EFFECTS OF CENTERLINE RUMBLE STRIPS ON SAFETY, EXTERIOR NOISE, AND OPERATIONAL USE OF THE TRAVEL LANE

by

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B.Sc., Federal Technological University of Parana – Brazil, 2005

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Industrial and Manufacturing Systems Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2011

Abstract

Centerline rumble strips (CLRS) are effective in preventing cross-over crashes and are promoted in the United States (U.S.) as a low-cost safety measure. However, there may be negative issues and/or concerns that question their use under certain road conditions. This dissertation is the result of studying these issues and concerns to provide guidance to policy makers on future installations of CLRS, based on current good practices and on the results of specific investigations of exterior noise, safety effectiveness, economics, and drivers' behavior, including their interaction with shoulders and shoulder rumble strips (SRS).

From a survey conducted, good practices in the U.S. were summarized. From a before-and-after study of CLRS safety effectiveness, results showed that total correctable crashes were reduced by 29.21%. Crashes involving fatalities and injuries were reduced by 34.05%. Cross-over crashes were reduced by 67.19%, and run-off-the-road crashes were reduced by 19.19%. Both Naïve and Empirical Bayes methods were applied and showed statistically similar results. There was no statistical difference between football shaped and rectangular shaped CLRS. From the external noise study performed, it was found that external noise depends on vehicle speed, type of vehicle, and distance. Both football and rectangular CLRS substantially increased the levels of external noise at distances up to 45 m (150 ft). Therefore, before installing CLRS, the distance from houses or businesses should be considered. A distance of 60 m (200 ft) was recommended as the limit of the potential exterior noise problem area. From a study of drivers' behavior, the analyzed configurations of rumble strips and shoulder width levels affected vehicular lateral position and speed levels, although speed deviations were not practically significant. The study of safety performance function models provided technical and economical recommendations for installation of CLRS.

Overall, this study recommends the installation of CLRS on rural, two-lane, undivided rural roads in Kansas. Both patterns, rectangular and football, currently installed in Kansas have provided crash reductions, which have been reflected in economic benefits for society. Shoulder width and traffic volume should be considered as crash predictors for enhancement of the benefits. Guidelines were recommended for future better applications of CLRS.

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Acknowledgements

Initially, I would like to thank God, the author of life, who should receive all the glory.

I thank my major advisor, Dr. Margaret Rys, and my co-advisor, Dr. Eugene Russell, for their mentoring, instruction and corrections. I would also like to express my gratitude to KDOT for funding this research project and to my committee members, Dr. Leigh Murray, Dr. Zhijian Pei, and Dr. Patrick Knight for their active participation and advice during the conduction of this project.

I thank my dear wife Elisa, for all her love, patience and support. In addition, I would like to thank my family members that even at a distance helped me with their prayers, and my friends in Manhattan Kansas that made me feel at home.

Preface

Centerline rumble strips (CLRS) are effective in preventing cross-over crashes and are promoted in the United States (U.S.) as an effective, low-cost safety measure. However, there may be negative issues and/or concerns that question their use on some roads or under certain road conditions. Several Departments of Transportation (DOTs) reported concerns from the public about CLRS that generally included the levels of exterior noise created by the patterns, the decrease in visibility of the pavement markings installed over CLRS and their influence on operational use of the travel lane. This dissertation is the result of studying these issues and concerns to determine under what circumstances they could reduce the applicability of CLRS to a limited number of highways in the US and thus, decrease their major advantage of reducing roadway departure, cross-over crashes.

Roadway departure crashes correspond to approximately 40% of all traffic crashes. According to the most recent crash statistics, in 2009 there were 11,185 fatal roadway departure crashes on rural highways, resulting in 23,169 fatalities. Thus, roadway departure crashes are a significant problem in the United States. Centerline rumble strips are raised or indented patterns installed mainly on two-lane undivided highways, utilized to alert drivers that they are crossing the center of the travel lane, by producing noise and vibration when crossed by vehicles' tires. CLRS primarily address the problem of drowsy or inattentive drivers on two-lane, two-way highways drifting left out of their lane and striking an oncoming vehicle. It is estimated that 50 – 70 million adults in the United States have chronic sleep and wakefulness disorders. Understanding the disadvantages associated with the use of CLRS may result in reliable guidelines, which can widespread the use of CLRS, contributing to saving lives.

Thus, the primary goal of this research was to provide guidance to policy makers on future installations of CLRS, based on current good practices and on the results of specific investigations of exterior noise, safety effectiveness, economics and operational use of the travel lane, including their interaction with shoulders and shoulder rumble strips (SRS).

Therefore, the objectives of this research were: a) to obtain updated information on DOTs' policies and guidelines for installation of CLRS in the United States in order to identify current good practices; b) to verify the before-and-after safety effectiveness of CLRS currently installed in Kansas; c) to determine if CLRS cause levels of exterior noise that can disturb nearby residents and propose a minimum distance from houses for installation of CLRS in Kansas; d) to estimate the effects of CLRS on vehicles' operational speed and lateral position and to verify if it is safe to install CLRS on sections of highways with narrow shoulders; and e) provide recommendations of when it is beneficial to install rumble strips, given known values of traffic volume, shoulder width, and the presence of other types of rumble strips.

The methodologies that were applied in this research include: a) an email survey that was sent to all state DOTs to verify their current guidelines for installation of CLRS; b) application of Bayesian before-and-after methods to investigate the safety effectiveness of CLRS in Kansas; c) field data collection according to standard procedures to verify if CLRS produce exterior noise levels that can disturb residents that live nearby to treated highways, d) standard field data collection methods to investigate how CLRS impact vehicular lateral position and operational speed; and e) modeling and interpretation of regression equations to predict number of crashes.

From the survey conducted, results indicated that the use of CLRS has grown over the years increasing of about 372% over five years (from 2005 to 2010). Currently there are 36 states using CLRS and 17 states have written policies or guidelines for installation of CLRS.

Guidelines for installation of CLRS usually include crash history, annual average daily traffic (AADT) levels, pavement structural condition, lane and shoulder widths, and posted speed limit. The combination of CLRS and shoulder rumble strips (or rumble stripes) is rarely used on sections of highways with narrow or no shoulder.

From the study of the before-and-after safety effectiveness of CLRS in Kansas, the results showed that following the installation of CLRS in several roads, total correctable crashes were reduced by 29.21%, with 95% CI of (-10.00%, -48.42%). Correctable crashes involving fatalities and injuries were reduced by 34.05%, with 95% CI of (-6.34%, -61.76). Cross-over crashes were reduced by 67.19%, with 95% CI of (-37.56%, -96.82%) and run-off-the-road crashes showed a not statistically significance reduction of 19.19%, with 95% CI of (-46.91%, +8.52%). The two methods applied (Naïve and Empirical Bayes - EB) presented statistically similar results and there was no statistical difference between football shaped and rectangular shaped CLRS, based on EB crash reductions.

From the external noise study performed, it was found that external noise depends on vehicle speed, type of vehicle, and distance. Both football and rectangular CLRS substantially increased the levels of external noise at distances up to 45 m (150 ft). Therefore, before installing CLRS, the distance from houses or businesses should be considered. A distance of 60 m (200 ft) was recommended as the limit of the potential exterior noise problem area.

From the study of drivers' behavior, the analyzed configurations of rumble strips and shoulder width levels affected vehicular lateral position and speed levels, although speed deviations were not practically significant. On roadways with narrow shoulders, for both CLRS only and neither rumble strip conditions, drivers operated closer to the centerline, perhaps to avoid the risk of running-off-the-road in these conditions. On roadways with medium shoulder widths, drivers tended to drive closer to the centerline if SRS were not present and closer to the edgeline if SRS were present. On roadways with wide shoulders, drivers tended to travel closer to the centerline if CLRS were present and closer to the edgeline otherwise.

The study of safety performance function models developed with data from 29 Kansas highway sections that received installation of CLRS provided technical and economical recommendations for installation of CLRS.

Overall, this study recommends the installation of CLRS on rural, two-lane, undivided rural roads in Kansas. Both patterns, rectangular and football, currently installed in Kansas have provided crash reductions, which have been reflected in economic benefits for society. Shoulder width and traffic volume should be considered as crash predictors for enhancement of the benefits. Guidelines were recommended for future better applications of CLRS.

Chapter 1 - Project Description

This section gives the description and justification for this research project.

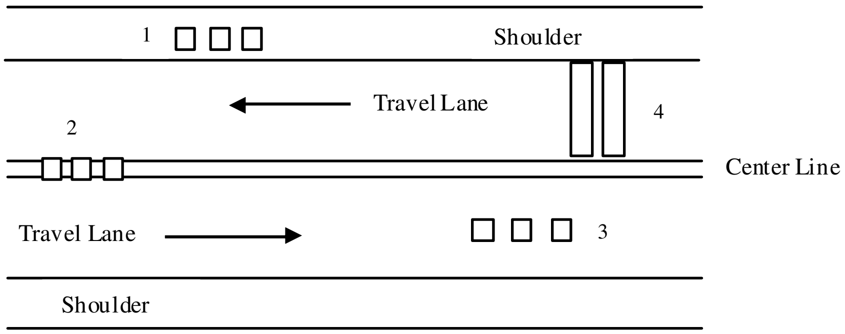
Introduction / Background

Worldwide, it is estimated that more than 500,000 people are killed (corresponding to one life per minute) and over 15 million people are injured in road crashes annually. Moreover, about 60% of these crashes occur on two-lane rural roads (Lamm et al. 2007). In the United States, roadway departure crashes correspond to approximately 40% of all traffic crashes, and their associated estimated annual cost is $100 billion (FWHA 2003). According to the most recent crash statistics, in 2009 in the United States (U.S.) there were 11,185 fatal roadway departure crashes on rural highways, resulting in 23,169 fatalities (NHTSA 2009). Thus, roadway departure crashes are a significant problem in the U.S.

A roadway departure crash is defined as a non-intersection crash which occurs after a vehicle leaves the intended traveled way, crossing the center line of undivided highways, or crossing an edge line (longitudinal pavement marking located at the edge of the traveled lane and the shoulder) of the roadway. Roadway departures are usually severe and involve run-off-the-road (ROR) i.e. departure to the right, sideswipes, and head-on crashes. There are many contributing factors for the occurrence of roadway departures, and the principal of these are related to drivers (drowsiness, fatigue, speeding, alcohol/drug impairment, and inattention), to the environment (poor visibility caused by inclement weather and animal crossings) and to roadway design and maintenance conditions (alignment inconsistencies, presence of narrow lanes, lack of proper shoulder width, and poor condition of travel lanes and pavement markings). According to Persaud et al. (2003), engineering improvements such as roadway widening, and median barrier installation may reduce the risk of roadway departures. However, such measures can be costly and may treat only specific spots, so the benefits of such improvements may be limited. More widely applied measures are necessary. A relatively cheap and efficient countermeasure for this problem is the installation of rumble strips, which have been used by several State Departments of Transportation (DOTs) since 1955.

Rumble strips are raised or indented patterns utilized to alert drivers that they are moving out of the travel lane. When the vehicles' tires pass over the rumble strips, noise and vibration are produced by this contact, which provides motorists with a warning that they are leaving the travel lane. Rumble strips are designed to alert drowsy and inattentive motorists and these roadway treatments can generally be classified by their position in relation to the travel lane as: a) shoulder rumble strips (including edgeline rumble strips), b) centerline rumble strips, c) midlane rumble strips, and d) transverse rumble strips. Figures 1.1 – 1.5 illustrate the position of each type of rumble strip in relation to the travel lane.

Figure 1.1 Placement of Rumble Strips in a Roadway



Note: [1]Shoulder Rumble Strips, [2]Centerline Rumble Strips, [3]Midlane Rumble Strips, and [4]Transverse Rumble Strips

Figure 1.2 Typical Placement of Shoulder Rumble Strips. Source: Torbic et al., 2009

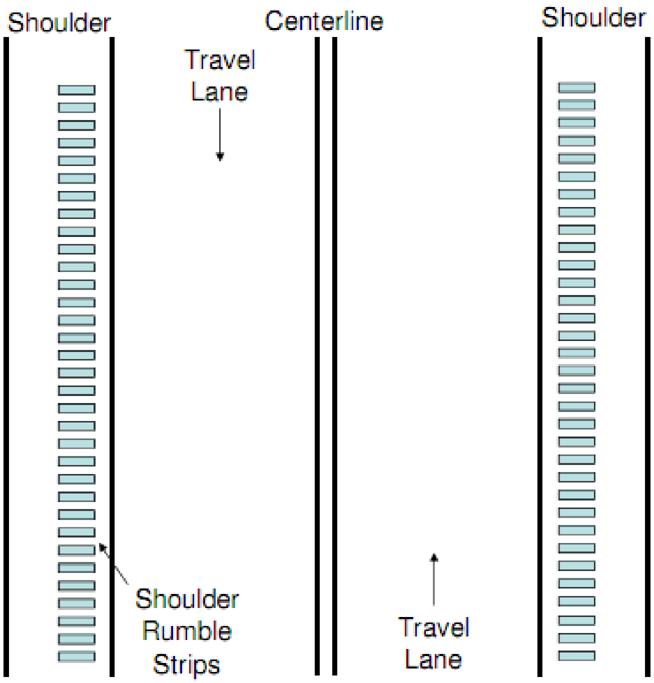


Figure 1.3 Typical Placement of Centerline Rumble Strips. Source: Torbic et al., 2009

