group of curves with degree of curvature between 1 and 7 degrees, horizontal alignment signs and advisory speed plaques were used on eight curves, chevrons were used on eight curves, PMDs were used on five curves, and no-passing zone signs were used on six curves. In addition, CLRS were used on two curves and SRSs were used on two other curves. Eight curves with degree of curvature greater than 7 degrees had horizontal alignment signs, advisory speed plates, and chevrons. One-direction arrow signs were used on two of the curves. Only one curve had a no-passing zone sign, and other treatments, PMDs, CLRS, and SRS, were not used.

The second classification method contained two groups: 21 horizontal curve sections with degree of curvature less than or equal to 3.5 degrees, and 22 curve sections for curves with degree of curvature greater than 3.5 degrees. Basic treatments (edge line and centerline) were used on all sections. For curves with degree of curvature less than or equal to 3.5 degrees, three curves had PMDs, two curves had no-passing zone signs, one curve had CLRS, and two curves had SRS.

For curves with degree of curvature greater than 3.5 degrees, 15 curves with horizontal curve alignment signs and advisory speed plates were observed, 16 curves had chevrons, two curves had PMDs, five curves had no-passing zone signs, two curves utilized CLRS, and one curve had SRS.

2.6.1 Policies on Chevron Alignment Signs Use

According to FHWA (2009), chevron signs are required at horizontal curve sections when the difference between posted speed and advisory speed is 15 mph or greater. The ball bank indicator method determines the advisory speed at horizontal curve sections. The research team found an approximation method to use degree of curvature or radius of curve as a threshold for implementing chevron alignment signs. The observed highest posted speed on two-way highways in Kansas is 65 mph. Chevron alignment signs are required when the advisory speed is 15 mph less than posted speed, meaning the advisory speed would be a maximum of 50 mph on two-way highways. The maximum radius or minimum degree of curvature can be calculated with Equations 2.6 and 2.7, respectively.

$$R = \frac{v^2}{15\ (0.01e + f_{max})}$$ Equation 2.6

$$D = \frac{5729.58\ (15\ (0.01e + f_{max}))}{v^2}$$ Equation 2.7

Where:
R: maximum radius of a horizontal curve in which chevron alignment signs are required,
D: minimum degree of curvature for chevron alignment implementing,
V: advisory speed or 85th percentile speed at a horizontal curve section,
e: superelevation rate in percent, and
f_{max}: maximum side friction factor.

Maximum superelevation rates vary from 4% to 12% in the design procedure (Stein & Neuman, 2007). According to a superelevation measurement on a two-way highway in Kansas, the lowest value of maximum superelevation was 4.4% for selected curves.

Figure 2.4 shows the maximum side friction factor for various design speeds. Values for the maximum design side friction factor “are established so that the friction required to maintain a vehicle’s path along the curved alignment will nearly always be achievable” (Donnell, Hines, Mahoney, Porter, & McGee, 2009). Therefore, the maximum design side friction factor for each design speed could be achieved in any condition, including poor tire and pavement conditions. In other words, in good or average conditions a driver can navigate the curve safely at higher speeds.

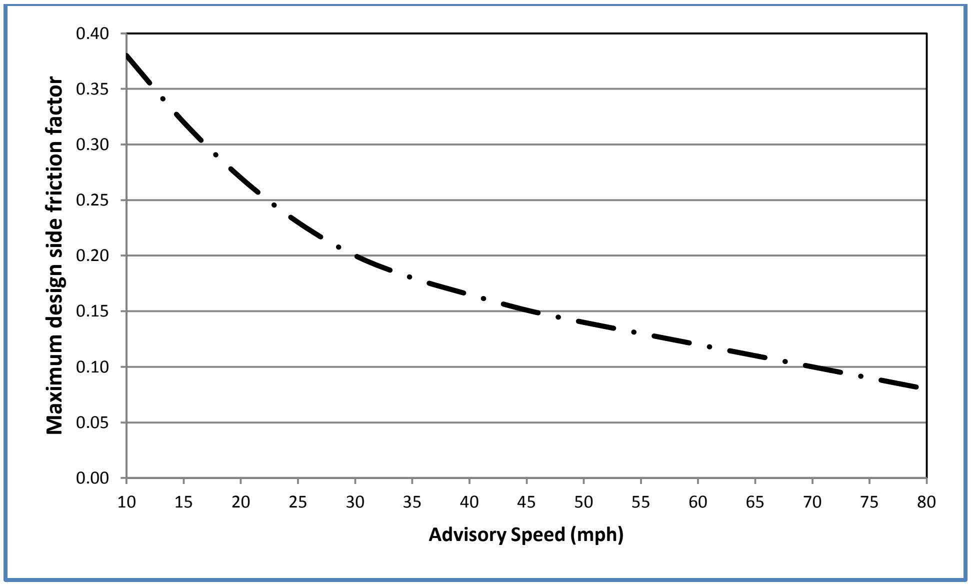


Figure 2.4: Maximum Side Friction Factor vs. Design Speed
Source: Donnell et al., 2009

Table 2.16 provides maximum radius and minimum degree of curvature for various speed limits on two-way highways. For a speed limit of 65 mph, the assumption was made that the executed maximum superelevation was 3.5%, and the rate was reduced by 0.5% for sequential lower speed limits. According to Table 2.16, chevron alignment signs are recommended for curves with degree of curvature greater than 6 degrees or curves with radii less than 950 feet.