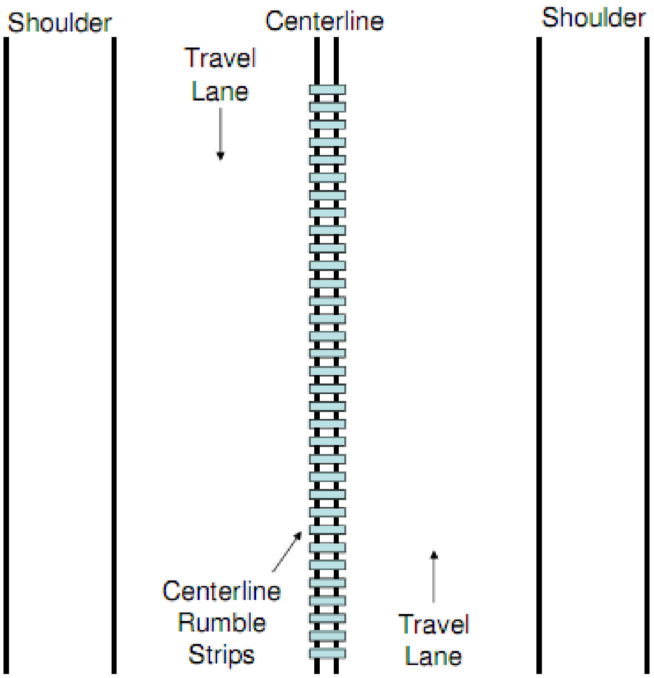


Figure 1.4 Concept of Midlane Rumble Strips. Source: Torbic et al., 2009

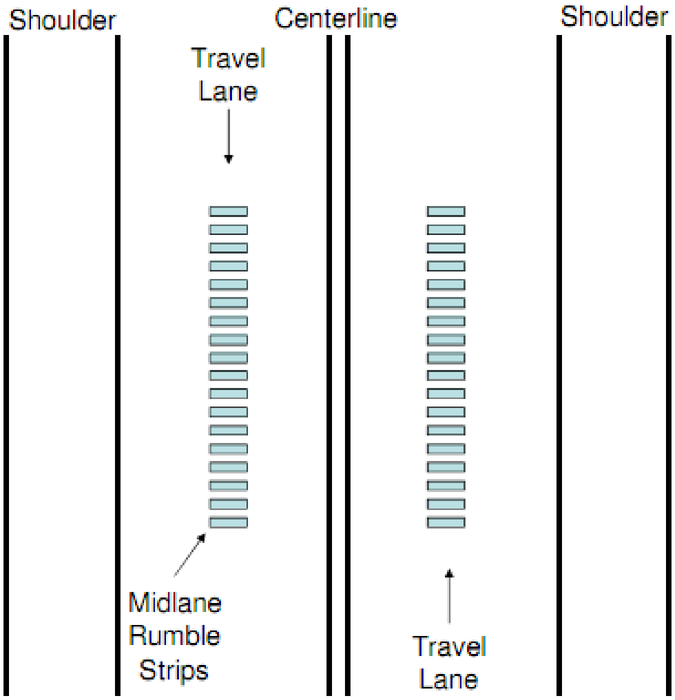
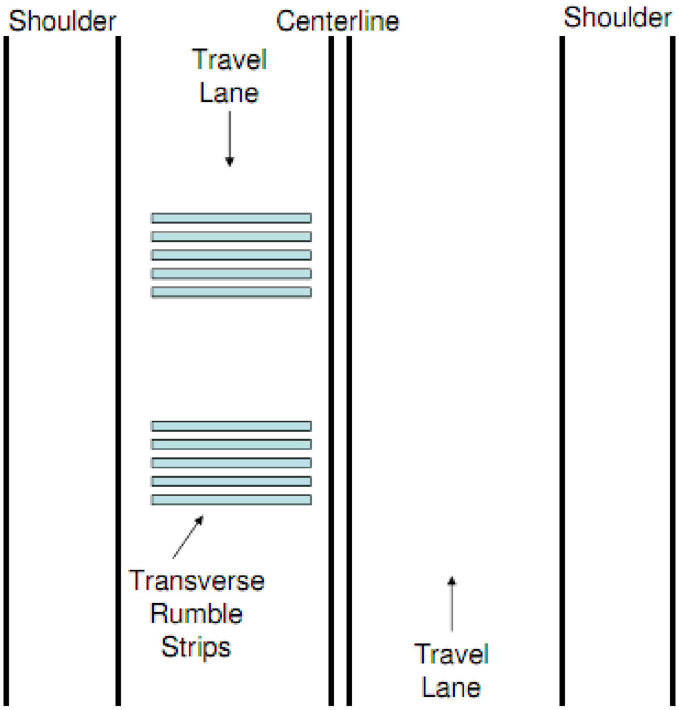
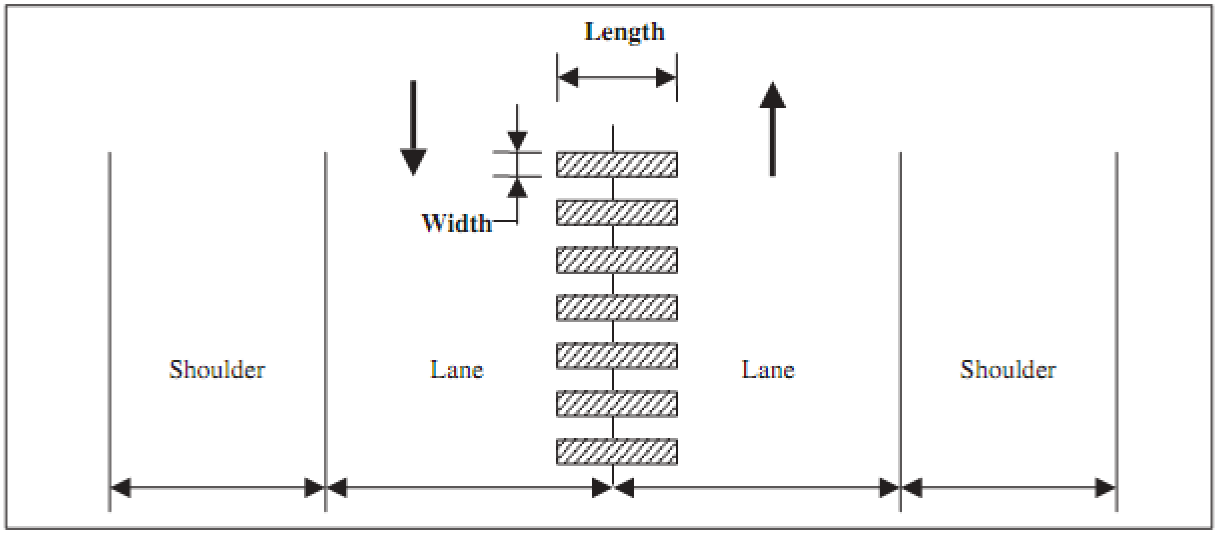


Figure 1.5 Typical Placement of Transverse Rumble Strips. Source: Torbic et al., 2009



The commonly referred dimensions of rumble strips are: length, normally defined as the dimension perpendicular to the traffic direction; width, usually defined as the dimension parallel to the traffic direction; depth of height; and spacing, usually measured from center to center of rumble strip patterns. The spacing can be continuous, if the rumble strips are placed with constant spacing along the roadway, or alternatively, if the spacing changes along the roadway (for example: 30.5 cm or 12 in., followed by 61 cm or 24 in. spacing). The commonly defined length and width of centerline rumble strips (CLRS) are shown in Figure 1.6.

Figure 1.6 Commonly defined length and width of CLRS. Source: Russell and Rys, 2005



Shoulder rumble strips (SRS) are placed on the shoulders or on the edge line of the roadway and are a countermeasure for run-off-the-road (ROR) type crashes. On divided highways, SRS may be installed on both the outside and median shoulders. When installed along the edge lines, they are commonly referred to as “rumble stripes” or edgeline rumble strips (ELRS). Midlane rumble strips is a concept with no actual installations known in the U.S. There is a known installation of midlane rumble strips in Sweden (Anund et al. 2010). Their placement is in the center of the travel lane, serving to potentially prevent both cross-over and run-off-the-road crashes. Transverse rumble strips (TRS) are usually placed across the full width of the travel lanes. They are designed to alert motorists of approaching roundabouts, intersections, and toll plazas. Centerline rumble strips (CLRS), presented in Figure 1.7, are primarily installed on the centerline of undivided, rural, two-lane highways. These types of roads do not present physical barriers to separate opposing traffic. As a result, a major problem on these roads involves vehicles crossing the centerline and either sideswiping or hitting the front ends of opposing vehicles. The main purpose of CLRS is reduction of these specific crashes, referred herein as “cross-over crashes”. In 2009 there were 2,579 fatal cross-over crashes in rural, two-lane roads in the U.S. (NHTSA 2009).

Figure 1.7 Centerline Rumble Strips. Source: http://safety.transportation.org

According to Elefteriaou et al. (2000), there are four types of rumble strips classified by their installation process: a) raised, b) milled, c) rolled and d) formed, as presented in Figure 1.8. The milled type is the most common rumble strip in the United States. They can be installed on new or existing asphalt and Portland cement concrete (PCC) pavements. This type of rumble strip is produced by a machine, which cuts a groove in the pavement. Raised rumble strips are made by adherence of proper material to new or existing pavement surfaces. Formed rumble strips are installed on PCC surfaces, by forming grooves or indentations into the concrete during its finishing process. Rolled rumble strips are installed only on asphalt surfaces, by a roller that presses grooves into the hot surfaces when the asphalt is being compacted. This study focuses on the applications of milled CLRS.

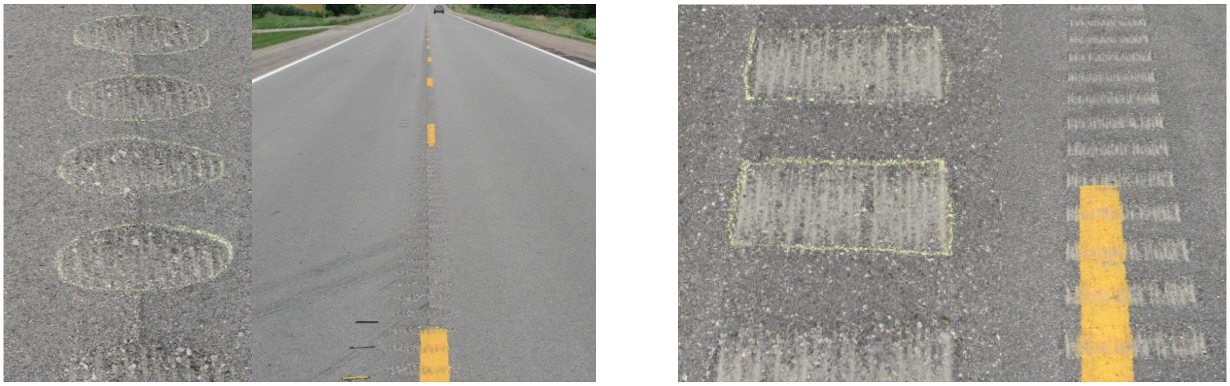
Figure 1.8 Types of Rumble Strips. Source: Richards and Saito (2005)

a)

Raised b) Milled c) Rolled d) Formed

CLRS are accepted as a low-cost countermeasure, effective to prevent cross-over crashes, making two-lane rural roads safer. Therefore, their use in the United States has increased over the years. In Kansas there are more than 400 miles of CLRS installed and two different shape patterns of milled-in CLRS are used: rectangular and football shaped, as shown in Figure 1.9.

Figure 1.9 Patterns of Milled-in CLRS installed in Kansas



a) Football Shaped

b) Rectangular

Problem Statement

CLRS primarily address the problem of drowsy or inattentive drivers on two-lane, two-way highways drifting left out of their lane and striking an oncoming vehicle. Falling asleep at the wheel is a serious problem in the U.S. According to the Institute of Medicine, an estimated 50 – 70 million adults in the United States have chronic sleep and wakefulness disorders (Institute of Medicine 2006). The Centers for Disease Control and Prevention (CDC) analyzed data from a new sleep module added to the Behavioral Risk Factor Surveillance System (BRFSS) in 2009. Results indicated that among 74,571 adult respondents in 12 states, about 38% reported unintentionally falling asleep during the day at least one day in the preceding 30 days, and about 5% reported nodding off or falling asleep while driving in the preceding 30 days (CDC 2011). Thus, the presence of a countermeasure to cross-over crashes (which are usually caused by drivers' drowsiness and inattention) on rural, two-lane, undivided highways is very important.

Safety Effectiveness of CLRS and Benefit/Cost Ratio

The Federal Highway Administration (FHWA) website states "A crash reduction factor (CRF) is the percentage crash reduction that might be expected after implementing a given countermeasure at a specific site. For example, the installation of centerline rumble strips on a two-lane roadway can expect a 14% reduction in all crashes and a 55% percent reduction in head-on crashes." (FHWA 2011A).

The most reliable evidence of the value of CLRS in reducing crashes is a study conducted by the Insurance Institute of Highway Safety (IIHS). Persaud et al. (2004) used data from seven states and found an estimated reduction of approximately 21% (95% CI = 5-37%) in frontal and sideswipe opposing-direction types of accidents in treated sections on undivided, two-lane rural highways after the installation of CLRS. All types of accidents were reduced by an estimated 15% (95% CI=15-25%). The total length of treated sections was 338 km (210 miles) at 98 sites.

Several authors have reported advantages other than crash reduction in installing CLRS, such as low interference in passing maneuvers, versatile installation conditions, and public approval (Miles et al. 2005; Richards and Saito 2007). Due to their associated low costs of installation and maintenance, CLRS provide high benefit-cost ratios. For instance, Carlson and Miles (2003) reported estimated benefit-cost ratio associated with CLRS in the range of 0.17 to 39.16 (the higher the roadway traffic volume, the greater the benefit), considering five states and assuming cross-over crash reduction of 20%. However, some concerns or potential disadvantages involving CLRS such as the levels of exterior noise, potential decreased visibility of painted strips, potential effect on the capacity of highways (effect on operational speed), and the effect on the transversal vehicle lateral position on the roadways should be investigated and minimized, so the safety benefits associated with CLRS would widespread their use . In addition, the investigation of these advantages and disadvantages may contribute for the determination of reliable policies or guidelines for installation of CLRS and to assess an objective criterion for determining when it is economically feasible to install CLRS based on roadway geometry, traffic volume, and the presence of other types of rumble strips.

External Noise Created by CLRS

According to Lay (2009), sound is produced by the vibration of pressure waves in a medium (usually air), within the range of amplitudes and frequencies that the human hearing system can respond. In addition, noise can be defined as unwanted sound. It is considered as environmental pollution because it affects the standard of living. The intensity of sound (power transmitted per area) can be measured by the pressure levels using the decibel (dB) unit, which is a logarithmic scale. The human ear does not respond to all frequencies of sound. The A-scale on a sound-level meter, measured in dBA, is the scale that best approximates the frequency to which human ear can respond. Sound from traffic generally takes 2 to 3 meters to assume a well-defined periodic form and the sound energy is dissipated with distance. In addition, sound is transmitted by air, so it will depend on the air temperature, pressure and humidity (Lay 2009). In order to regulate the need for construction of noise barriers, the FHWA states that noise impact occurs when the levels of noise approach or exceed the noise abatement criteria (NAC), which is presented in Table 1.1, or when there is a substantial increase in the existing noise environment (FHWA 1995). There are three criteria acceptable to the FHWA to define “substantial increase”, as shown in Table 1.2.

Table 1.1 Noise Abatement Criteria – Hourly A-Weighted Exterior Noise

Activity Category	L_{eq}(h) dBA	L_{10}(h) dBA	Description of Activity Category
A	57	60	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67	70	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72	75	Developed lands, properties, or activities not included in Categories A or B above.

Note: L_{10} - the sound level that is exceeded 10 percent of the time (the 90th percentile) for the period under consideration.
Note: L_{eq} - the equivalent steady-state sound level which in a stated period of time contains the same acoustic energy as a time-varying sound level during the same period.
Source: FHWA (1995)

Table 1.2 Definition of Substantial Noise Increase

	Increase	Subjective Descriptor
Criterion 1	0 to 5 dB	Little increase
	5 to 15 dB	Some increase
	> 15 dB	**Substantial increase**
Criterion 2	< 10 dB	Little increase
	> 10 dB	**Substantial increase**
Criterion 3	0 to 5 dB	No increase
	5 to 10 dB	Minor increase
	10 to 15 dB	Moderate increase
	> 15 dB	**Substantial increase**

Source: FHWA (1995)

Several studies have been conducted in order to verify if rumble strips increase exterior noise levels and disturb residents, but none provided definitive noise values or a guideline for minimum distance from buildings for the installation of CLRS. From these studies, it is possible to verify that:

- Rumble strips increase the levels of exterior noise (Higgins and Barbel 1984; Gupta 1993; Chen 1994; Sutton and Wray 1996; Finley and Miles 2007);
- Different configurations (formed and milled type) of TRS have no statistically significant effect on exterior noise (Higgins and Barbel 1984);
- At approximately 61 m (200 ft) the effect of the rumble strips' noise on surrounding environments can be ignored – difference between SRS and baseline was 9 dBA (Chen 1994);
- In order for the difference of external noise levels between baseline and TRS to be zero, the distance would be approximately 200 ft (61 m) based on the results of Sutton and Wray (1996);
- Pavement type (chip seal vs. hot mix asphalt) has a significant effect on the noise levels. The change in external noise levels as compared to the baseline is greater for hot mix asphalt (Finley and Miles 2007);
- Differences in external noise levels as compared to baseline levels increases as milled rumble strips' width increases and as the spacing decreases (Finley and Miles 2007);
- A limited number of nearby residents of a highway treated with CLRS are aware of the safety contributions of CLRS and they believe the safety effect is worth some level of noise; and
- External noise levels of commercial trucks driven over smooth pavement are usually higher than external noise created by passenger cars driven over CLRS (Higgins and Barbel 1984; Finley and Miles 2007).

There is a trade-off between safety and maximum levels of exterior noise. The loudest the noise, the better the awareness for drivers, but the worst the effect for highways' nearby residents. The determination of a minimum distance from houses and businesses at which CLRS may be installed without disturbing nearby residents is important. This would provide guidance for state agencies of transportation to spread the use of CLRS without causing major noise pollution problems.

Potential Effect in the Visibility of Pavement Markings Caused by CLRS

The most recent U.S. national crash statistics show that about half of the total fatal crashes occur at night (NHTSA 2009). Limited visibility of the intended path may be a cause influencing this number. There are several factors influencing the pavement marking performance. Mostly, these factors can be classified as visibility factors and durability factors, as presented in Table 1.3.

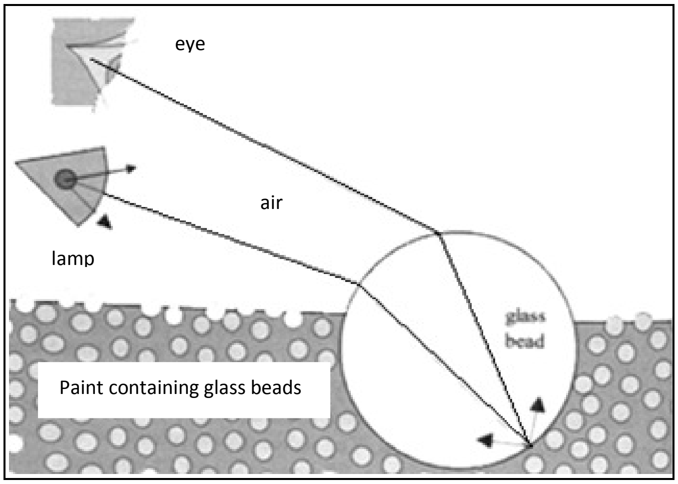
Table 1.3 Factors Influencing the Pavement Marking Performance

Visibility Factors	**Durability Factors**
Contrast	Marking Material
Retroreflectivity	Marking Thickness
Presence	Pavement Type
Pavement Texture	Pavement Texture
Pavement Color	Traffic Volume
Marking Color	Weather
Marking Size	Maintenance Activities
Headlamp Type	Marking Location (edgeline, centerline, lane line)
Viewing Geometry	Roadway Geometry
Ambient Lighting Conditions	

Source: Benz et al. (2009)

At night-time and especially when vehicles' headlights are the main source of illumination, the visual effectiveness of a linemarking relies on its retroreflectivity, measured in millicandelas per square meter per lux (mcd/lx*m^2). In 1993, Congress issued a mandate to define minimum retroreflectivity levels for signs and markings. The minimum retroreflectivity values for signing have been established, but the rule for pavement markings has yet to be established (Benz et al. 2009). Minimum retroreflectivity acceptable coefficients for pavement markings are around 100 mcd/lx*m^2 (Lay 2009). The utilization of retroreflective pavement markings is a common practice for improving the visibility of vehicle paths on roadways. Retroreflectivity is a property of the marking material that reflects light back to its source and it is usually enhanced by application of glass or ceramic beads incorporated in the pavement markings (Lay 2009). This phenomenon is presented by Figure 1.10. The major factors that contribute to decrease in retroreflectivity of pavement markings over time are: dirt accumulation on the reflective elements, traffic abrasion, weather exposure, and snowplow operations.

Figure 1.10 Retroreflective Behaviour of a Glass Bead in a Paint Film. Source: Lay (2009)



Since pavement markings are not perfect retroreflectors, when illuminated by vehicles' headlights the light is reflected in a cone shape around its source (vehicles' headlights) and only a part of this light is directed to the driver's eye, making the pavement markings visible at night. The influence of water in retroreflectivity readings is explained by Carlson et al. (2007):

> "Pavement markings are intended to perform well when new and dry, but a significant difference in the dry and wet retroreflective performance of markings is typical. When water covers a marking, there are several factors that can reduce the ability of the marking to retroreflect the incoming light. The major factors are a scattering of light due to specular reflection off the water's surface

> and the change in refraction of light due to the light rays passing through an additional medium (water) with a different refractive index (RI) from that of the bead and the air. The RI for water is about 1.33. In comparison, most highway beads have an RI of 1.5 to 1.9 (the ideal RI for pavement marking beads is 1.913). The 1.5 RI bead is more common as beads with a lower RI are more durable and less expensive. To account for the additional refraction associated with water covering the beads, markings specifically designed for wet conditions include beads with an RI in the 2.4 to 2.5 range. The development of wet-weather marking materials is a recent trend in the transportation industry to address concern over the poor performance of markings in rainy conditions."

A common marking practice in the U.S. is the installation of pavement markings over centerline rumble strips, which may affect the visibility of the markings and the service life of the painting. The service life of a pavement markings ranges from less than 1 year up to 8 years and in some cases even longer (Benz et al. 2009). The investigation on whether pavement markings installed over rumble strips impacts retroreflectivity levels is necessary since literature has shown conflicting results. For instance, Outcault (2001) reports that the sand that is applied during snow removal on winter maintenance activities may accumulate in the grooves affecting the visibility of painting at the bottom of the grooves. In addition, Torbic et al. (2009) reports that a group of people interviewed in Minnesota felt that the painted centerline markings were less visible at night, particularly under wet conditions. On the other hand, studies conducted in

Alabama (Lindly and Narci 2006), Mississippi (Filcek et al. 2004), North Dakota (NDDOT 2008), and Texas (Carlson et al. 2007) concluded that the retroreflectivity levels of pavement markings over rumble strips are greater than over flat pavement markings. In all cases, the results were obtained when readings were taken over edgeline rumble strips and no measurements were conducted over CLRS, so there is a gap in knowledge regarding this topic (the colors of the pavement markings materials on the edgeline and on the centerline are different).

The cost and performance of pavement markings over flat and CLRS and their relationship with driver safety and operational use of the roadways make research on their management important.

A pilot study to draw initial conclusions about the effects of CLRS on the retroreflectivity of pavement markings installed on two different highways was conducted, as described in Appendix A.

Potential Effect in the Operational Use of Highways Caused by CLRS

If installing CLRS cause drivers to travel slower, CLRS may affect the capacity of roadways in carrying traffic. Also, CLRS may cause drivers to travel closer to the edgeline affecting the longitudinal position at which drivers are observed operating on the travel lane. It is assumed that if CLRS cause vehicles to change their mean longitudinal lateral position closer to the shoulders, it may increase the risk of ROR crashes. However, this increase in separation from the centerline may reduce the risk of cross-over crashes. Thus, the safest hypothetical situation would be when vehicles operate closer to the center of the travel lane, with small variation in this position. In fact, a research conducted in Texas has shown that the installation of only CLRS or both shoulder and centerline rumble strips along the same two-lane undivided roadway with narrow shoulders (0.3 m to 0.9 m or 1 to 3 ft), as compared to control sites, resulted in drivers positioning their vehicles closer to the center of the travel lane (Finley et al. 2008). However, no statistical tests were conducted (the authors assumed that their elevated sample size could lead to unpractical statistically significant results at small differences in the vehicles' disaggregated lateral position data) and no relationship with crash data was established.

Furthermore, five studies indicated that CLRS affect the mean lateral position of vehicles on the travel lane (Harder et al. 2002; Porter et al. 2004; Hirasawa et al. 2005; Miles et al. 2005; Räsänen 2005). According to these studies, after the installation of CLRS drivers have the tendency of moving their vehicles' position to the right, i.e. operating further from the center line to avoid the contact with CLRS. The variation of vehicles' lateral position is reduced after the installation of CLRS (Porter et al. 2004, Räsänen 2005). Moreover, operating speeds seem to be unchanged by the presence of CLRS (Miles et al. 2005, Räsänen 2005).

Several states have reported the existence of shoulder (or combination of lane + shoulder) width guidelines for the installation of CLRS. The predominant guidelines are 0.60 m to 1.2 m (two to four feet) minimum shoulder width (see Chapter 2). These guidelines are often set to avoid increased risk of ROR crashes, but this assumption has not being validated with crash analyses. An investigation on how CLRS and the combination of CLRS + SRS affect vehicular lateral position and the intrinsic consequences on the number of crashes is important because there is a high number of two-lane undivided highways with narrow shoulders in the country that could benefit from the use of these treatments.

Research Objectives

The primary goal of this research will be to provide guidance for future installations of CLRS based on current good practices and on specific investigations of safety effectiveness, exterior noise, and operational use of the travel lane. Therefore, the objectives of this research are:

- To obtain updated information on policies and guidelines for installation of CLRS in the United States in order to identify current good practices in the country. This result will be useful for future installations of CLRS.
- To verify the before-and-after safety effectiveness of CLRS currently installed in Kansas and to obtain Safety Performance Functions for several types of crashes;
- To compare the safety effectiveness of football shaped CLRS versus rectangular shaped CLRS;
- To determine if CLRS cause levels of exterior noise that can disturb nearby residents, based on FHWA criteria for disturbance, and to propose a minimum distance from houses guideline for installation of CLRS in Kansas;
- To estimate the effects of CLRS (and SRS) on drivers' behavior, expressed by vehicles' lateral position and speed, depending on shoulder width levels; and
- To establish a criterion of when it is technically and economically beneficial to install CLRS, given known values of traffic volume, shoulder width, and SRS presence.

Chapter 2 - State of the Art: CLRS Usage in the United States

Several authors have reported advantages in installing CLRS, such as safety benefits, low costs of installation and maintenance, CLRS provide high benefit-cost ratios, low interference in passing maneuvers, versatile installation conditions, and public approval (Carlson and Miles 2003; Miles et al. 2005; Richards and Saito 2007). However, some concerns involving CLRS, such as the levels of exterior noise, potential decreased visibility of the painted strips, potential tendency to speed up pavement deterioration, possibility of causing driver erratic maneuvers, and ice formation in the grooves have been cited in the current literature (Russell and Rys 2005). The policies and guidelines for CLRS installation are very distinct among the states using them. A better understanding of good practices and gaps in research about the use of CLRS would contribute to future enhancement of their associated advantages and reduction of their potential weaknesses. For these reasons, the objectives of this chapter were to obtain nationwide, updated information about states' policies and guidelines for utilization of CLRS and provide a list of gaps in research along with good practices in the country. It is expected that the information from this study will be useful for planers and policy makers, providing guidance for future applications of CLRS.

Literature Review

This section presents a review of the pertinent studies that focus on the different effects of CLRS and the previous national surveys on CLRS policies. Studies of other types of rumble strips, for example shoulder rumble strips are not part of the scope of this work.

Safety Effectiveness of CLRS

There are several published and unpublished studies revealing that CLRS reduces cross-over crashes. Generally the methods utilized in these studies are the Naïve before-and-after, which just compares the before and after numbers with no adjustments, and the Empirical Bayes method, which uses more sophisticated, state-of-the-art statistics. Some of these studies are summarized in Table 2.1. The results of these studies are not uniform. The differences in the crash reduction effects may be partially attributed to differences of the CLRS applications, since different patterns of rumble strips have been proved to generate different levels of noise and vibration stimuli for drivers. The best pattern and application of CLRS along the roadway can be considered a gap in research since it remains unknown. Chen et al. (2003) claim that the performance of rumble strips should be a function of the difference between noise and vibration stimuli over rumble strips and over smooth pavement conditions (the best pattern would be the one that produces the largest differences). In addition, an increase in order of nine to 10 dBA (dBA corresponds to the unit of the A-scale on a sound-level meter, which is the scale that best approximates the frequency that human ear can respond) in the level of sound is necessary for a person to be alerted by the presence of that sound (Lipscomb 1995, cited by Rys et al. 2008). Therefore, CLRS should raise the levels of sound by at least 9 to 10 dBA. Miles and Finley (2007) stated that the “standard” rumble strips dimensions (milled, length equal or greater than 30.5 cm or 12 in., width of 17.8 cm or seven in., depth of 1.3 cm or 0.5 in., and spacing of 30.5 to 61 cm or 12 to 24 in.) in the U.S. provide adequate increase in the sound level to alert all drivers, regardless of the speed or the type of pavement.

Table 2.1 Safety Effectiveness of CLRS

State	Study	Statistical Method	Type of Crash Studied	Crash Reduction
Arizona	AECOM (2008)	Comparison Group	Fatal and serious injury cross-over	61.0%
	Kar and Weeks (2009)	Naïve Before-and-After	Fatal and serious injury cross-over	56.0%
California	Fitzpatrick et al. (2000)	Naïve Before-and-After	Fatal head-on	90.0%
			Total head-on	42.0%
	Persaud et al. (2003)	Empirical Bayes	Cross-over	12.0%
			All types	14.0%
Colorado	Outcalt (2001)	Naïve Before-and-After	Head-on	34.0%
			Sideswipe	36.5%
	Persaud et al. (2003)	Empirical Bayes	Cross-over	31.0%
			All types	11.0%
Delaware	Delaware DOT (2003)	Naïve Before-and-After	Head-on	95.0%
			Drove left to the center	60.0%
			PDO	Increase 13%
			Injury	Increase 4%
			All Types	8.0%
	Persaud et al. (2003)	Empirical Bayes	Cross-over	81.0%
			All types	23.0%
Kansas	Karkle et. al (2009)	Naïve Before-and-After	Fatal head-on	80.0%
			Head-on	81.0%
			Sideswipe	78.0%
			Cross-over	80.0%
			Fatal and serious injury cross-over	59.0%
		Empirical Bayes	Cross-over	85.0%
			All types	33.0%
Maine	Unpublished Maine DOT	Naïve Before-and-After	Head-on	91.7%
			ROR	28.9%
Maryland	Persaud et al. (2003)	Empirical Bayes	All types	19.0%
Massachusetts	Noyce and Elango (2004)	Comparison Group	Several	Inconclusive
Minnesota	Persaud et al. (2003)	Empirical Bayes	Cross-over	Increase 12%
			All types	0.0%
	Briese (2006)	Cross-Sectional Comparison	Cross-over	43.0%
			All types	42.0%
			Cross-over - Fatal and severe injury	Increase 13%
			All types - Fatal and severe injury	73.0%
	Knapp and Schmit (2009)	Cross-Sectional Comparison	Cross-over - Fatal and severe injury	47.0%
			All types - Fatal and severe injury	40.0%
	Torbic et. al (2009)	Empirical Bayes	All Types	11.1%
			Fatal and injury	21.8%
			Cross-over	48.9%
			Fatal and injury cross-over	44.7%
Missouri	Unpublished Missouri DOT	Naïve Before-and-After	Head-on	29.0%
			Sideswipe	61.0%
		Empirical Bayes	Head-on	53.0%
			Sideswipe	62.0%
Nebraska	Unpublished Nebraska DOT	Naïve Before-and-After	Cross-over	64.0%
Oregon	Monsere (2002) cited by Russell and Rys (2005)	Naïve Before-and-After	Cross-over	69.5%
		Comparison Group	Cross-over	79.6%
	Persaud et al. (2003)	Empirical Bayes	All Types	46.0%
Pennsylvania	Golembiewski et al. (2008)	Naïve Before-and-After	Cross-over	48.0%
	Torbic et. al (2009)	Empirical Bayes	All Types	1.6%
			Fatal and injury	6.2%
			Cross-over	25.8%
			Fatal and injury cross-over	44.4%
Washington	Persaud et al. (2003)	Empirical Bayes	Cross-over	21.0%
			All types	25.0%
	Torbic et. al (2009)	Empirical Bayes	All Types	Increase 2.3%
			Fatal and injury	Increase 4.1%
			Cross-over	35.4
			Fatal and injury cross-over	35.4

Furthermore, Liu and Wang (2011) studied the effects of rumble strip dimension on dynamic jerking (vibration), in order to find a best pattern configuration in terms of depth, spacing and width, using a quarter vehicle model and a series of equations to describe the jerking effects. Liu and Wang claimed that the vibration effect is magnified when the contact time between rumble strips and tires decreases. Thus, dynamic jerk increases as the rumble depth increases and as the width decreases. The authors stated that a too deep rumble strip pattern may promote pavement structural degradation, so the width is more appropriated to be used as the control variable. Liu and Wang (2011) claimed that the depth should be great enough to produce the expected awareness, but not too deep to avoid driver's panic and overcorrection, so the authors recommended depths between 5 and 15 mm (0.2 and 0.59 inches). Liu and Wang also recommended patterns with width in the order of 180 mm (7 inches), which would provide enough vibration to alert drivers, and also would take into consideration the preference of bicyclists for wider patterns. The spacing recommended by Liu and Wang was between 30 and 40 cm (11.8 and 15.7 inches).

Anund et al. (2008) conducted a study to verify if behavioral, physical and subjective indicators of drivers' sleepiness were affected after the contact with milled-in rumble strips (CLRS and edgeline rumble strips were used), and if so, for how long the effects would last. There were 35 participants in the simulation experiment. They drove a moving-base driving simulator after an entire night shift of work. Four patterns of rumble strips were tested, as follows: Pennsylvania pattern (length = 50 cm or 19 in., width = 30 cm or 11.8 in., depth = 1.2 cm or 0.47 in., and spacing = 30 cm or 11.8 in.) that produced an increase in noise levels of 16 dBA; Swedish pattern (length = 50 cm or 19.7 in., width = 30 cm or 11.8 in., depth = 2 cm or 0.79 in., and spacing = 53 cm or 20.9 in.) that produced an increase in noise levels of 17 dBA;

Malilla pattern (length = 35 cm or 13.8 in., width = 15 cm or 5.9 in., depth = 1 cm or 0.39 in., and spacing = 120 cm or 47.2 in.) that produced an increase in noise levels of 7 dBA; and Finish pattern (length = 17.5 cm or 6.9 in., width = 2 cm or 0.79 in., depth = 1.5 cm or 0.59 in., and spacing = 30 cm or 11.8 in.) that produced an increase in noise levels of 4.6 dBA. The authors found and increase in the sleepiness indicators before hitting the rumble strips, an decrease in objective (not the subjective) sleepiness indicators after hitting the rumble strips, but the duration of the awareness effect was short (5 minutes). There were no statistically significant differences between types of rumble strips.

Pavement Deterioration due to Water / Ice Accumulation, and Winter Maintenance Issues

Water and ice accumulation in CLRS grooves may or may not cause accelerated pavement degradation. Torbic et al. (2009) claimed that several DOTs maintenance crews have reported that heavy traffic would speed pavement deterioration due to presence of rumble strips and that the water and ice accumulated in the grooves would crack the pavement. The authors state that these concerns have not been validated. Moreover, in a survey conducted in 2005, 15 DOTs did not believe that CLRS cause pavement deterioration due to ice or water accumulation in the grooves (Russell and Rys 2005). However, a Virginia inspection on the milled CLRS found that approximately 1% of the strips inspected were deteriorating (Torbic et al. 2009). The reason of deterioration may be poor pavement conditions before the installation of CLRS, as indicated in the following studies.

According to Kirk (2008), the Kentucky Transportation Center (KYTC) held a meeting with personnel from the Kentucky DOT to investigate if the joint deterioration found on Daniel Boone Parkway, and Mountain Parkway in Kentucky was caused by CLRS. The conclusion was that these roads had poor pavement performance even before the rumble strip installation. In addition, the conclusion was that water and ice accumulation in the centerline rumble strip is a non-issue. Another study also suggests that the center joint degradation promoted by CLRS only appears to occur when the pavement condition is not adequate before the CLRS installation (Knapp and Schmit 2009). The same authors also conducted a survey about winter maintenance problems caused by CLRS. Seven of the nine surveyed states indicated that they were not aware of any maintenance problems. Two states responded that the snow/ice in the CLRS may melt and then refreeze at a time when winter maintenance activities are no longer occurring. Minnesota DOT engineers anecdotally noted that more salt appears to be needed along roadway sections with CLRS, which might suggest the need to reconsider CLRS designs and/or winter maintenance practices.