Table 2.16: Thresholds for Chevron Alignment Signs at Horizontal Curve Sections

Posted Speed (mph)	**Advisory Speed** (mph)	**Maximum Side Friction (f_{max})**	**Maximum Superelevation (e_{max})** %	**Maximum Radius** (ft)	**Minimum Degree of Curvature**
65	50	0.14	3.5	950	6
60	45	0.15	3.0	750	7.5
55	40	0.16	2.5	575	10
50	35	0.18	2.0	410	14

2.7 Conclusion

In order to study increasingly effective countermeasures at horizontal curve sections, the most hazardous sections and implemented treatments on identified sections were examined. Due to study time and cost constraints, 43 curves in 11 counties (approximately 10% of the total number of counties in Kansas) with high numbers of crashes at horizontal sections were selected from the KDOT database. Various methods were utilized to rank crash-prone sections, including crash frequency, crash rate, and EPDO crashes. Applied methods identified the K-5 highway in Leavenworth County as being the most hazardous roadway for horizontal curve crashes because, in each method, at least two curves had the highest rank among the selected 43 curves. The project team further investigated the K-5 curves to discern reasons for the vulnerability of horizontal curve sections on this highway. In-depth analysis of this investigation is discussed in Chapter 3.

2.8 Chapter Summary

In this chapter, available information in the KDOT database and the procedure of selecting counties with high numbers of crashes at horizontal curve sections was described. Required geometric characteristics of horizontal curves and the applied method to obtain these characteristics were also discussed. Crash severity and EPDO crashes were explained and two methods for horizontal curve classification were introduced. Selected horizontal curves were ranked based on crash rates and EPDO crash rates, and countermeasures on selected horizontal curves were summarized in various tables according to the chosen horizontal curve classification method. Considering ranks of horizontal curves, K-5 highway, which displayed the highest ranked horizontal curves, was selected for more detailed investigation. Ultimately, a method was examined to use geometric characteristics of curves, such as degree of curvature or radius, instead of ball-bank reading indicator in order to determine whether or not to implement chevron alignment signs.

Chapter 3: Horizontal Curves of K-5 Highway in Leavenworth County

3.1 Introduction

Chapter 2 investigated horizontal curves with the highest number of crashes in 11 Kansas counties, crash and EPDO crash numbers, and crash rate and EPDO crash rate. Three curves on K-5 highway in Leavenworth County were among the top-ranked curves, therefore this highway was selected for additional study. First, changes of countermeasures used on horizontal curves of this roadway were investigated by studying available video-logs of three years at KDOT facilities in Topeka, Kansas. Since no significant change in countermeasures was observed, roadway and roadside geometry changes were also studied using existing video-logs. The Roadside Hazard Rating (RHR) for each direction of existing curves was determined using features shown in the video-log. Moreover, due to the speed limit change on the roadway in late June 2009, impact of the speed limit change on crash occurrence at horizontal curve sections was analyzed using a statistical t-test. Findings of this analysis did not prove any changes in the crash occurrence were due to the speed limit change.

3.2 Countermeasures on Horizontal Curves of K-5

To study countermeasures effectiveness, the installation date of the studied measures had to be known. Since the KDOT database does not contain this information, available video-logs were studied to list applied measures at each horizontal curve section. Available video-logs were from 2004, 2007, and 2010. Investigation of those logs pertaining to 25 horizontal curves on K-5 highway showed that the only alteration of applied countermeasures is the change of a “Winding Road” sign on one curve to a “Reverse Turn” sign. The first sign existed in video-logs of 2004 and 2007, while the second sign was observed in the video-log of 2010. Utilized countermeasures on the 25 studied curves consisted of centerline, edge line, horizontal alignment signs, advisory speed plaque, a one-direction large arrow sign, PMDs, chevrons, and a no-passing zone sign. During the study period, crashes occurred on 10 of the curves and the remaining 15 curves had no crashes. With the exception of centerline and edge line markings on all curves, the use of other treatments is shown in Table 3.1.

Table 3.1: Number of Curves with Specific Treatment

Treatment	Number of Curves	
	With Crash	Without Crash
Horizontal Alignment Signs	8	7
Advisory Speed Plaque	7	6
One-Direction Large Arrow Sign	2	1
PMDs	0	6
Chevrons	8	1
No-Passing Zone Sign	0	2

Approximately 80% of the curves with crashes had signs and supplemental treatments such as chevrons, while less than half of curves without crashes had identical applied countermeasures of curves with crashes.

3.3 Roadside Hazard Rating

Roadside characteristics for each curve were investigated individually from the three years of video-logs. RHR was determined for each curve using the first edition of the Highway Safety Manual (HSM) guidelines (AASHTO, 2010). According to the video-logs, few changes were evident in roadside characteristics. Table 3.2 shows RHRs for each roadside of the studied curves.