Regarding the effect of CLRS on winter maintenance and operation activities, additional passes of snowplow appeared to be needed in Alaska due to the presence of milled CLRS. However, CLRS may be beneficial because they provide guidance for snowplow drivers (Russell and Rys 2005). In addition, Hirasawa et al. (2005) claimed that the Japanese CLRS pattern produces sufficient warning (sound and vibration) for drivers on slushy winter roads, even when the center line was invisible due to snow accumulation.

The concerns reviewed in this section can be qualified as gaps in research because there is limited literature about these topics, and a specific scientific investigation is yet to be done in order to prove or disprove any hypothesis. Results available and presented in this section were obtained mainly from questionnaires.

Other Users of the Highways

The noise and vibration caused by CLRS may affect bicyclists, motorcyclists and nearby residents of highways. The policies on CLRS can play a role to equilibrate the trade-off between safety and other aspects. Three studies are consistent with the conclusion that CLRS did not appear to be a safety hazard to motorcyclists (Miller 2008; Hirasawa et al. 2005; Bucko and Khorashadi 2001). Only one study evaluated the safety effectiveness of CLRS. Miller (2008) investigated 26 of the 29 motorcyclist crashes that occurred in Minnesota after the installation of CLRS and concluded that those crashes were unrelated to CLRS. An estimate of the safety effectiveness of CLRS regarding motorcyclists remains a gap in research.

Three studies concluded that the patterns of rumble strips that produce the greatest levels of noise and vibration for drivers are the least comfortable for bicyclists (Bucko and Khorashadi 2001; Outcalt 2001; and Elefteriadou et al. 2000). In addition, Torbic (2001) concluded that there is a linear relationship between bicyclists' whole-body vibration and comfort. Another study found that the space that drivers leave between their vehicles and bicyclists is greater along roadway sections with CLRS as compared to similar situations without CLRS (Zebauers 2005 cited by Knapp and Schmit 2009).

Several studies have found that rumble strips increase the level of external noise, which may affect roadside residents. Finley and Miles (2007) concluded that pavement type and rumble strip dimensions affect the levels of exterior noise. Karkle et al. (see Chapter 4) concluded that distance, type of vehicle and speed of vehicles affect the levels of exterior noise and that at the studied distances up to 45 m or 150 feet, the noise caused by a 15 passenger van and a sedan hitting CLRS could disturb residents. The authors recommended that a minimum distance from houses and business should be considered for installation of CLRS and suggested that 61 m or

200 feet of distance from the center of the roadway should be considered as the minimum. Makarla (2009), based on a survey with a limited number of roadside residents, suggests that the respondents were willing to accept the levels of noise generated by the CLRS due to the increase in safety aspects.

The Operational Usage of the Travel Lane by Drivers

CLRS may affect the lateral position, i.e. may cause vehicles to operate closer to the shoulders, the speed at which the drivers travel and other operational aspects. Several studies found that CLRS cause drivers to move to the right, farther away from the center line (Torbic et al. 2009). If installed in conjunction with rumble stripes, drivers appear to position the vehicle closer to the center of lanes at locations with lane widths as narrow as 3.35 m or 11 ft and shoulder widths of 0.91 m or 3 ft (Finley et al. 2008). Moreover, the vehicle travel speed does not appear to be changed much by the presence of CLRS and the passing opportunity maneuvers seems to be unchanged by the presence of CLRS (Miles et al. 2005)**.**

In addition, CLRS may influence other operational aspects, such as: a) the presence of both CLRS and shoulder rumble strips on the same roadway may cause drivers to react to the left after hitting CLRS under drowsiness or inattention condition. Noyce and Elango (2004), using a simulated environment reported that 27% of the participants initially reacted leftward after encountering CLRS; and b) CLRS may affect operational aspects of emergency vehicles. This result was not confirmed in a survey conducted in 2005, which revealed that 17 DOTs had no evidence or opinion of CLRS causing people to react to the left (Russell and Rys 2005).

The Visibility of Pavement Markings

It is controversial how CLRS affect the visibility of pavement markings. According to Bahar and Parkhill (2005), there is a debate whether the degradation of the pavement marking visibility occurs faster if the markings are painted on top of the rumble strips. However, several authors reported that the visibility of pavement markings placed over rumble strips is higher than over smooth pavement, especially during wet-night situations (Torbic et al. 2009). The current belief is that CLRS improve the night visibility of the pavement markings.

Methodology

A survey was emailed to the 50 state DOTs between April and May 2010 and consisted of 17 questions regarding the following topics: use of CLRS, type of construction and pattern dimensions, total mileage, placement of CLRS in relation to the longitudinal joint and center line, type of CLRS application along the longitudinal roadway, type of pavement and policy on depth and age of pavement, minimum lane and shoulder width requirements for CLRS installation, and concerns from the public about CLRS.

Results and Discussion

The total response rate of this survey was 60% or 30 state DOTs. The results are summarized below.

1. *Are there any centerline rumble strips installed on your highways? (Yes or No).*

Among the total of 30 respondents, 90% (n=27) answered "*Yes*" and 10% (n = three) answered "*No*" to this question.

Combining the information from three previous state-of-the-art studies (Russell and Rys 2005; Richards and Saito 2007; Torbic et al. 2009) with this current survey, the number of state agencies that have at least once reported the use of CLRS is 36.

2. *What is the type of construction used by your agency? (Milled, rolled, raised, or combination).*

Among the 27 respondents that have reported the use of CLRS, only one state (Florida) does not use the milled type. Florida has reported the use of only the raised type of CLRS. Two states (Texas and North Carolina) reported the use of combination, i.e. both raised and milled types. The other 24 states reported the use of the milled type of CLRS.

3. *What are the strip dimensions used by your agency? The length refers as the dimension perpendicular to the center line and spacing is measured from center to center.*

Florida uses a continuous raised pattern with length and width of 6.35 cm (2.5 in.), height of 1.27 cm (0.5 in.) and spacing of 76.2 cm (30 in.).

Among the states that use the milled CLRS type, the dimensions varied as follows:

- Length: the range was 15.24 to 61 cm (six to 24 inches), with 40.64cm (16 inches) the predominant value used by about 42% (n = 11) of the respondents.
- Width: the range was 12.7 to 22.86 cm (five to nine inches), with 17.78 cm (seven inches) the predominant width used by about 85% (n = 22) of the respondents.
- Depth: the range was 0.95 to 1.59 cm (0.375 – 0.625 inches), with 1.27 cm (0.5 inches) the predominant depth used by about 73% (n = 19) of the respondents.
- Spacing: the range was 12.7 to 121.9 cm (five to 48 inches), with30.48 cm (12 inches) the predominant spacing used by about 77% (n = 20) of the respondents.
- Continuous or Alternating: About 65% (n=17) answered continuous, about 19% (n = five) reported the use of alternating pattern, and about 12% of the respondents use both continuous and alternating patterns.
- Class of Highway: the answers for this topic varied. Some of the reported classes of highways were: all classes, rural undivided and rural two-lane arterial.

4. *How many miles are there installed by type of highway and dimensions?*

Responses varied from 4.8 km or three miles (Delaware) to 5150 km or 3,200 miles (Pennsylvania), as shown by Table 2.2. The total length reported was approximately 18239 km or 11,333 miles. This number does not include the states of Colorado and Texas that did not report the number of CLRS km installed.

5. *Where are the rumble strips installed in relation to the longitudinal joint and centerline? (CLRS completely within pavement markings, CLRS extended into the travel lane, CLRS on either side of pavement markings).*

Among the 27 states using CLRS, about 67% (n=18) answered that CLRS are installed completely within pavement markings. About 45% (n=12) answered CLRS extended into the travel lane and about 15% answered CLRS on either side of pavement markings. Some of the states reported more than one type of CLRS placement.

6. *Where are the CLRS installed in relation to longitudinal roadway? (Continuous or specific locations).*

Among the states using CLRS, about 89% (n=24) install them in a continuous manner. Only 18.5% (n = five) of the states reported the use of CLRS at specific locations such as curves, and no passing zones. Some of the states reported both alternatives.

Table 2.2 Number of Miles of CLRS per State

State	# km (miles)	State	# km (Miles)
AK	189.9 (118)	MI	4828.0 (3,000)
AR	119.1 (74)	MN	48.3 (30)
AZ	280.0 (174)	MS	643.7 (400)
CO	Unknown	MO	1126.5 (700)
DE	4.8 (3)	NE	482.8 (300)
FL	109.4 (68)	NC	51.5 (32)
HI	16.1 (10)	NH	> 160.9 (100)
ID	431.8 (268.28)	OK	14.9 (9.25)
IA	96.6 (60)	OR	149.7 (93)
KS	373.4 (232)	PA	5149.9 (3,200)
KY	305.8 (190)	TX	Unknown
LA	656.6 (408)	VA	29.8 (18.5)
MD	663.1 (412)	WA	2293.3 (1,425)
ME	12.1 (7.5)	**Total**	**Approx. 18,238.7 (11,333)**

7. *In what type of pavement has your agency installed centerline rumble strips? (Only asphalt, only concrete, or both). Do you have any policy regarding depth and age of the pavement?*

About 74% (n=20) of the respondents reported the use of CLRS only on asphalt pavements. About 26% (n = seven) reported the use of CLRS on both asphalt and concrete pavements. The guidelines regarding the age and minimum depth of the pavement for installation of CLRS are summarized in Table 2.3. Examples of guidelines are given below.

Table 2.3 Guidelines Regarding Age and Depth of Pavement

State	Min. Pavement Depth cm (in.)	Min. Pavement Age (years)
AK	5.08 (2)	No
DE	Requires consultation of pavement management section	
IA	6.35 (2.5)	7
KS	3.81 (1.5)	No
KY	Pavement in good condition	
LA	5.08 (2)	≥ 10
MD	Pavement in good condition	
MI	Engineering judgment	
MN	Engineering judgment	
MS	Considering for new pavement in future	
MO	4.45 (1.75)	New overlays
NE	No	New Pavement
OR	Pavement in good condition	
PA	3.81 (1.5)	Older than 1 year
TX	5.08 (2)	No
WA	Pavement is structurally adequate	

- Kansas: CLRS are installed in asphalt pavement surfaces 3.81 cm (1.5 inches) or more in depth. Age of pavement is not addressed in the policy. However, they are typically installed as part of resurfacing projects.
- Pennsylvania: CLRS should not be installed on existing concrete pavements with overlay less than 6.35 cm (2.5 in.) depth. New pavements (less than one-year-old) should present a minimum 3.81 cm (1.5) inch depth and existing concrete pavements should not have overlays less than 6.35 cm (2.5 in.) in depth for installation of CLRS. The pavement should be in sufficiently good condition, as determined by the District, to effectively accept the milling process without deteriorating. Otherwise the pavement needs to be upgraded prior to milling.
- Washington has no specific policy. However, the policy reads: "Ensure that the pavement is structurally adequate to support milled rumble strips. Consult the Region Materials Engineer to verify pavement adequacies."

A supplementary question was sent to the seven state DOTs that reported the installation of CLRS on concrete pavement. This question asked the state DOTs about their experience and if they have any center joint deterioration caused by CLRS on concrete pavements. The answers are given below.

- Texas: “I have not heard of any reports of pavement deterioration caused by CLRS. Most of our centerline rumble strips are installed on hot mixed asphaltic surfaces and we have also not had any negative pavement reports.”
- Nebraska: “We do not place rumble strips on the joint. We place them on the south side of east-west highways and the east side of north south highways to match our paint striping”.
- Iowa: “We have yet to install any on PCC pavement.”
- Idaho: “I haven't heard of any deterioration yet, but we are fairly new to the installations. We may know more in a few years.”
- Missouri: “To date, I am not aware of joint deterioration due to the CLRS with our concrete pavements. As I indicated previously, we have installed the CLRS more in the last year or two. This may be an issue more after a few years, but currently we do not seem to be having issues.”
- Colorado: “I have not seen or heard of any deterioration of the concrete joints, but I have not inspected them for such an occurrence.”
- Michigan: “I can tell you that we have very little experience with CLRS on concrete, but what I heard recently from two of our regions is that milling on the CL joint on an old PCC pavement is a bad idea. We will be changing our specifications to reflect that.”

8. *Is there a minimum lane width requirement for the installation of centerline rumble strips? (Yes or No, Elaborate).*

About 67% (n=18) of the respondents answered “*Yes”* to this question and about 33% (n = nine) did not report a lane width requirement. Some states have suggestions or guidelines rather than requirements. Table 2.4 shows the lane width values reported by the respondents.

Table 2.4 Minimum Lane Width for Installation of CLRS

State	Min. Lane Width m (feet)
AK	Requires Lane + Shoulder ≥ 4.26 (14)
WA	Requires Lane + Shoulder ≥ 3.66 (12)
MI, MO, PA	Require Roadway ≥ 6.01 (20)
DE, MD	Require 3.05 (10)
HI, KY, LA	Require 3.35 (11)
NE	Requires 3.66 (12)
MN	Proposal to Require 3.66 (12)
NC	Suggests 3.05 (10)
IA, TX	Suggest 3.35 (11)
AZ	Suggests 3.66 (12)
OK	Experimented 3.66 (12)

9. *Is there a minimum shoulder width requirement for installation of centerline rumble strips? (Yes or No, Elaborate).*

About 70% (n=19) answered "*No*" to this question. About 30% (n = eight) of the respondents have a minimum shoulder width requirement for the installation of CLRS. Some states have a suggested value rather than a requirement. Table 2.5 shows the shoulder width values reported by the respondents.

Table 2.5 Minimum Shoulder Width for Installation of CLRS

State	Min. Shoulder Width m (feet)
WA	Requires Lane + Shoulder ≥ 3.66 (12)
AK	Requires Lane + Shoulder ≥ 4.27 (14)
KS	Requires 0.91 (3). Less is allowed to provide continuity
MN	Proposal to require 0.60 (2)
AZ	Suggests 1.22 (4)
MO	Suggests 1.22 (4)
IA	Eng. Judgment
OK	Experimental sites with 2.44 (8) shoulder

10. Are there both centerline rumble strips and shoulder rumble strips along the same roadway? (Yes or no, number of miles).

About 74% of the respondents have installed both CLRS and SRS along the same roadway. The total number of km reported for this dual application was approximately 2,575 (1,600 miles). Some states answered “*Yes”* to this question, but did not report the number of km. Seven states answered “*No”* to this question.

11. Are there both centerline rumble strips and edge line rumble strips (also referred as rumble stripes) along the same roadway? (Yes or no, number of miles).

About 33% (n = nine) of the respondents answered “*Yes”* to this question. The total number of miles for this type of dual application was 722. The other 18 states answered “*No”* to this question.

12. If you have answered yes on the previous question, has your agency installed both centerline rumble strips and edge line rumble strips in sections of highway with narrow (width less than 0.91 m or 3 feet) or no shoulder?

Only three states (MS, OK, and WA) reported that they have installed dual application on sections of highways with narrow or no shoulder. Only Washington reported the number of km (less than 1.6 km or one mile for this case).

13. Are there other requirements for installation of centerline rumble strips (traffic volume, crash rate, traffic volume, etc)?

About 52% (n=14) of the respondents have other requirements such as crash rates, minimum AADT, and speed limit for installation of CLRS. For instance, Texas has the following requirements: "Apply CLRS in roadways with high-incidence crash rate with regard to head-on, opposite direction sideswipe and/or single vehicle cross-over crashes as a result of inattentive drivers or impaired visibility of pavement markings during adverse weather; CLRS shall not be milled or rolled into bridge decks; breaks in the CLRS will start at least 15.24 m (50 feet) and no more than 45.72 m (150 feet) prior to each approach for the following instances: bridges, intersections, and driveways with high usage or large trucks; CLRS may be installed along the edge line delineating pavement stripes for two way left turn lanes (TWLTL). The TWLTL should have at least a 4.26 m (14 feet) width from the outside edges of the solid edge lines, and the CLRS will be reduced to 30.48 cm (12 inches) in width for each edge line. Consider noise impacts when the installation is near residential areas, schools, and churches. A minimum of 0.42 cm (3/18 inch) depth of milled CLRS or rolled CLRS may be considered in these areas. Posted speed limit should be greater or equal to 72 km/h (45 mph)".

14. Does your agency have a written policy or guidelines for the installation of centerline rumble strips? (Yes or no).

About 63% (n = 17) of the respondents reported that they have some type of written policy or guidelines for the installation of CLRS. About 37% (n = 10) of the respondents answered "*No*" to this question.

15. Has your agency performed a before-and-after study to evaluate the effectiveness of centerline rumble strips and/or edge line rumble strips? (Yes or no).

About 52% (n=14) of the respondents reported that they have, at least anecdotally, performed a before-and-after safety evaluation of CLRS. About 48% (n=13) of the respondents answered “*No”* to this question.

16. Has your agency received any concerns from the public about vehicles hydroplaning due to the contact with rumble strips?