Table 3.2: RHR for Curves of K-5 Highway, Leavenworth County

Year	2004		2007		2010	
Roadside	North Bound	South Bound	North Bound	South Bound	North Bound	South Bound
Curve No.	RHR	RHR	RHR	RHR	RHR	RHR
C-160	6	6	-	-	6	6
B-160	5	5	-	-	5	5
A-160	5	4	-	-	5	4
160	5	5	5	5	5	5
160-A	4	5	4	5	4	5
160-B	4	5	4	5	4	5
160-C	4	4	4	4	3	3
160-D	5	5	5	5	4	5
160-E	6	6	6	6	6	6
160-F	4	5	4	5	4	5
160-G	5	5	5	5	5	5
160-H	4	4	4	4	4	4
160-I	5	4	5	4	5	4
161	4	4	4	4	4	4
161-A	4	4	4	4	4	4
162	5	5	5	5	5	5
162-A	4	4	4	4	4	4
163	3	5	3	5	3	5
164	5	5	5	5	5	5
164-A	5	5	5	5	5	5
165	3	5	3	5	3	5
166	4	4	4	4	4	4
167	3	4	3	4	3	4
168	5	5	5	5	5	5
169	4	4	4	4	4	3

Images for the first three curves of the list did not exist in the video-logs of 2007. Only four differences in RHRs of the three curves (160-C, 160-D, and 169) were observed among the 25 studied curves, indicating that no significant changes in roadside characteristics occurred during the study period. Similarly, no change of roadside characteristics of the curves with crashes was observed.

3.4 Superelevation of Horizontal Curves

No information from KDOT is available regarding superelevations of horizontal curve sections of the K-5 highway in Leavenworth County and other roadways. Therefore, superelevations of horizontal curves of the studied highway were measured in the field, but the measurement of all superelevations of all horizontal curves was not possible due to safety measures available to the research team, i.e., inadequate walking space along the curve sections and no equipment for traffic control. Maximum superelevations of the horizontal curve sections studied are shown in Table 3.3.

Table 3.3: Superelevations of Studied Horizontal Curves

Curve No.	Max. Super-elevation (%)	Curve No.	Max. Super-elevation (%)	Curve No.	Max. Super-elevation (%)	Curve No.	Max. Super-elevation (%)
C-160	n/a	160-D	n/a	161-A	n/a	166	6.1
B-160	n/a	160-E	n/a	162	4.7	167	4.4
A-160	n/a	160-F	n/a	162-A	n/a	168	4.9
160	4.4	160-G	n/a	163	4.7	169	5.2
160-A	n/a	160-H	n/a	164	n/a		
160-B	n/a	160-I	n/a	164-A	n/a		
160-C	n/a	161	10.5	165	n/a		

n/a: Not Available

According to design principles, the maximum amount of superelevation is required at the 1/3 past the PC and before the PT. Also, the cross slope changes from normal slope (usually 1.6%) through a superelevation runoff length. Therefore, the amount of superelevation should be smaller at the beginning of a curve compared to the center of a curve (IDOT, 2006). However, superelevations of horizontal curves on K-5 did not follow the principle pattern.

3.5 Speed Limit Reduction on K-5 Highway

According to the KDOT database, in 2009 the speed limit of K-5 highway was reduced by 5 mph, from 55 mph to 50 mph. Since the KDOT database documents crashes until the end of

2012, data for 3.5 years before and 3.5 years after the speed limit change were used. Figure 3.1 shows the segment of highway on which the speed limit change was applied. During the study period, 45 crashes occurred at these ten horizontal curves. Among those crashes, 29 occurred before the speed limit reduction and 16 occurred after the speed limit was reduced. Thirty-six PDO crashes were noted, 24 of which occurred before the speed limit reduction and 12 occurred after the speed limit reduction. Nine injury crashes occurred during the study time period: five occurred before the speed limit change and four occurred after. No fatal crashes were recorded at the horizontal curve sections during the study period.

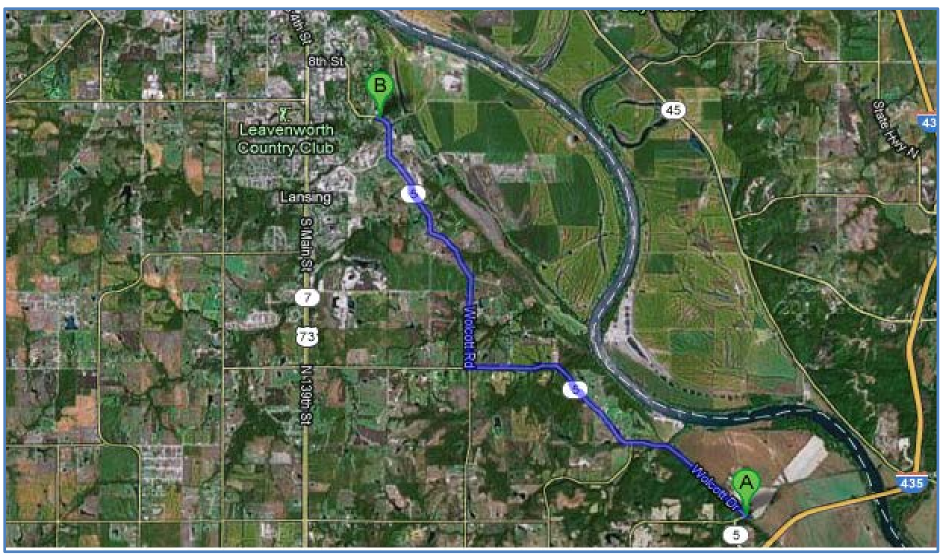


Figure 3.1: Segment of K-5 Highway with Speed Limit Change
Source: Google, n.d.

Overall, 171 EPDO crashes occurred during the study period, with 99 EPDO crashes occurring before the speed limit reduction and 72 EPDO crashes occurring after the speed limit reduction. Weather, light, and road surface conditions were considered for the EPDO crashes.

For weather conditions, two characteristics were defined: no-adverse and adverse weather conditions. For no-adverse weather conditions, 76 EPDO crashes and 69 EPDO crashes occurred before and after the speed limit reduction, respectively. For adverse weather conditions, 26 EPDO crashes occurred: 23 before the speed limit change occurred and only three after the speed limit change.