Only one state (Kansas) reported that only one person has presented a concern about vehicles hydroplaning after hitting CLRS.

17. Has your agency received other type of concerns from the public about centerline rumble strips? (Yes or no, elaborate).

About 70% (n=19) of the respondents have received concerns from the public regarding CLRS. The causes of concerns cited were: roadside residents about external noise (n=11), motorcyclists (n=11), bicyclists (n = three), pavement deterioration (n = two), lack of advance signing of treated sections (n = one), and snow and ice removal maintenance issues (n = one). Other eight states did not report any kind of concern received from the public.

Based on the results found in this current survey and in the literature review, it is possible to summarize the gaps in research and good practices involving the use of CLRS. Good practices are given below.

- For enhancing the safety effectiveness of CLRS: adopt a minimum AADT (DOTs responses ranged between 1500 and 3000), a minimum speed (DOTs responses ranged between 64.4 and 88.5 km/h or 40 and 55 mph), a minimum crash rate for the installation of CLRS, a minimum lane width (DOTs responses ranged between 3.0 and 3.66 m or 10 and 12 feet), and a minimum shoulder width (DOTs reported two to four feet). In addition, install CLRS in roadways continuously in no-passing and passing zones, but discontinue the use of CLRS at intersections and at bridge decks, and adopt a pattern that is able to generate approximately 10 dBA above the ambient in-vehicle sound level. The predominant pattern in the country (length=40.6 cm or 16 in., width = 17.78 cm or seven in., depth = 1.27 cm or 0.5 in. and spacing = 30.48 cm or 12 in.) has this characteristic (Miles and Finley 2007). Thus, this pattern is recommended. This pattern has the properties found by Liu and Wang (2011) to maximize the effects of vibration.

- To avoid potential pavement deterioration caused by CLRS, good practices include: install CLRS only on new construction or overlays; adopt a minimum pavement depth to install CLRS (DOTs responses ranged between 3.81 to 6.35 cm or 1.5 and 2.5 in.). Do not install CLRS if the center joint is not in good condition (use engineering judgment).
- A widely applied practice to reduce the impact of CLRS on winter maintenance activities is to avoid the raised type of CLRS in areas where snow is frequent.
- Bicyclists are not expected to hit CLRS very often. However, an intermittent gap in the spacing of CLRS may help bicyclists to cross the travel lane when needed.
- External noise issues may be addressed by the adoption of a minimum distance from houses or business to install CLRS. Karkle et al. (see Chapter 4) recommended 60.96 m or 200 feet of distance, but semi-trucks were not considered in the study.
- To reduce the potential impact of CLRS on vehicles' position on the travel lane, good practices include: adopt a minimum shoulder and lane width for installation of CLRS (DOTs reported lane widths ranging from 3.0 to 3.66 m or 10 to 12 feet and shoulder widths ranging from two to four feet). Utilize CLRS in conjunction with "rumble stripes", when technically feasible, since one study showed that CLRS in conjunction with "rumble stripes" resulted in drivers positioning the vehicle closer to the center of lanes (safer condition) at locations with lane widths as narrow as 3.35 m (11 ft) and shoulder widths of 0.91 m or three feet (Finley et al. 2008).
- In order to avoid potential drivers' mistakes on initial reactions after hitting CLRS, when CLRS are installed in conjunction with shoulder rumble strips (SRS) on the same roadway, different patterns of CLRS and SRS should be used.
- Other factors suggested for inclusion in CLRS installation guidance found in the reviewed literature were: type of roadway, location of roadway, local and regional conditions, roadway alignment, consistency within a state, and experience of others (Russell and Rys, 2005). Furthermore, Carlson and Miles (2003) recommended that CRLS may be installed along the edge line delineating pavement stripes for two-way left turn lanes.

The gaps in knowledge associated with CLRS are: to determine the optimum dimensions for CLRS pattern, to determine the effects of CLRS on the visibility of pavement markings, to estimate the safety effectiveness of CLRS regarding motorcyclists, and to verify the effects of CLRS on pavement deterioration rates.

Conclusions

This paper presented the most recent survey about the DOT policies and practices regarding CLRS. The use of CLRS has grown over the years. In 2005, the total length of CLRS installed in the U.S. was 3,867 km or 2,403 miles (Richards and Saito 2007). This current survey found a total length of approximately 18,239 km or 11,333 miles (not including the states of Texas and Colorado), which represents an increase of about 372% over five years. The state DOTs are in the process of implementing written policies or guidelines for installation of CLRS. In 2006 only seven U.S. states had written policies or guidelines (Torbic et al. 2009). This survey reported that 17 states have written policies or guidelines. According to survey results, the milled type of CLRS construction is the predominant type, and the CLRS predominant pattern dimensions are: length=40.6 cm or 16 in., width = 17.78 cm or seven in., depth = 1.27 cm or 0.5 in. and spacing = 30.48 cm or 12 in., continuous. This pattern is recommended since it produces sufficient amount of noise to alert drivers. Moreover, the installation of CLRS on only asphalt pavement is predominant. Among the states that use CLRS on concrete pavements, the center joint deterioration appears not to be an important issue. This result is consistent with the literature review. Some previously cited studies have reported that pavement deterioration after the installation of CLRS seems to occur on roads that had poor pavement conditions before the CLRS application. Several state DOTs made the recommendation to investigate the condition of the pavement and to install CLRS only on sections with pavement in good condition.

The combination of CLRS and rumble stripes is rarely used on sections of highways with narrow or no shoulder, despite the results that drivers appear to position the vehicle closer to the center of lanes at locations with lane widths as narrow as 3.35 m (11 ft.) and shoulder width of 0.91m or three ft. (Finley et al. 2008).

The main causes of concerns received from the public regarding CLRS are the external noise produced by them that may disturb roadside residents and from motorcyclists, although some published results from the literature state that CLRS do not have a negative effect on motorcyclists.

Centerline rumble strips are an efficient countermeasure to reduce cross-over crashes. The policies and guidelines for CLRS installation are not very consistent among the states using them. Therefore, a list of good practices was given in this study. It can be useful in providing guidance for future applications of CLRS.

Future research may be performed on the gaps in research topics summarized by this study, which includes: to determine the optimum dimensions for CLRS pattern, to determine the effects of CLRS on the visibility of pavement markings, to estimate the safety effectiveness of CLRS regarding motorcyclists, and to verify the effects of CLRS on pavement deterioration rates.

Chapter 3 - Safety Effectiveness of CLRS

Centerline rumble strips (CLRS) are mainly installed on the center of two-lane, undivided, rural highways to prevent cross-over crashes, more specifically head-on and sideswipe in opposite direction types of crashes.

The previous chapter indicates that currently in the U.S. there are more than 18,239 km or 11,333 miles of CLRS installed in 36 states. There are 17 states with written guidelines for installation of CLRS. Requirements for installation of CLRS varied among states and included minimum crash rates, minimum traffic volumes, and minimum lane and/or shoulder width. In general, CLRS are installed in sections with elevated crash history. In Kansas there are more than 645 km (400 miles) of CLRS installed and two different shape patterns of milled-in CLRS are used: rectangular and football shaped.

The objective of this chapter is to investigate the effectiveness of two patterns of milled-in CLRS in reducing the number of targeted crashes in Kansas. The before-and-after Empirical Bayes (EB) method and the Naïve before-and-after method were applied and compared.

Literature Review

Studies that calculated the effectiveness of CLRS often employed the Naïve before-and-after method and/or the Empirical Bayes Method. The Naïve before-and-after method consists of a comparison between the number of crashes on a treated section in the after period (considered period of time after the installation of CLRS) and the number of crashes in the same section during the before period (considered period of time before the installation of CLRS). This type of comparison is known to be biased due to the "regression to the mean" phenomenon, explained in details further in this paper. Although the Naïve method does not account for the regression to the mean (RTM) bias (the crash reductions are then inflated), this method has been widely used for the estimation of the effectiveness of CLRS in reducing crashes, due to its simplicity and ease of calculation.

A recent study applied the Naïve before-and-after method, comparing crash rates of 793 km (493 miles) of Washington's two-lane, rural highways (Olson et al. 2011). Authors found that following the installation of CLRS, the rate of lane departure crashes was reduced by 24.9%. Run-off-the-road (ROR) crash rates were reduced by 6.9% and cross-over crash rates were reduced by 44.6%. Considering only the fatal and serious injury severity levels, lane departure crash rates were reduced by 37.7%, ROR crash rates were reduced by 19.5% and cross-over crash rates were reduced by 48.6%. In addition, the authors concluded that CLRS were effective in all posted speed limits analyzed (in the range of 72 – 105 km/h), in all types of road geometry analyzed, and in all levels of traffic volumes analyzed. According to Olson et. al, CLRS were more effective on tangent sites as compared to horizontal curve sites, and the performance of CLRS in reducing crash rates was better for outside the curves as compared to inside of the curves.

A method that accounts for the regression to the mean bias is the Empirical Bayes (EB) method. By using the EB method, the most reliable evidence of the value of CLRS in reducing crashes is a study conducted by the Insurance Institute of Highway Safety (IIHS). Persaud et al. (2004) used data from seven states and found an estimated reduction of approximately 21% (95% CI = 5-37%) in frontal and sideswipe opposing-direction types of accidents in treated sections on undivided, two-lane rural highways after the installation of CLRS. All types of accidents were reduced by an estimated 15% (95% CI=15-25%). The total length of treated sections was 338 km at 98 sites. Another multi-state analysis that employed the EB method was conducted by Torbic et al. (2009). In this study, authors calculated the effectiveness of CLRS on rural and urban sites, using data from Minnesota, Pennsylvania, and Washington. Combined results from rural sites of the three states indicated that CLRS promoted: a) 4.1% reduction on the total number of crashes, which was not significant at 90% confidence level; b) a statistically significant 9.4% reduction in the number of total fatal and injury crashes; c) a statistically significant 37% reduction in the number of cross-over crashes; and d) a statistically significant 44.5% reduction on the number of fatal and injury cross-over crashes.

The acceptable effectiveness of CLRS is 14% for reduction of all crashes and 55% reduction of head-on crashes (FHWA 2011A). Results of published studies are consistent in revealing that CLRS are effective to reduce the number of cross-over crashes. Previously given Table 2.1 summarizes the effectiveness of CLRS in the United States.

Methodology

Two methods were applied to calculate the safety effectiveness of CLRS in Kansas, namely the Naïve before-and-after method, and the EB method.

In this study, the Naïve before-and-after method consists of a comparison between the average annual crash frequency of the after period and the average annual crash frequency in the same treated section in the before period, as given by equation 3.1.

$$E_{Naive} = \frac{(Annual\ Crash\ Frequency_{AFTER} - Annual\ Crash\ Frequency_{BEFORE})}{Annual\ Crash\ Frequency_{BEFORE}} \tag{3.1}$$

According to Hauer et al. (2002), methods that estimate the safety-effectiveness of a treatment, based only on the counted accidents in the section of interest in the before period, show results that can be inflated due to regression to the mean (RTM) bias. The before period may have presented an elevated number of crashes and the tendency is that, over time, the number of crashes may be reduced to its mean, even if no treatment is applied. In addition, highway sections that present high crash rates are the most likely to be selected for improvements. In order to account for such bias, Hauer introduced the Empirical Bayes (EB) method. The assumption of this method is that a treated highway section is sampled from a population of sections with similar characteristics, usually in terms of traffic volumes, geometry, and crash rates. The EB method takes into account the specific probability distribution of the response variable (specific number of crashes) (Garber and Hoel 2010). From the population of similar sites, a regression model is built, and the model is usually referred as a Safety Performance Function (SPF). A SPF consists of an equation that predicts the number of crashes based on variables such as traffic volumes, lane width, shoulder width, and others. The EB method calculates a projected number of crashes for the after period, based on a weighted average of two parameters: the SPF and the crash counts in the before period. The concept of the EB method is to estimate the number of crashes that the sections of interest would have had in the after period if no treatment had been applied, and compare this number to the actual number of crashes in the after period on the section subjected to treatment. In this manner, it is possible to estimate the influence of the treatment (CLRS) on the final result.

The procedure followed in this paper for the implementation of the EB method was based on works of Hauer (1997), Hauer et al. (2002), and Harwood et al. (2002), and consisted on the following steps:

Step 1: Selection of highway sections with similar characteristics (in terms of average annual daily traffic - AADT, shoulder width, and route classification) to the treated sections. The characteristics of the similar sites used to fit SPF models are given in Table 3.1.

Table 3.1 Characteristics of the Similar Locations

Number of comparable sections	119
Total length of comparable sections	1274 km (792 miles)
Route classification	B, C, D, and E
AADT range	221 - 8159
Shoulder width range	0.3 – 3.3 m (1 ft – 10.8 ft)
Lane width range	3.35 – 3.70 m (11 ft – 12.14 ft)
Shoulder rumble strips presence	No (83 sections); Yes (23 sections); and No/Yes[1] (13 sections)
Data period	2005 - 2008

Note: [1] Sections that had no SRS in the before period and had SRS in the after period considered

According to the Kansas State Highway Classification System, Class B routes are the ones that serve as the most important statewide and interstate corridors for travel. These routes serve distinct trip movements since they are widely spaced throughout the State. On major sections of the routes traffic volumes are relatively constant. The Class C routes are defined as arterials. Average trip lengths are typically long. And Class D routes are the ones that provide access to arterials and serve small urban areas not on a Class A (interstate), B, or C route. These routes are important for inter-county movement Class E routes are used primarily for local service only. These routes are typified by very short trips. Class E routes are frequently used on a daily basis, sometimes several times a day, to connect rural residents with other routes or to provide access to small towns in the area. (KDOT 2011). The research team received crash data from the “similar” sections shown in Table 3.2, corresponding to the years of 2005 to 2008.

Step 2: Development of SPFs using, crash estimation models that predict the mean of the frequency of crashes per km, per year, without CLRS. The following predictors were tested: length of the section in kilometers (considered as an offset), presence of shoulder rumble strips, shoulder width in meters, lane width in meters, the interaction between presence of shoulder rumble strips and the shoulder width in meters, the interaction between presence of shoulder rumble strips and lane width in meters, and AADT. Crash data from 119 sections of comparison sites, totaling more than 1270 km (790 miles), was used to obtain models for the following response variables:

a) Total correctable crashes: defined as those crashes that CLRS would potentially affect. Crashes that occurred on the following locations were excluded: at intersections, intersection related, and other locations than the traffic lane, shoulder, roadside and median of the roadway. Crashes that occurred due to the presence of ice on the pavement were excluded. Finally, collision with animals, railway trains, not-fixed objects, and non-collision crashes other than overturn/rollover were considered as non-correctable crashes;

b) Cross-over crashes: among the total correctable, head-on and sideswipe in opposite direction collisions. These types of collision are usually the principal target of CLRS;

c) Run-off-the-road (ROR) crashes: among the total correctable, collisions with fixed objects and non-collisions caused by vehicles that overturned or rollover. ROR crashes are known to be mainly affected by the presence of shoulder rumble strips, instead of CLRS. However, this study was performed to investigate the hypothesis that after the installation of CLRS, the risk of ROR crashes may increase because vehicles could have a tendency to operate closer to the edgeline, to avoid the contact with CLRS;

d) Fatal and injury crashes;

In this study, the GENMOD procedure in the commercial Statistical Analysis System (SAS) software was used to compute the SPF functions. The link function was the natural logarithm and the responses were assumed to be negative binomially distributed. Equation 3.2 shows the model form used, for a given segment of highway i and year j:

$$E(\kappa)_{ij} = e^{(\beta_0 + \beta_1 * \text{SRS presence} + \beta_2 * \text{Shoulder width} + \beta_3 * \text{Lane width} + \beta_4 * \text{AADT} + \beta_5 * \text{SRS presence} * \text{Shoulder width} + \beta_6 * \text{SRS presence} * \text{Lane width})} \tag{3.2}$$

Where:

- $E(\kappa)_{ij}$ = expected number of crashes per km, per year, in a section without CLRS with the similar characteristics to the sections of interest; and
- SRS presence = Yes = 0 or No = 1;

The results of fitting equation 2 were multiplied by the length (given in km) of each segment of highway, in order to express crashes per section, per year.

Step 3: Calculation of the estimated annual number of crashes $E\{\kappa/K\}_{ij}$, given by equation 3.3, for a specific subsection *i* of a treated road *r*.

$$E\{\kappa / K\}_{ij} = \alpha_{ij} * E(\kappa)_{ij} + (1 - \alpha_{ij}) * K_{ij} \tag{3.3}$$

The calculation occurred per subsection for the best precision, since AADTs varied on the same year *j* across diverse segments *i* within the same treated road *r*. This calculation is a linear interpolation, or a weighted average of two safety parameters, i.e., the number of counts *K* that occurred in a subsection *i* in the year *j* of the before period, and the estimated crash frequency on similar sites $E(\kappa)_{ij}$. The weight factor α is given by equation 3.4. It is a value between zero and one, which sets the importance of the before period counts and the similar sites estimated counts. The weight factor depends upon the dispersion parameter *d* of the appropriate negative binomial relationship, given by the SAS output of the regression analysis as the scale parameter that the GENMOD procedure of SAS uses for convergence criteria to obtain Maximum Likelihood estimates (SAS Institute, 2011).

$$\alpha_{ij} = \frac{1}{1 + E(\kappa)_{ij} / d} \tag{3.4}$$

The variance of $E\{\kappa/K\}_{ij}$ can be calculated by equation 3.5.

$$\text{Var } E\{\kappa / K\}_{ij} = (1 - \alpha_{ij}) * E(\kappa / K)_{ij} \tag{3.5}$$

Step 4: Calculation of the average across the years of the crash frequency and its variance at a subsection *i* in the before period *BEF*, as expressed by equations 3.6 and 3.7. In these equations, *n* stands for the number of years in the before period.

$$E\{\kappa / K\}_{\text{i BEF}} = \frac{\sum_{j=1}^{n} E\{\kappa / K\}_{ij}}{n} \tag{3.6}$$

$$\text{Var } E\{\kappa/K\}_{\text{i BEF}} = \frac{\sum_{j=1}^{n} Var\ E\{\kappa / K\}_{ij}}{n} \tag{3.7}$$

Step 5: Projection for each year *p* of the after period, of the mean annual crash frequency per subsection *i*. This projection π_{ip}, given by equation 3.8, uses the last year of the before period as the reference year *ref*. For each year of the after period, a correction for AADT, or traffic volume adjustment given by *CTF,* is calculated as expressed by equation 3.9.

$$\hat{\pi}_{ip} = E\{\kappa / K\}_i * CTF_{ip} \tag{3.8}$$

$$CTF_{ip} = \frac{E(\kappa)_{ip}}{E(\kappa)_{i\,ref}} \tag{3.9}$$

Step 6: Calculation of the projected crash frequency averaged across the number of years *m* on the after period *AFT*, and its variance, per subsection *i* and per road *r*, as expressed by equations 3.10 –13.

$$\hat{\pi}_{iAFT} = \frac{\sum_{p=1}^{m} \hat{\pi}_{ip}}{m} \quad (3.10)$$

$$\hat{\pi}_{rAFT} = \sum_{i} \hat{\pi}_{iAFT} \quad (3.11)$$

$$Var\hat{\pi}_{iAFT} = VarE\{\kappa / K\}_{iBEF} * (\frac{\sum_{p=1}^{m} CTF_{ip}}{m})^{2} \quad (3.12)$$

$$Var\hat{\pi}_{rAFT} = \sum_{i} Var\hat{\pi}_{iAFT} \quad (3.13)$$

Kansas overall projected mean annual crashes and variance for the after period was the sum across the considered roads.

Step 6: Calculation of the actual counts (the number of crashes that really happened) per subsection and per road in the after period, as well as the variance of these counts. The crash frequency per subsection λ_i , which is equal to its variance, was averaged across the years on the after period, in order to express crashes per year. The actual counts per road λ_r, which is equal to its variance, were the sum of the accident counts of all subsections within a road. These calculations are expressed by equations 3.14 and 3.15.

$$\lambda_{iAFT} = \frac{\sum_{p=1}^{m} \lambda_{ip}}{m} = Var\lambda_{iAFT} \quad (3.14)$$

$$\lambda_{rAFT} = \sum_{i} \lambda_{iAFT} = Var\lambda_{rAFT} \quad (3.15)$$

Kansas overall annual crash counts and variance for the after period was the sum across the considered roads.

Step 7: Calculation of the biased estimator $\hat{\theta}$, given by equation 3.16, and the unbiased estimator $\hat{\theta}^*$, given by equation 3.17, of the effectiveness of CLRS. These are comparisons of the projection of annual crash frequency for the after period (without treatment) to the annual average of the actual counts that took place in the after period on a subsection or a road (with treatment). Although $\hat{\pi}$ is an unbiased estimator of π, the ratio $\lambda/\hat{\pi}$ is biased (Harwood et al. 2002). Hauer et al. (2002) recommend removing this bias by the use of $\hat{\theta}^*$. The bias of the estimator given by equation 3.16 is often small, so results from this equation should be comparable to results from equation 3.17 (unbiased estimator).

$$\hat{\theta}_r = \frac{\lambda_{rAFT}}{\hat{\pi}_{rAFT}} \tag{3.16}$$

$$\hat{\theta}_r^* = \frac{\hat{\theta}_r}{(1 + Var\hat{\pi}_{rAFT} / \hat{\pi}_{rAFT}{}^2)} \tag{3.17}$$

The variance of the unbiased estimator was given by:

$$Var\hat{\theta}_r^* \cong \hat{\theta}_r{}^2 * \frac{\left[(Var\lambda_{rAFT} / \lambda_{rAFT}{}^2) + (Var\hat{\pi}_{rAFT} / \hat{\pi}_{rAFT}{}^2)\right]}{\left[1 + Var\hat{\pi}_{rAFT} / \hat{\pi}_{rAFT}{}^2\right]^2}$$

(3.18)

The overall estimator of the effectiveness of CLRS in Kansas was obtained by applying equations 3.16 – 3.18 to the sum of the road estimators.

Step 8: Obtain confidence intervals for the estimators and compare the results of the Naïve method to the results of the EB method. The effectiveness of CLRS in reducing targeted crashes can be expressed as a percentage of accident reduction by applying equation 3.19.

$$E_{EB} = 100 * (\hat{\theta}^* - 1)\% \tag{3.19}$$

Negative values of E_{EB} express crash reduction in the after period due to the use of the treatment (CLRS). The 95% confidence interval of E_{EB} can be obtained by applying equation 3.20.

$$95\%\ CI\ E_{EB} = E_{EB} \pm 1.96 * \sqrt{Var\hat{\theta}^{*}} \tag{3.20}$$

Results were considered statistically significant at the 95% confidence level if the confidence interval does not contain zero. Moreover, if results from the Naïve method were within the confidence interval of the EB method, the results of the two methods were considered statistically comparable.

Results and Discussion

In order to apply the EB method, SPF regression models were built using data from similar sites. The responses (specific number of crashes per km, per year) were assumed to be negative binomially distributed. The natural logarithm link was selected for all models in the GENMOD procedure of SAS. Table 3.2 summarizes the SPF equation parameters.

Table 3.2 SPFs of Several Considered Responses

Equation Term / Response	**Estimates (P-values)**			
	Total Correctable	Cross-over	ROR	Injury FI
Intercept	-3.1815 (0.0001)	-1.2793 (0.4916)	-3.3093 (0.0001)	-4.0936 (0.001)
SRS Presence = no	0.3825 (0.0064)	-6.4150 (0.0017)	0.6933 (0.0002)	0.5223 (0.0041)
Shoulder Width (m)	-	-1.1742 (0.0742)	-0.1994 (0.0198)	-
AADT	0.0003 (0.0001)	0.0003 (0.0003)	0.0003 (0.0001)	0.0003 (0.0001)
Shoulder Width * SRS no	-	2.1292 (0.0039)	-	-
Dispersion Parameter	0.3865	0.1332	0.4006	0.3076
Model: Deviance/DF	0.9408	0.4225	0.8403	0.8048
Model: AIC – Neg. Binomial Dist.	1198.55	323.26	970.44	829.13

The applicability of the SPFs fitted in this study to estimate the number of specific targeted crashes is limited to undivided, two-lane, rural roadways of Kansas classes B, C, D, and E with shoulder width varying from 0.3 to 3.3 meters (one to 10.82 ft), lane width varying from 3.35 to 3.70 meters (11 to 12.1 ft) and AADT varying from approximately 200 to 8000 vehicles.

The goodness of fit of the models was verified in terms of the model deviance/degrees of freedom. The closer to one this parameter is, the better is the goodness of fit. In addition to the statistically significant predictors expressed in Table 3, other predictors were tested, such as lane width and the interaction between lane width and SRS presence. However, these parameters were not statistically significant at the 95% confidence level, so they were not included in the models. All responses had the length as an offset (longer sections are expected to produce more crashes) and all responses depended on the traffic volume (AADT). For sections without CLRS (comparable sections), the total correctable crashes per km, per year, depend only upon the presence of shoulder rumble strips (sections without SRS are expected to produce more crashes) and upon the traffic volume (the higher the AADT, the higher the number of crashes). Considering only the correctable crashes that resulted in injuries or deaths (Injury FI), the presence of rumble strips is expected to reduce the occurrence of these crashes. In addition, the higher the AADT, the higher the number of expected injury FI crashes.

The expected number of cross-over crashes on comparison sites (without CLRS) depend upon the interaction of shoulder width and the presence of shoulder rumble strips, which means that there are different intercept terms and different slope terms for shoulder width, based on the presence or not of shoulder rumble strips. The model for sections without shoulder rumble strips was estimated as: Cross-over / km = exp (–7.6943 + 0.955 * Shoulder width + 0.0003 * AADT).

On the other hand, the model for sections with shoulder rumble strips was estimated as: Cross-over / km = exp (–1.2793 – 1.11742 * Shoulder width + 0.0003 * AADT). For sections with SRS, increasing the shoulder width will decrease the number of expected cross-over crashes per km, per year. For sections without SRS, increasing the shoulder width will increase the number of expected cross-over crashes per km, per year, but this effect is balanced by a more negative intercept value. For both cases, and the greater the AADT, the higher the number of expected cross-over crashes. For the same shoulder width and the same AADT, the expected number of cross-over crashes is smaller for sections without shoulder rumble strips on sections with shoulder width up to 3.0 m (9.85 ft). For shoulder widths between 3.0 and 3.3 m (9.85 and 10.82 ft), the installation of SRS is beneficial to reduce the expected number of cross-over crashes.

The expected number of run-off-the-road crashes on comparison sites (without CLRS) depend upon the presence of SRS (sections without SRS are expected to present higher number of ROR crashes as compared to sections with SRS), the shoulder width (the greater the shoulder width, the lesser the number of run-off-the-road crashes, as expected), and the traffic volume (the higher the AADT, the higher the number of crashes).

After the SPF regression models were built, the Naïve and EB methods were applied and compared. The characteristics of the treated sections are given in Table 3.3.

Table 3.4 summarizes the results for the total correctable crashes. The overall number of correctable crashes per year on the treated sections in Kansas was 131.75. The projected number of correctable crashes per year for the after period if no treatment were applied was estimated as 113.95. The annual number of crashes that actually occurred in the after period (with CLRS) was 81.22. Therefore, the total correctable crashes in Kansas were reduced by 38.36% (Naïve method) or 29.21%, with 95% confidence interval (CI) of (-10.00%, -48.42%), based on the EB method.

Table 3.3 Description of the CLRS Treated Sections

Section	CLRS Cut Shape	Installation Date	Before Period	After Period	Length (km)
1	Rectangular	10/20/2009	2007 - 2008	2010	7.49
2	Rectangular	6/19/2008	2006 - 2007	2009 - 2010	13.02
3	Rectangular	9/14/2009	2007 - 2008	2010	32.97
4	Football	10/2/2008	2006 - 2007	2009 - 2010	21.00
5	Rectangular	1/1/2007	2004 - 2006	2007 - 2010	17.73
6	Football	6/6/2008	2006 - 2007	2009 - 2010	9.95
7	Rectangular	1/1/2008	2005 - 2007	2008 - 2010	17.03
8	Rectangular	1/1/2007	2004 - 2006	2007 - 2010	32.75
9	Rectangular	5/12/2009	2007 - 2008	2010	28.22
10	Rectangular	1/1/2007	2004 - 2006	2007 - 2010	15.71
11	Rectangular	9/16/2009	2007 - 2008	2010	45.41
12	Rectangular	5/18/2009	2008	2010	19.44
13	Rectangular	10/27/2009	2005 - 2008	2010	42.97
14	Rectangular	1/1/2007	2004 - 2006	2007 - 2010	9.66
15	Rectangular	6/29/2005	2003 - 2004	2006 - 2010	17.33
16	Rectangular	1/1/2007	2004 - 2006	2007 - 2010	22.13
17	Rectangular	10/3/2008	2006 - 2007	2009 - 2010	28.48
18	Rectangular	1/30/2006	2004 - 2005	2007 - 2010	2.02
19	Rectangular	1/1/2007	2004 - 2006	2007 - 2010	24.53
20	Football	10/2/2008	2006 - 2007	2009 - 2010	4.37
21	Rectangular	10/2/2008	2006 - 2007	2009 - 2010	11.38
22	Rectangular	6/22/2009	2007 - 2008	2010	14.07
23	Football	10/30/2009	2007 - 2008	2010	28.49
24	Football	6/28/2008	2006 - 2007	2009 - 2010	22.90
25	Rectangular	1/30/2006	2004 - 2005	2007 - 2010	16.10
26	Rectangular	10/20/2009	2007 - 2008	2010	22.72
27	Rectangular	6/4/2009	2007 - 2008	2010	17.19
28	Rectangular	10/3/2008	2006 - 2007	2009 - 2010	22.70
29	Football	6/13/2008	2006 - 2007	2009 - 2010	22.58
Overall - Kansas					**590.34**
Only Sections with Rectangular Shaped CLRS					**481.06**
Only Sections with Football Shaped CLRS					**109.28**

The confidence interval reveals that the estimated reduction of total correctable crashes was statistically significant and that the Naïve results are comparable to the EB results. These results are comparable with the FHWA recommendation of crash reduction factor, which assumes that CLRS promotes 14% reduction in the total number of crashes. Sections with rectangular shaped CLRS presented reduction of total correctable crashes estimated by the EB method as 22.85% with 95% CI of (-0.91%, -44.80%). Sections with football shaped CLRS presented reduction of total correctable crashes estimated by the EB method as 66.93% with 95% CI of (-36.41%, -97.44%). Since the EB confidence intervals of rectangular and football shaped CLRS overlap, there was no statistically significant difference between these two shapes of CLRS in terms of total correctable crashes.

Table 3.5 presents the results for the cross-over crashes. The overall number of cross-over crashes per year on the treated sections in Kansas was 19.00. The projection of cross-over crashes per year for the after period if no treatment were applied was estimated as 17.28. The annual number of cross-over crashes that actually happened in the after period (with CLRS) was 5.92. Therefore, cross-over crashes in Kansas were reduced by 68.86% (Naïve method) or 67.19%, with 95% confidence interval of (-37.56%, -96.82%), according to the EB method. The confidence interval reveals that the estimated reduction of cross-over crashes was statistically significant and that the Naïve results are comparable to the EB results. These results are somehow comparable with the FHWA recommendation of crash reduction factor, which assumes that CLRS promotes 55% reduction in the number of head-on crashes. Sections with rectangular shaped CLRS presented reduction of cross-over crashes estimated by the EB method as 60.35% with 95% CI of (-22.15%, -98.55%). Sections with football shaped CLRS presented reduction of cross-over crashes estimated by the EB method as 90.28% with 95% CI of (-62.17%, -100%). Since the EB confidence intervals of rectangular and football shaped CLRS overlap, there was no statistically significant difference between these two shapes of CLRS in terms of cross-over crashes.