Light condition was divided into two groups: day-light condition and dark-time condition. For day-light condition, 44 and 53 EPDO crashes occurred before and after the speed limit reduction, respectively. For dark-time condition, 55 and 19 EPDO crashes occurred before and after the speed limit change, respectively.

Two primary groups were defined for road surface condition: dry and wet conditions. For dry road surface condition, 59 and 53 EPDO crashes occurred before and after the speed limit change, respectively. For wet road surface condition, the dispersion before and after speed limit change was wider, with 40 and 19 EPDO crashes occurring before and after the speed limit reduction, respectively. The numbers of crashes for each group and for each time period are summarized in Table 3.4.

According to traffic count maps for the study period, 2006 to 2012, and considering before and after the speed limit change, AADTs were 1,636 and 2,088 vpd before and after the speed limit change, respectively, indicating a 27% increase in AADT for the studied sections. KDOT video-logs did not show specific geometric change on the studied sections.

Table 3.4: Number of Crashes for Each Crash Group Before and After Speed Limit Reduction

Crash group	Number of crashes		Percent Difference (%)
	Before speed limit change	After speed limit change	
Overall crashes	29	16	-44.83
PDO crashes	24	12	-50.00
Injury crashes	5	4	-20.00
EPDO crashes	99	72	-27.27
EPDO crashes- no-adverse weather condition	76	69	-9.21
EPDO crashes- adverse weather condition	23	3	-86.96
EPDO crashes- day light condition	44	53	20.45
EPDO crashes- dark time condition	55	19	-65.45
EPDO crashes- dry on road surface condition	59	53	-10.17
EPDO crashes- wet on road surface condition	40	19	-52.50

Figure 3.2(a) through Figure 3.2(f) graph of the total number of crashes, PDO and injury crashes, EPDO crashes, EPDO crashes for weather conditions, EPDO crashes for light conditions, and EPDO crashes for road surface conditions before and after the speed limit change.

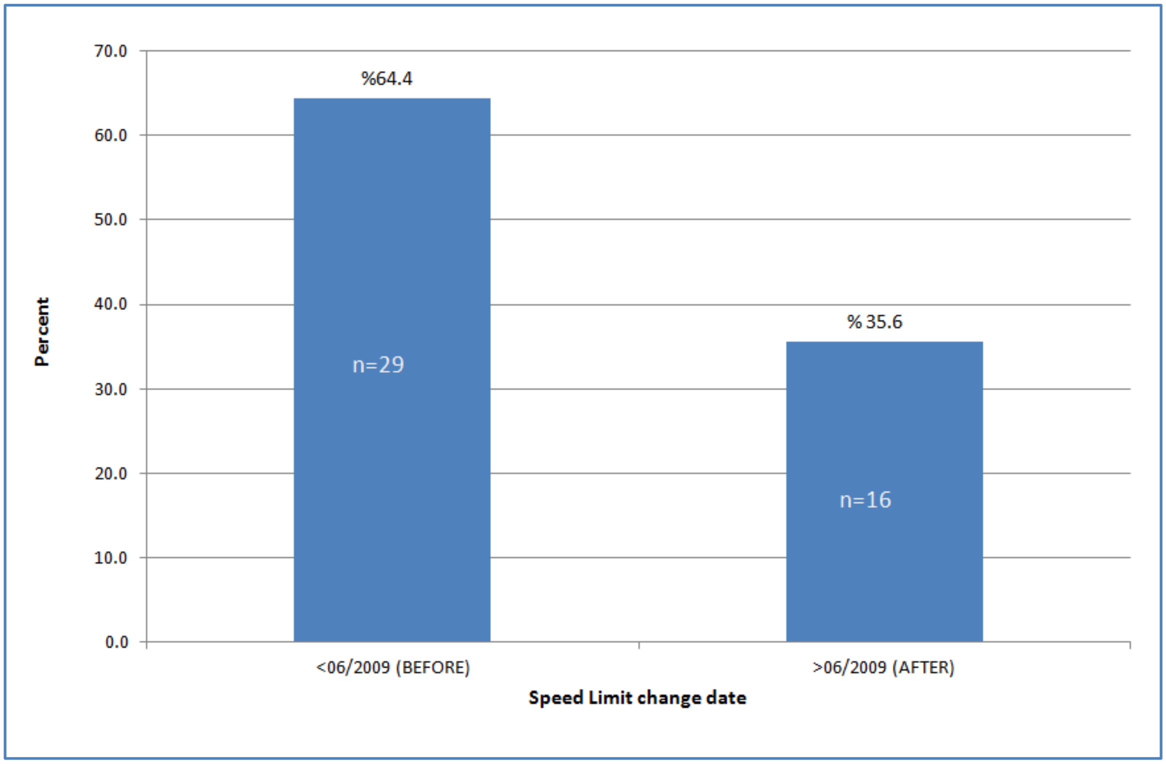


Figure 3.2 (a)

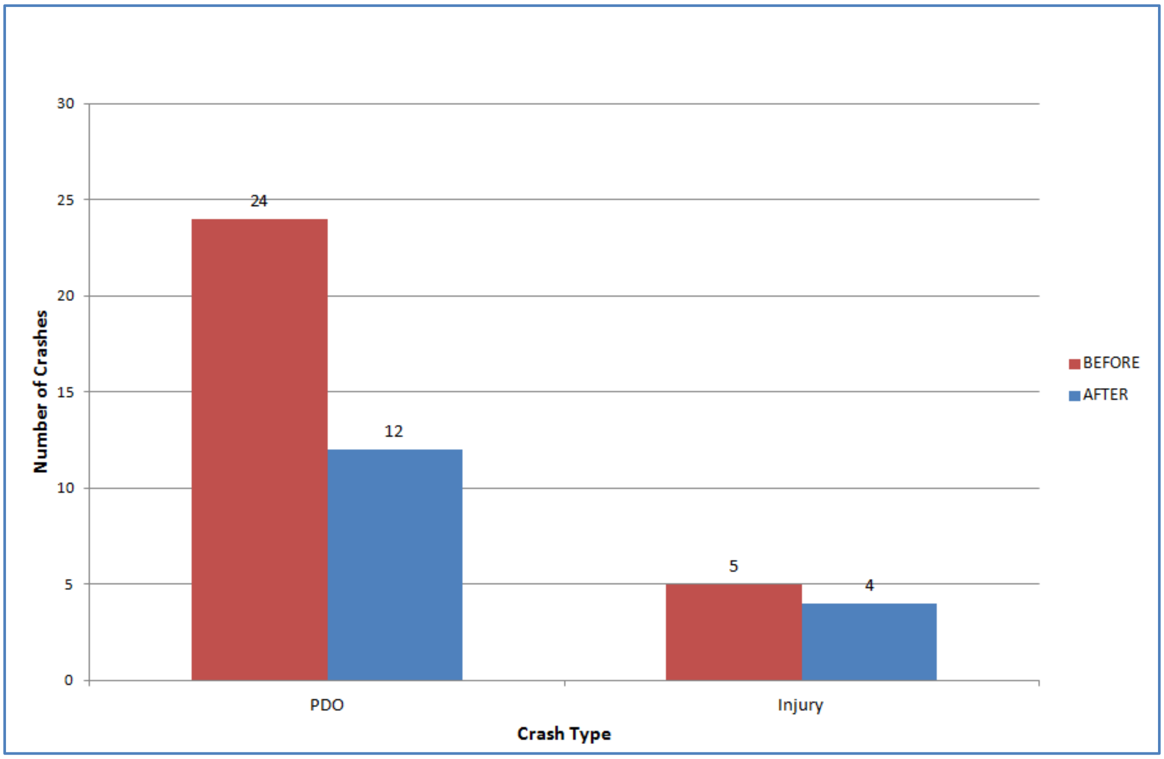


Figure 3.2 (b)

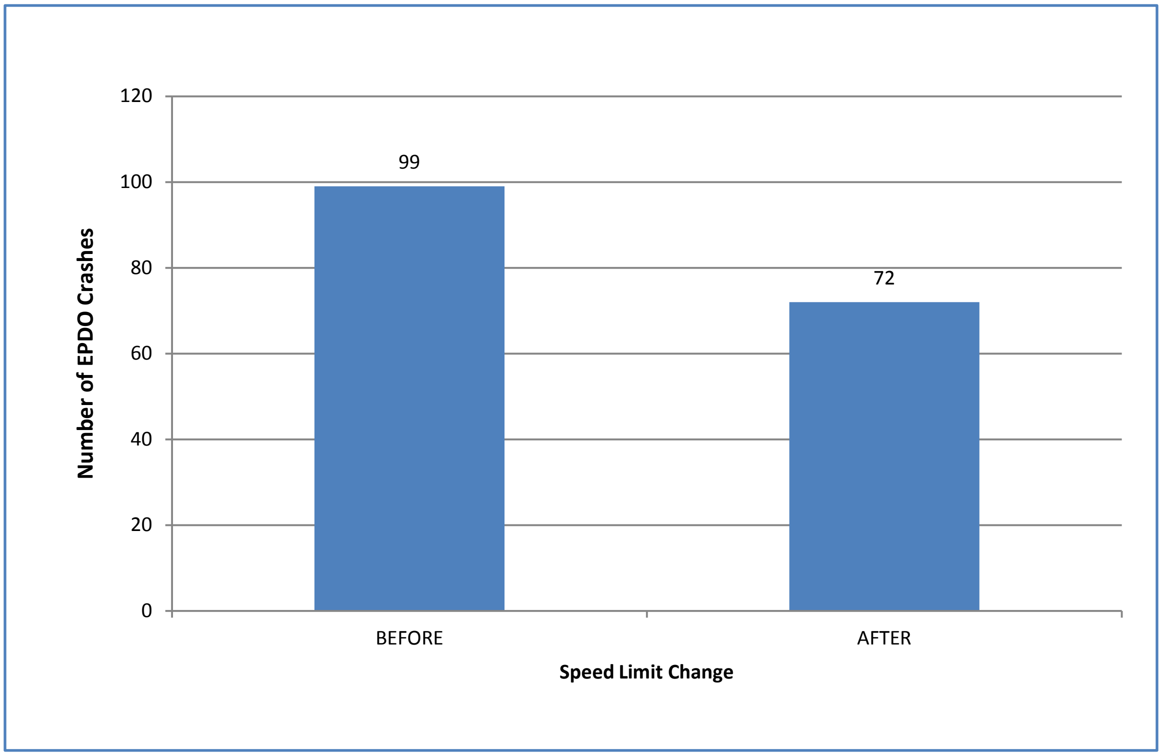


Figure 3.2 (c)