Table 3.4 Results for Total Correctable Crashes

Section	Annual Crashes Treated Sections - Before Period	Expected Annual Crashes Similar Sections - Before Period	Annual Crashes - Projection for After Period -No Treatment	Annual Crashes - What Happened in the After Period	Naïve Before-and-After Comparison	EB Before-and-After Comparison (95% CI)
1	4.00	3.21	2.97	3.00	-25.00%	-16.89%
2	5.50	4.95	5.46	5.00	-9.09%	-19.96%
3	6.50	5.93	6.16	2.00	-69.23%	-71.49%
4	3.00	3.04	3.23	4.00	33.33%	2.26%
5	4.00	4.03	2.06	3.50	-12.50%	27.45%
6	1.00	1.10	1.43	0.00	-100.00%	-100.00%
7	6.00	5.77	6.99	2.67	-55.56%	-66.98%
8	11.33	9.70	9.74	9.50	-16.18%	-9.33%
9	3.00	2.57	2.56	0.00	-100.00%	-100.00%
10	6.33	6.09	4.88	2.25	-64.47%	-59.87%
11	6.50	6.22	6.47	5.00	-23.08%	-32.14%
12	1.00	0.73	0.48	0.00	-100.00%	-100.00%
13	4.25	4.19	4.25	1.00	-76.47%	-79.50%
14	3.00	3.09	2.02	5.50	83.33%	118.76%
15	23.50	14.31	13.24	15.80	-32.77%	14.69%
16	4.33	4.04	2.62	2.25	-48.08%	-28.56%
17	4.50	4.39	4.50	3.00	-33.33%	-44.64%
18	0.50	0.27	0.31	0.00	-100.00%	-100.00%
19	5.00	4.84	5.50	4.50	-10.00%	-28.59%
20	1.00	0.94	0.98	0.00	-100.00%	-100.00%
21	5.50	5.34	4.87	2.00	-63.64%	-64.65%
22	2.00	1.69	1.68	0.00	-100.00%	-100.00%
23	1.50	0.91	0.89	0.00	-100.00%	-100.00%
24	7.00	6.13	9.96	2.00	-71.43%	-81.89%
25	3.50	3.58	2.13	3.25	-7.14%	21.24%
26	1.00	1.27	1.20	3.00	200.00%	45.36%
27	1.50	1.68	1.77	1.00	-33.33%	-61.09%
28	5.00	4.87	4.87	1.00	-80.00%	-82.67%
29	0.50	1.00	0.71	0.00	-100.00%	-100.00%
Overall - Kansas	**131.75**	**115.87**	**113.95**	**81.22**	**-38.36%**	**-29.21% (-10.00% , -48.42%)**
Only Rectangular	**117.75**	**102.74**	**96.75**	**75.22**	**-36.12%**	**-22.85% (-0.91% , -44.80%)**
Only Football	**14.00**	**13.12**	**17.20**	**6.00**	**-57.14%**	**-66.93% (-36.41% , -97.44%)**

Table 3.5 Results for Cross-over Crashes

Section	Annual Crashes Treated Sections - Before Period	Expected Annual Crashes Similar Sections - Before Period	Annual Crashes - Projection for After Period -No Treatment	Annual Crashes - What Happened in the After Period	Naïve Before-and-After Comparison	EB Before-and-After Comparison (95% CI)
1	0.00	0.08	0.07	0.00	0.00%	-100.00%
2	1.50	1.24	1.36	0.50	-66.67%	-75.40%
3	1.50	1.20	1.25	0.00	-100.00%	-100.00%
4	0.50	0.53	0.58	0.50	0.00%	-55.44%
5	1.33	1.13	0.51	1.00	-25.00%	-48.49%
6	0.50	0.29	0.26	0.00	-100.00%	-100.00%
7	0.33	0.39	0.47	0.67	100.00%	-53.93%
8	1.00	0.99	1.01	1.25	25.00%	-23.95%
9	0.50	0.10	0.10	0.00	-100.00%	-100.00%
10	1.00	0.89	1.07	0.50	-50.00%	-75.25%
11	0.50	0.52	0.54	0.00	-100.00%	-100.00%
12	0.00	0.08	0.06	0.00	0.00%	-100.00%
13	0.00	0.26	0.27	0.00	0.00%	-100.00%
14	0.00	0.21	0.14	0.50	100.00%	1.68%
15	1.50	0.21	0.19	0.00	-100.00%	-100.00%
16	0.67	0.59	0.58	0.00	-100.00%	-100.00%
17	1.00	0.94	0.97	0.00	-100.00%	-100.00%
18	0.00	0.05	0.06	0.00	0.00%	-100.00%
19	0.67	0.95	1.11	0.75	12.50%	-59.81%
20	0.00	0.07	0.07	0.00	0.00%	-100.00%
21	1.50	1.23	1.12	0.00	-100.00%	-100.00%
22	0.00	0.12	0.12	0.00	0.00%	-100.00%
23	0.00	0.08	0.07	0.00	0.00%	-100.00%
24	3.00	1.99	3.20	0.00	0.00%	-100.00%
25	0.00	0.11	0.10	0.25	100.00%	-69.77%
26	0.00	0.10	0.10	0.00	0.00%	-100.00%
27	0.50	0.40	0.43	0.00	-100.00%	-100.00%
28	1.50	1.31	1.30	0.00	-100.00%	-100.00%
29	0.00	0.16	0.17	0.00	0.00%	-100.00%
Overall - Kansas	**19.00**	**16.22**	**17.28**	**5.92**	**-68.86%**	**-67.19% (-37.56% , -96.82%)**
Only Rectangular	**15.00**	**13.10**	**12.92**	**5.42**	**-63.89%**	**-60.35% (-22.15% , -98.55%)**
Only Football	**4.00**	**3.12**	**4.36**	**0.50**	**-87.50%**	**-90.28% (-62.17% , -100%)**

Table 3.6 presents the results for the ROR crashes. The overall number of ROR crashes per year on the treated sections in Kansas was 76.75. The projection of ROR crashes per year for the after period if no treatment were applied was estimated as 61.31. The annual number of ROR crashes that actually happened in the after period (with CLRS) was 50.07. Therefore, ROR crashes in Kansas were reduced by 34.77% (Naïve method) or 19.19%, with 95% confidence

interval of (-46.91%, +8.52%), according to the EB method. The confidence interval reveals that the estimated reduction of ROR crashes was not statistically significant and that the Naïve results are comparable to the EB results. The non-statistically significant reduction in the number of ROR crashes after the installation of CLRS does not provide evidence to contradict the previously stated hypothesis that partially motivated this study: "after the installation of CLRS, the risk of ROR crashes may increase because vehicles could have a tendency to operate closer to the edgeline, to avoid the contact with CLRS".

Sections with rectangular shaped CLRS presented reduction of ROR crashes estimated by the EB method as 15.15% with 95% CI of (-45.54%, +15.24%). Sections with football shaped CLRS presented reduction of ROR crashes estimated by the EB method as 54.97% with 95% CI of (-0.22%, -100%). Since the EB confidence intervals of rectangular and football shaped CLRS overlap, there was no statistically significant difference between these two shapes of CLRS in terms of ROR crashes.

Table 3.7 presents the results for the fatal and injury (FI) crashes. The overall number of FI crashes per year in Kansas was 55.42. The projection of FI crashes per year for the after period if no treatment were applied was estimated as 45.40. The annual number of FI crashes that actually happened in the after period (with CLRS) was 30.38. Therefore, FI crashes in Kansas were reduced by 45.17% (Naïve method) or 34.05%, with 95% confidence interval of (-6.34%, -61.76%), according to the EB method. The confidence interval reveals that the estimated reduction of FI crashes was statistically significant and that the Naïve results are comparable to the EB results. Sections with rectangular shaped CLRS presented reduction of FI crashes estimated by the EB method as 31.11% with 95% CI of (-0.76%, -61.47%). Sections with football shaped CLRS presented reduction of FI crashes estimated by the EB method as 60.22%

with 95% CI of (-3.73%, -100%). Since the EB confidence intervals of rectangular and football shaped CLRS overlap, there was no statistically significant difference between these two shapes of CLRS in terms of FI crashes.

Table 3.6 Results for Run-off-the-Road Crashes

Section	**Annual Crashes Treated Sections - Before Period**	**Expected Annual Crashes Similar Sections - Before Period**	**Annual Crashes - Projection for After Period -No Treatment**	**Annual Crashes - What Happened in the After Period**	**Naïve Before-and-After Comparison**	**EB Before-and-After Comparison (95% CI)**
1	2.50	1.85	1.71	3.00	20.00%	32.81%
2	1.50	1.69	1.85	3.50	133.33%	38.27%
3	4.00	3.57	3.70	2.00	-50.00%	-55.53%
4	2.00	1.83	1.94	2.50	25.00%	1.58%
5	2.00	2.15	0.91	0.75	-62.50%	-43.20%
6	0.00	0.38	0.68	0.00	0%	-100.00%
7	3.00	2.76	3.35	0.67	-77.78%	-84.59%
8	6.33	5.10	5.08	4.00	-36.84%	-30.05%
9	2.50	2.19	2.18	0.00	-100.00%	-100.00%
10	3.67	3.50	2.06	1.50	-59.09%	-41.42%
11	3.50	3.63	3.75	5.00	42.86%	7.88%
12	1.00	0.67	0.45	0.00	-100.00%	-100.00%
13	2.75	2.74	2.79	1.00	-63.64%	-69.76%
14	1.33	1.67	1.09	3.00	125.00%	95.86%
15	20.00	11.97	11.11	11.40	-43.00%	-1.94%
16	2.33	2.33	1.11	1.00	-57.14%	-31.81%
17	3.00	2.73	2.80	2.00	-33.33%	-44.76%
18	0.50	0.16	0.18	0.00	-100.00%	-100.00%
19	2.33	2.08	2.33	1.75	-25.00%	-39.22%
20	1.00	0.72	0.75	0.00	-100.00%	-100.00%
21	1.00	1.28	1.17	2.00	100.00%	6.82%
22	2.00	1.35	1.35	0.00	-100.00%	-100.00%
23	1.50	0.87	0.85	0.00	-100.00%	-100.00%
24	0.50	1.45	2.41	1.00	100.00%	-68.84%
25	2.00	2.11	0.92	2.50	25.00%	91.08%
26	0.50	0.79	0.75	1.00	100.00%	-36.75%
27	1.00	1.15	1.20	0.00	-100.00%	-100.00%
28	2.50	2.39	2.39	0.50	-80.00%	-84.46%
29	0.50	0.74	0.43	0.00	-100.00%	-100.00%
Overall - Kansas	**76.75**	**65.87**	**61.31**	**50.07**	**-34.77%**	**-19.19% (-46.91% , +8.52%)**
Only Rectangular	**71.25**	**59.87**	**54.23**	**46.57**	**-34.64%**	**-15.15% (-45.54% , +15.24%)**
Only Football	**5.50**	**6.01**	**7.07**	**3.50**	**-36.36%**	**-54.97% (-0.22% , -100%)**

Table 3.7 Results for Fatal and Injury Crashes

Section	Annual Crashes Treated Sections - Before Period	Expected Annual Crashes Similar Sections - Before Period	Annual Crashes - Projection for After Period -No Treatment	Annual Crashes - What Happened in the After Period	Naïve Before-and-After Comparison	EB Before-and-After Comparison (95% CI)
1	2.50	1.64	1.52	1.00	-60.00%	-51.09%
2	3.00	2.27	2.50	1.50	-50.00%	-52.56%
3	4.00	3.61	3.75	1.00	-75.00%	-77.96%
4	1.00	0.97	1.06	2.00	100.00%	32.07%
5	2.00	2.08	0.48	1.50	-25.00%	-0.96%
6	0.50	0.46	0.69	0.00	-100.00%	-100.00%
7	2.33	2.15	2.60	1.33	-42.86%	-62.71%
8	4.67	3.54	3.57	4.00	-14.29%	-4.05%
9	3.00	2.07	2.05	0.00	-100.00%	-100.00%
10	2.67	2.52	1.76	0.75	-71.88%	-68.07%
11	2.00	2.11	2.18	0.00	-100.00%	-100.00%
12	0.00	0.41	0.27	0.00	0.00%	-100.00%
13	1.25	1.61	1.63	0.00	-100.00%	-100.00%
14	1.00	1.22	0.80	3.50	250.00%	186.05%
15	11.00	5.28	4.86	6.80	-38.18%	28.79%
16	1.67	1.65	0.93	0.75	-55.00%	-44.41%
17	2.00	1.88	1.93	2.00	0.00%	-27.57%
18	0.00	0.11	0.13	0.00	0.00%	-100.00%
19	1.33	1.71	1.97	1.75	31.25%	-34.38%
20	0.50	0.42	0.44	0.00	-100.00%	-100.00%
21	2.50	2.36	2.15	0.50	-80.00%	-82.58%
22	0.50	0.55	0.55	0.00	-100.00%	-100.00%
23	0.00	0.27	0.26	0.00	0.00%	-100.00%
24	1.50	1.67	2.78	0.50	-66.67%	-86.21%
25	1.00	1.14	0.59	1.00	0.00%	-3.90%
26	1.00	1.13	1.07	0.00	-100.00%	-100.00%
27	1.00	0.98	1.02	0.00	-100.00%	-100.00%
28	1.50	1.52	1.52	0.50	-66.67%	-78.81%
29	0.00	0.35	0.35	0.00	0.00%	-100.00%
Overall - Kansas	**55.42**	**47.66**	**45.40**	**30.38**	**-45.17%**	**-34.05% (-6.34%, -61.76%)**
Only Rectangular	**51.92**	**43.51**	**39.82**	**27.88**	**-46.29%**	**-31.11% (-0.76%, -61.47%)**
Only Football	**3.50**	**4.14**	**5.59**	**2.50**	**-28.57%**	**-60.22% (-3.73%, -100%)**

An assumption of no occurrence of any geometric changes during the considered before and after periods was made in this study. This assumption was verified by an evaluation of a database containing geometric features, which revealed that cross-section geometric features remained unaltered on all sections during the evaluation period. However, based on the results presented in Tables 3.4 – 3.7, it is noticeable that on one road (# 14), the number of crashes considerably increased after the installation of CLRS. This result appears to be contradictory and it is made more so by the fact that the AADTs decreased in the after period. The research team asked KDOT for further investigation of any external factors such as changes in, sign placement or pavement type that may have occurred in the after period on this section in order to explain such results, but no apparent external reason was found. Thus, this isolated result appears to have occurred: a) only by chance; or b) the selected years on the before period had an unusual low number of crashes.

The later hypothesis was assumed to better explain this unexpected result, after a review of the total number of crashes (not only the correctable ones) that occur prior to the selected before period (2004-2006). In the years 2000 – 2003, the annual average number of crashes in this section was 17.25. During the before period, this average dropped to 11.67, revealing that the selected before period had an unusually low number of crashes. In the after period, the annual average number of crashes was 18.5, returning to the normal level, but with no positive effect of CLRS.

Conclusions

This study had the objective of quantifying the safety effectiveness of CLRS in Kansas. In the U.S., roadway departures correspond to approximately 40% of all crashes, and their estimated annual cost is $100 billion (FWHA 2003). Centerline rumble strips are a relatively inexpensive (the installation cost of CLRS is approximately $ 2,175 per km or $3,500.00 per mile) in Kansas (Buckley 2008), varying with the length of the project) and efficient countermeasure to crashes, preventing mainly cross-over crashes. This study presented safety performance functions to estimate the number of targeted crashes per year on undivided, two-lane, rural roadways of Kansas classes B, C, D, and E with shoulder width varying from 0.3 m to

3.3 m and AADT varying from 200 to 8000 vehicles. By the application and comparison of the Naïve and the Empirical Bayes methods, it is possible to conclude that CLRS are efficient to prevent all types of crashes considered in this study. The results showed that following the installation of CLRS in several roads in Kansas, total, correctable crashes were reduced by 29.21%, with 95% CI of (-10.00%, -48.42%). This result is comparable to results from California, Colorado, Maryland, Minnesota, Oregon and Washington (see Table 2.1). The correctable crashes involving fatalities and injuries were reduced by 34.05%, with 95% CI of (-6.34%, -61.76%), which is comparable to Minnesota and Pennsylvania (see Table 2.1). The number of cross-over crashes was reduced by 67.19%, with 95% CI of (-37.56%, -96.82%), which is comparable to Delaware, Minnesota, Missouri, Nebraska, and Oregon (see Table 2.1 and Olson et al. 2011). The number of run-off-the-road crashes showed a not statistically significance reduction of 19.19%, with 95% CI of (-46.91%, +8.52%), which is comparable to Maine (see Table 2.1) and Washington (see Olson et al. 2011). The two methods applied presented statistically similar results and there was no statistical difference between football shaped and rectangular shaped CLRS, based on EB crash reductions.

Chapter 4 - A Study of Exterior Noise

Despite the safety advantages of CLRS, a potential trade-off of using them on rural highways is the amount of noise created when vehicles go over the strips, which may disturb roadside residents and businesses. Special attention should be given to this problem where many houses are positioned close to rural highways.

The objectives of this study were: to quantify the levels of exterior noise produced by CLRS and smooth asphalt pavement and verify the effects of speed, vehicle type, CLRS shape, and distance on exterior noise. Then the data was used to calculate the amount of noise created by CLRS which might impact residences and businesses located close to the studied highways.

Literature Review

This section presents the basic concepts related to noise perception by the human ear, the requirements for noise abatement on U.S. highways and the summary of findings from studies of the exterior noise caused by rumble strips.

Noise Fundamentals

According to the Federal Highway Administration (FHWA), sound is produced by the vibration of pressure waives in the air. In addition, noise can be defined as unwanted sound. It is considered as environmental pollution because it affects the standard of living. The intensity of sound can be measured by the pressure levels using the decibel (dB) unit, which is a logarithmic scale. The human ear does not respond to all frequencies of sound. The A-scale on a sound-level meter, measured in dBA, is the scale that best approximates the frequency to which human ear can respond. To better understand the response of the human ear to sound, some relationships are useful: a) doubling the noise source increases the sound pressure level by 3 dB, which is barely detectable by the human ear; b) a change of 10 dB in the sound pressure level is perceived by the human ear as double or half of the sound; and c) in general, sound intensity decreases proportionally to the square of the distance from the source. However, for traffic noise analysis, noise generally decreases 4.5 dB per distance doubling, since sound from a highway propagates close to "soft" ground i.e., absorptive surface in which the phase of the sound energy is changed upon reflection (FHWA 1995).

In order to regulate the need for construction of noise barriers, the FHWA states that noise impact occurs when the levels of noise approach or exceed the noise abatement criteria (NAC), which was presented in Table 1.1, or when there is a substantial increase in the existing noise environment (FHWA 1995). There are three criteria acceptable to the FHWA to define “substantial increase”, as shown previously in Table 1.2.

The locations where the noise measurements of this study took place can be defined as Activity Category “B” i.e. parks, residences, hotels, etc. Therefore, if the sound level that is exceeded 10 percent of the time (L_{10}) approaches or exceeds 70 dBA, a noise impact would occur, and a countermeasure would be necessary to correct this impact (see Table 1.1). This criterion is used in this study, assuming that in practice vehicles hit the CLRS more than 10 percent of the time. Another criterion used in this study is that “substantial increase” in noise levels would occur if the levels of noise increased 10 dBA due to the presence of rumble strips, which is the strictest criterion given in Table 1.2.