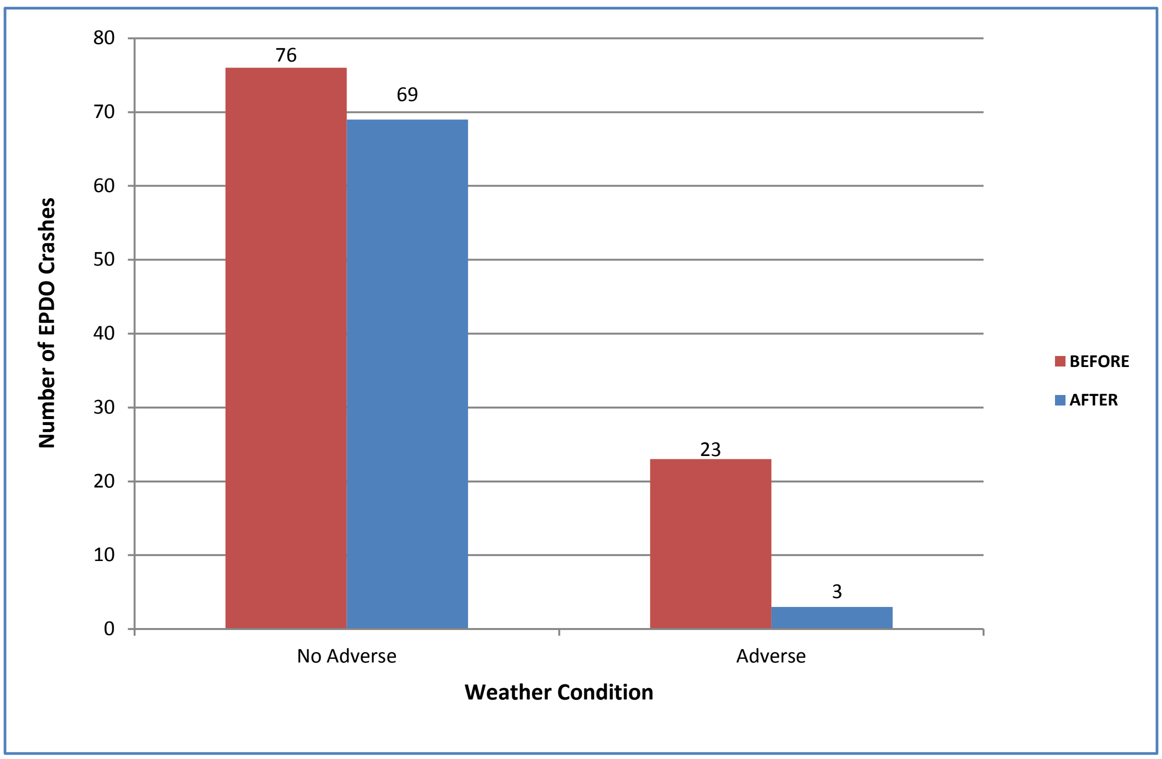


Figure 3.2 (d)

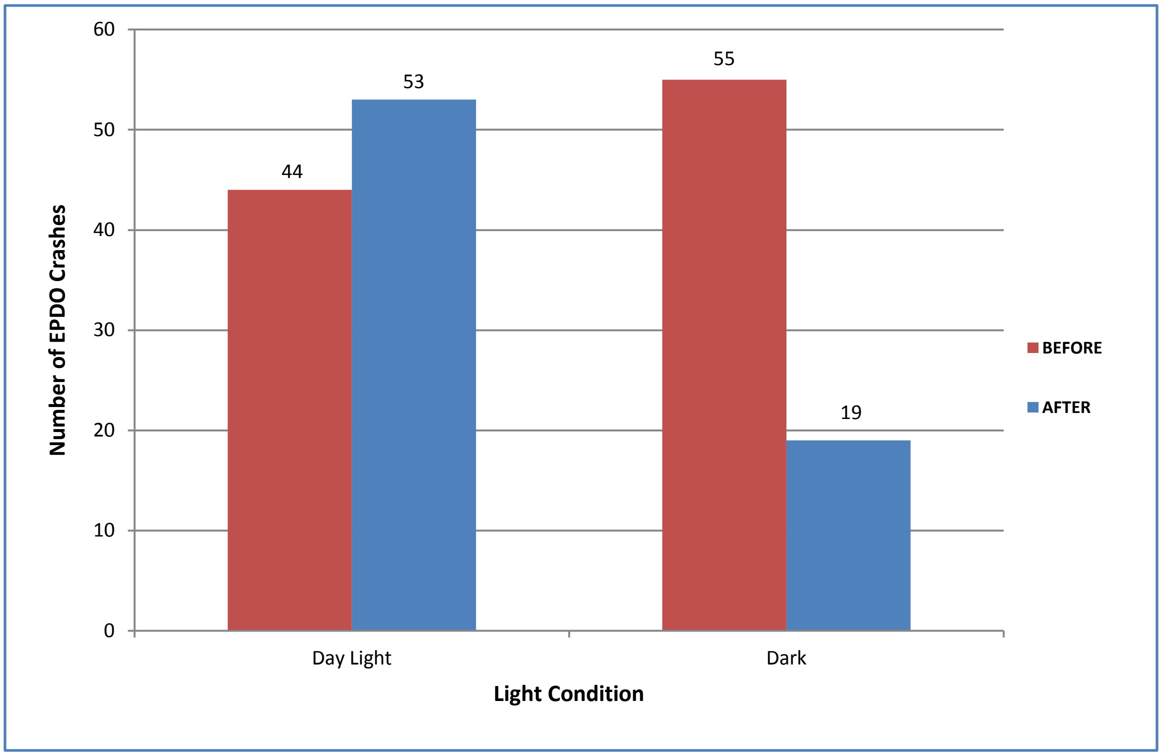


Figure 3.2 (e)

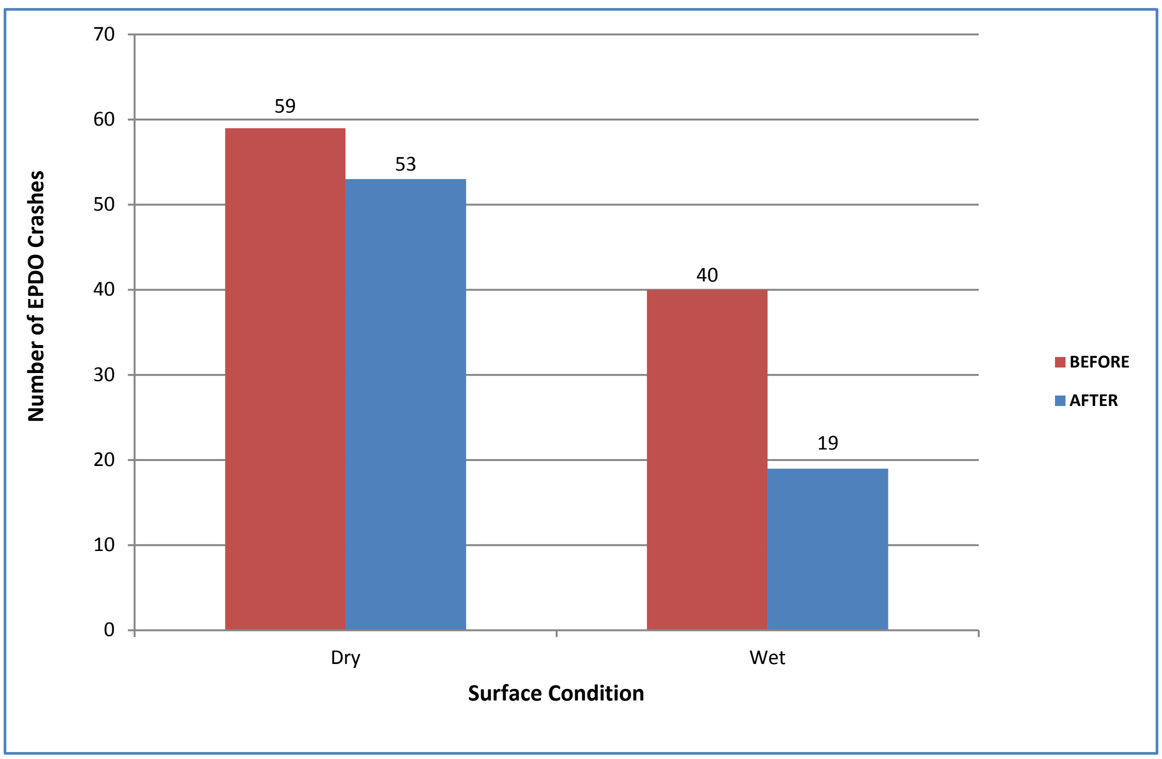


Figure 3.2 (f)

Figure 3.2: Graphs for Different Crashes Groups and Various Conditions

3.6 Data Analysis

To study the effectiveness of an applied policy countermeasure, a statistical t-test approach was used for crash frequencies and crash rates. In order to analyze small sample sizes, this statistical method is recommended. For this study, a paired t-test was applied using a SAS software package. Crash frequencies and crash rates before and after the speed limit change for the ten curves were used for each group of crashes.

SAS calculates the t-value and p-value for each group of crashes and condition and provides values in its output. A comparison of p-values to the significance level of 5% indicates whether or not the speed limit reduction significantly influenced the particular crash group. Results of the applied method for crash frequency and crash rate are shown in Table 3.5.

Table 3.5: Results for t-test

No	Crash group	Crash Frequency		Crash Rate	
		t-value	p-value	t-value	p-value
1	Overall crashes	1.74	0.115	1.84	0.099
2	PDO crashes	1.96	0.081	2.04	0.072
3	Injury crashes	0.43	0.678	0.71	0.497
	EPDO crashes	0.71	0.497	0.995	0.346
4	EPDO crashes no-adverse weather condition	0.21	0.831	1.02	0.3329
5	EPDO crashes- adverse weather condition	1.36	0.206	2.33	0.045
6	EPDO crashes- day light condition	-0.21	0.838	-0.15	0.887
7	EPDO crashes- dark time condition	1.54	0.157	1.75	0.114
8	EPDO crashes- dry road surface condition	0.23	0.820	0.73	0.426
9	EPDO crashes not dry road surface condition	0.77	0.463	0.75	0.474

Results of the t-test for crash frequencies, assuming a 5% significance level (equal to 95% confidence level), indicated that none of the crash group changes were statistically significant due to the speed limit reduction. EPDO crash rate at adverse weather condition was statistically significant after the speed limit change at the 95% confidence level. At the 10% significance level, the only change found statistically significant were PDO crashes for crash frequency. For crash rates, since p-values of overall crash rate, PDO crash rate, and EPDO crash rate for adverse weather condition were less than 0.10, crash rates were significantly reduced at the 90% confidence level for PDO and EPDO.

3.7 Conclusions

Data from 11 counties in Kansas indicated that highway K-5 is a roadway with the highest numbers of crashes on horizontal curves. Therefore, additional investigations were conducted on horizontal curve sections of this roadway. Video-logs from three years, 2004, 2007, and 2010, did not show any changes in applied countermeasures at horizontal curve sections or significant changes in roadside characteristics of the studied curves. The measured superelevation of some curves with crashes showed these sections meet the minimum requirement of superelevations; however, changes in superelevations along the curve sections are not constant and do not meet current design guidance/criteria.

Existing data revealed that the speed limit of a segment of the roadway, including approximately 25 horizontal curves, was reduced in June 2009. Therefore, impact of the speed limit change on crash reduction at horizontal curve sections was studied. For data analysis, a time period from 2006 to 2012, including 3.5 years for each before and after the speed limit change, was selected. Although initial data showed a reduction in crash frequencies for crashes and EPDO crashes in various light, weather, and road surface conditions, a statistical t-test did not indicate numbers high enough to state that crash frequencies and crash rates show statistically significant reduction due to speed limit change at the 95% confidence level (5% significance level). However, EPDO crash rates for adverse weather condition were statistically significant at the 5% significance level. Therefore, crash occurrences at horizontal curve sections of this highway require additional scrutiny over a longer period.

3.7.1 Recommended Countermeasures

Since the combination of conventional implemented countermeasures with speed limit reduction, as a policy countermeasure, did not significantly reduce crash occurrence, use of other intermediate- or high-cost countermeasures is recommended. Due to narrow shoulders of the roadway, shoulder widening, particularly on problematic curves, could provide additional space in order for drivers to prevent head-on crashes and edge line encroachments. However, the presence of trees close to the roadway imposes serious limitation to this treatment due to right-of-way issues and cost barriers. Thus, tree removal to right-of-way line on horizontal curves, particularly those curves which have sight distance problem due to presence of trees, is recommended as an appropriate alternative countermeasure. Implementing centerline rumble strips and edge line rumble stripes at horizontal curve sections with high number of crashes would be another recommended countermeasure. In addition to their cost, the vicinity of residential areas requires the consideration of noise generated by rumble strips/stripes and probable complaints by nearby residents. Snow-plowable RRMs markers have similar effects of rumble strips/stripes and can be considered an alternative treatment.

Recently, chevrons enhanced with LEDs have been implemented as a speed management approach to reduce vehicles speed at horizontal curve sections by TAPCO in five states, Colorado, Iowa, Missouri, Texas, and Washington, but results have not yet been published. A majority of horizontal curve crashes are ROR crashes caused by exceeding the advisory or safe speed. Due to limitations of other recommended countermeasures, available chevron alignment signs of problematic curves should be enhanced with LEDs and a vehicle detecting system in order to reduce vehicle speeds negotiating curves. Table 3.6 summarizes recommended countermeasures for horizontal curves with high number of crashes on K-5 highway in Leavenworth County. These countermeasures are ranked based on their effectiveness from Table 1.6 and Table 1.7.

Table 3.6: Recommended Countermeasures for Curves of K-5 Highway in Leavenworth County

Countermeasure	Effects	Limits and Considerations	More Details in Chapter 1	Rank
Rumble strips/stripes	- Cause vibration and noise to warn drivers about their lateral position at horizontal curve sections. - Edge line rumble stripes increase visibility at dark time and adverse weather conditions.	- Cost - Generated noise and resident complaints	Centerline Rumble Strips, Section 1.3.11. Edge Line Rumble Strips/Stripes, Section 1.3.12.	1
Tree removal	- Increases the sight distance at horizontal curve sections - Provides space for widening shoulder	- Cost - Right of way - Environmental issues	-	2
Chevrons enhanced with LEDs	- Are designed for speed management. - Can be activated when a vehicle exceeds a preset safe or advisory speed.	- Cost - Maintenance	Dynamic Curve Warning System (DCWS), Section 1.4.2.	3
Widening shoulder	- Provides more spaces to avoid head-on and run-off road crashes. - Provides a safe space to pull over vehicles.	- Cost - Right of way - Trees close to the roadway	Paved Shoulder and Widening Shoulder, Section 1.4.3.	4
Snow-plowable reflective raised markers	- Have vibration and auditory effects similar to rumble strips/stripes. - Are beneficial for low visibility conditions, like rain or darkness.	- Cost - Maintenance	Profile Thermoplastic Markings and Raised Pavement Markings (RPMs), Section 1.3.6.	5

3.8 Chapter Summary

This chapter studied horizontal curves of K-5 highway in Leavenworth County which contain several curves with the highest numbers of crashes within the 11-county study area and time period. The applied treatments and roadside characteristics of the horizontal curves were investigated through KDOT video-logs from three years. Measurement of superelevations of the horizontal curve sections were also discussed in this chapter. Effectiveness of the application of a policy countermeasure, such as speed limit reduction, was investigated utilizing a statistical t-test. Results of the t-test did not show a significant change in crash groups for crash frequencies and crash rates including EPDO crashes. Finally, using the 5% significance level, results of a statistical t-test showed that sufficient evidence was lacking to conclude that the speed limit change in 2009 reduced crash occurrences at horizontal curve sections enough to prove that the results were statistically significant at the (generally accepted) 95% significance level. Countermeasures were recommended for curves with high number of crashes on K-5 highway in Leavenworth County.

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