This study used the maximum noise level registered per run (L_{max}) instead of L_{10} due to the nature of the measurements (single-events).

Exterior Noise Studies

Several studies have been conducted in order to verify that rumble strips increase exterior noise levels and disturb residents, but no one provided definitive noise values. Some of the studies are listed below.

Higgins and Barbel (1984) tested several configurations of transverse rumble strips (TRS) in Illinois. The authors concluded that at 15.2 m the increase in the noise levels was 7 dB compared to the base noise levels. Different configurations (formed and milled type) of TRS had no effect on exterior noise. The noise created by a commercial vehicle traveling over smooth pavement was slightly higher and had a longer duration than the noise associated with cars traveling over TRS.

Gupta (1993) measured the noise generated by cars and trucks at three meters when driven over smooth pavement and over rumble strips in Ohio. Gupta concluded that rumble strips increased the maximum level of noise by 5 dB compared to the base lane. This difference was 7 dB for trucks.

Chen (1994) compared the exterior noise levels between a van driven over milled rumble strips to a truck driven over an asphalt surface without rumble strips, in Virginia. An important result found in this study was that at approximately 61 m the effect of the rumble strips noise on surrounding environments can be ignored.

Sutton and Wray (1996) studied the increase of external noise associated with TRS in Texas. The results showed that at the edge of the pavement, the maximum difference in comparison to the base level noise was 12 dB. At 7.6 m and 15.2 m, the difference was 8 and 7dB, respectively. An important conclusion drawn from this study is that in order for the difference to be zero, the distance would be approximately 61 m.

Meyer and Walton (2002) compared “rumbler” (removable) and asphalt rumble strips at two different work zone locations in Kansas. The authors concluded that the rumbler presented higher levels of noise than the rumble strips, and it could be an efficient alternative for work zones due to its versatility.

Finley and Miles (2007) measured the exterior noise produced by two types of vehicles (sedan and truck) traveling over five types of rumble strip applications at two different speeds (80.5 km/h and 112.7 km/h) in Texas. The results of this study indicated that 87 % of the maximum baseline noise levels for trucks were greater than the peak rumble strips levels. Differences greater than four dB in comparison to baseline conditions, occurred in more than half of the rumble strips configurations. Differences were greater at 112.7 km/h and lower for the truck. Pavement type (chip seal vs. hot mix asphalt) had a significant effect on the noise levels. Rumble strips caused a change in the exterior noise level of 5dB or less on chip seal and 11 to 19 dB on hot mix asphalt. In addition, noise levels increased as milled rumble strips’ width increased and as the spacing decreased.

Kragh et al. (2007) compared the noise generated by five different types of milled CLRS in comparison to baseline conditions in Denmark. Three types of vehicles were driven at a speed of 80 km/h, and the external noise was measured at 7.5 m from the center of the road. The authors concluded that sinusoidal strips presented the lowest difference, leading to an increase of only 0.5 – 1 dB in the external noise level. The rectangular strips presented the highest difference (3 – 7 dB).

A study conducted by Makarla (2009) qualitatively evaluated the perception of roadside residents of US-40 in Douglas County, KS, to the exterior noise produced by CLRS. A questionnaire was distributed to residents identified as living near to the section of US-40 with

CLRS. Nine surveyed residents answered that they live at more than 76 m from the highway, two residents answered at 30-76 m, and one surveyed answered at 15 to 30 m. The results of this survey indicated that 92% (n=11) of the respondents could hear the noise generated from the vehicles crossing over centerline rumble strips, but for 90% of these, the noise is not a concern. The frequency that the residents heard the noise from vehicles crossing CLRS was less than 10 times a day. In addition, 100% of the respondents (n = 12) answered that CLRS contribute to drivers safety and they believe that the safety effect is worth some level of noise.

Methodology

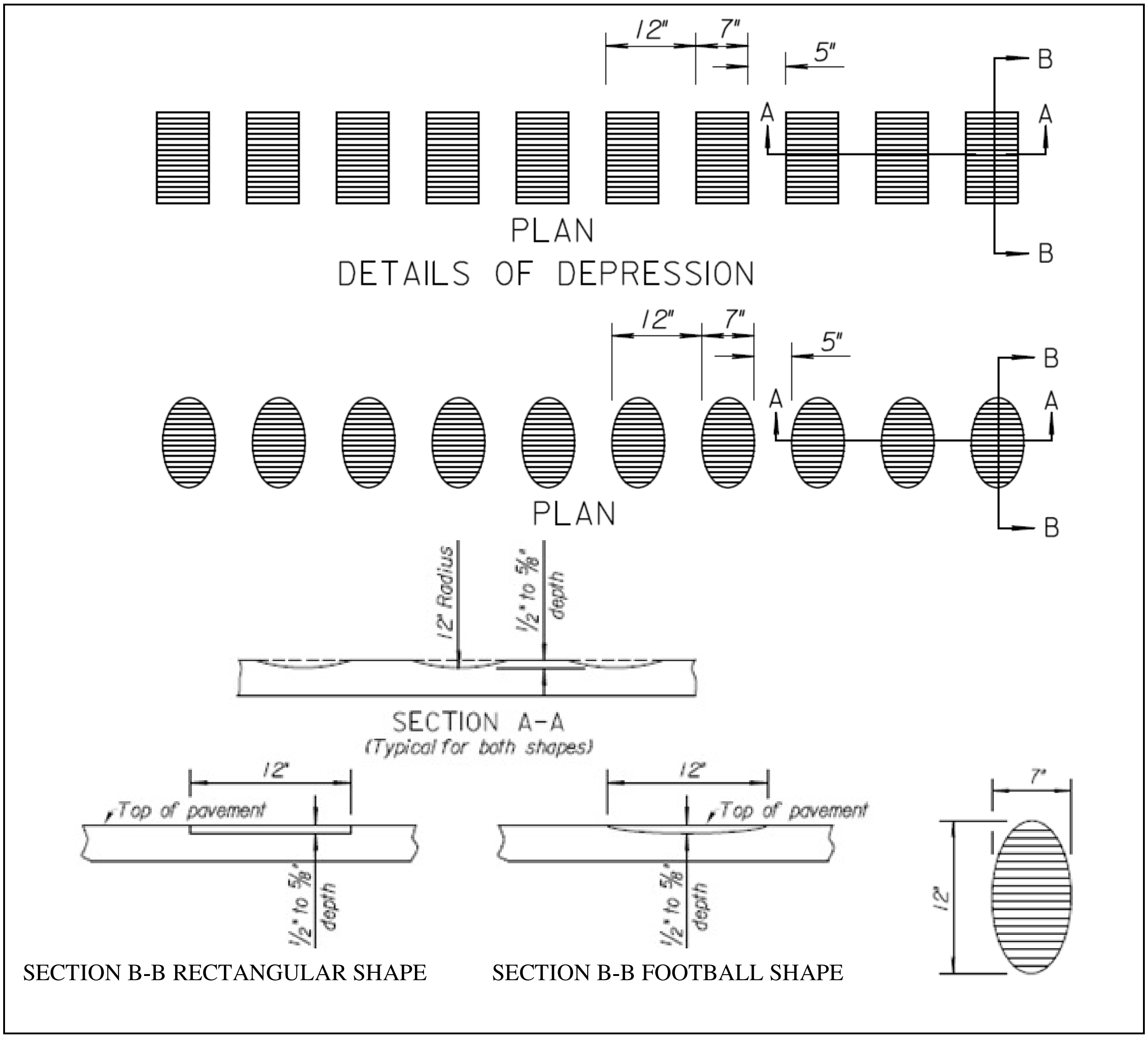
This section describes the methods used to collect the data and to conduct the statistical analysis of the experiment.

Data Collection

The study sites were selected from a list of locations where the Kansas Department of Transportation (KDOT) had already installed CLRS. Five locations that had rectangular CLRS, and five locations that had football-shaped CLRS were selected. Figure 4.1 shows the dimensions of the rectangular and football-shaped CLRS installed on the studied sections.

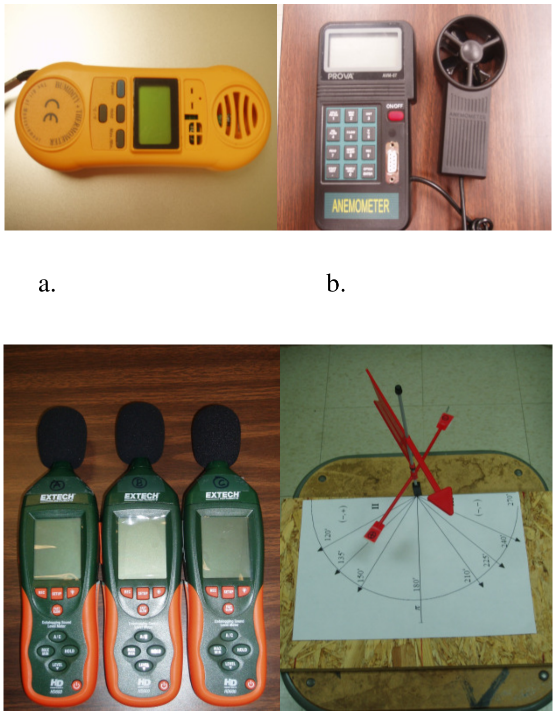
A previous investigation has concluded that the two patterns used in Kansas are not statistically different in terms of vehicular internal noise and vibration (Rys et al., 2008).

Figure 4.1 Patterns of CLRS Studied



The locations had a posted speed limit of 104.6 km/h or 65 mph, and were specifically chosen in order to minimize the travel distance from Manhattan, Kansas. Data were collected under dry, day time conditions, at flat and open space locations. Three noise meters with data logger systems were placed at 15 m, 30 m, and 45 m orthogonally measured from the center line of the highways. Three Extech HD600 noise meters (type 2 acoustical instrument) were used for data collection. The noise meter had a range of 30 to 130 dB and accuracy of 1.4 dB. The noise meters were calibrated before each series of measurements per location. The wind direction was measured using a wind vane / angle sheet equipment. A Prova AVM-07 anemometer was used to measure wind speed. Temperatures and humidity levels were measured at the beginning of the series of measurements per location and whenever perceptible changes in the weather occurred. A CE LM-81HT thermometer / anemometer / humidity meter was used to measure humidity and temperatures. Figure 4.2 shows the equipment used during the data collection. The rumble strip depth dimension was measured with a caliper. For each location, the depth was determined by averaging five measurements. The tire pressure for each test vehicle was measured at cold tire conditions.

Figure 4.2 Equipment Used for Data Collection



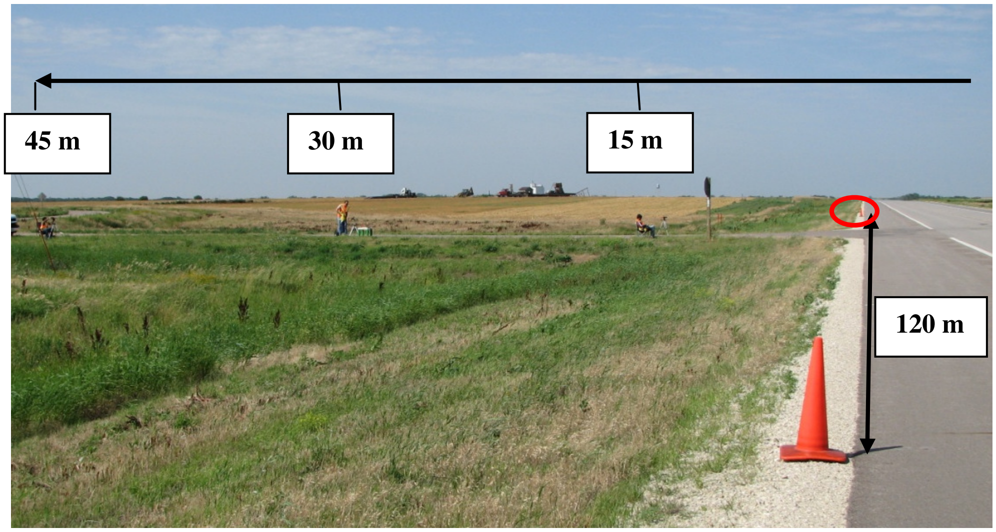
a. b.

c. d.

Notes: a. CE LM-81HT thermometer / anemometer / humidity meter
b. Prova AVM-07 anemometer.
c. Extech HD600 noise meters.
d. Wind vane / angle sheet equipment.

Exterior noise data were collected per “base level run” or “rumble strip run”. The base level run consisted of a test vehicle traveling over smooth asphalt pavement at two different speed levels, 64 km/h (40 mph) and 105 km/h (65 mph), in a 120 m (394 ft) straight segment of highway. The noise data were collected at the midpoint of this 120 m (394 ft) segment of the highway. The rumble strip run had the test vehicles traveling over CLRS under the same conditions. At each location, the segment of highway at which the noise data were collected was marked with two traffic cones, as shown in Figure 4.3. Runs that had another vehicle traveling within the 120 m (394 ft) segment of highway were not considered, in order to avoid noise contamination. Three runs of each vehicle, pavement, and speed combination were recorded to insure pure experimental error. The order of the runs and the position each of the three noise meters were randomly assigned per location. At one specific location, noise levels of 14 semi-trucks were collected at smooth pavement condition and highway operation speeds. The semi-truck baseline noise data was used to provide a comparison with the tested vehicles driving over CLRS, as other studies have done. No control was exercised over the speed or position of the semi-trucks. This data were collected assuming that the noise from semi-trucks possibly constitutes the worst case scenario.

Figure 4.3 Set up of the Experiment



The data point associated with each run was the highest noise level recorded L_{max}, at the fast response of the noise-meter (125 ms) and using the dBA scale added to the wind contribution factor, to get "corrected noise" values. The wind contribution was calculated using Equation (4.1), given by Cho et al. (2004).

$$A_{wind} = -[\, 0.88 \times \log_{10} (\, L \div 15 \,) \,] \times U \times \cos \theta \qquad (4.1)$$

Where:

- A_{wind} = wind contribution to the noise;
- L = distance horizontal in meters, from the source of the noise to the instrument;
- U = wind speed, in m/s;
- θ = angle in radian, between the wind direction and the line from the vehicles to the instrument.

The two vehicles used are shown in Figure 4.4. They were a 2006 Ford Taurus, that has a curb weight (defined as the weight of the vehicle without any passengers or cargo in it) of approximately 1.5 metric tons (3300 lb), and a 2008 Chevrolet Express - 15 passenger van, which has a curb weight of approximately 2.7 metric tons (5950 lb).

Figure 4.4 Vehicles Used on the Experiment

a. 2008 Chevrolet Express - 15 passenger van

b. 2006 Ford Taurus

Data Analysis

The purpose of this analysis was to verify the effects of type of vehicle, speed, and pavement conditions (football or rectangular rumble strips, or smooth) on the exterior noise. Noise levels from 24 runs per location were taken, in order to achieve a full factorial experiment with three replicates, and the total number of runs was 240. The data points per run were collected corresponding to distances of 15, 30, and 45 meters (50, 100, and 150 ft).

This experiment was analyzed as a split-plot design. The whole-plot level had a 3 way factorial in a completely randomized design. The factors were: vehicle (VEH), speed (SPD), and LP (factor that contained information about location and pavement). The error term for the whole-plot level was the three-way interaction. The split-plot level had the distance factor (DIST) and interactions. A slit-plot design was used because noise levels at different distances, in a straight line from the source, were assumed to be correlated with each other. The data point considered was the average of three replicates of each combination of speed, vehicle and pavement per location. The Mixed Procedure in Statistical Analysis System (SAS 2011) software was used to analyze the data.

Four different models were built and compared in terms of the Akaike Information Criterion (AIC), calculated according to Equation 4.2.

$$AIC = [-2 \times \ln (L)] + 2 \times K \tag{4.2}$$

Where:

- K = number of parameters in the model;
- L = maximum likelihood function for the estimated model.

The smaller the AIC, the better the goodness of fit in the SAS formulation of AIC. The first model had no covariate. The AIC for this model was 2,789. The second model had humidity as a covariate, generating the AIC of 2,789. The third with temperature as a covariate had an AIC of 2,789. The fourth, with both humidity and temperature as covariates, had an AIC of 2,789. Since the covariates did not help in improving the goodness of fit, as compared to the model without covariates, this simpler model (without covariates) was chosen, as shown in Tables 4.1 and 4.2.

Table 4.1 shows that there is a statistically significant difference of the response (noise levels) due to changes in: a) location and pavement (LP), b) types of vehicle (VEH), c) levels of speed (SPD), and d) levels of distances. The statistically significant interactions were: a) between types of vehicles and speed (which means that varying the speed has different noise effects among the vehicles), and b) between distance and LP (meaning that noise variations between distances are different among the locations). In addition, Table 4.2 is useful to reveal at which levels of the factors the F-tests given in Table 4.1 were significant. For instance, the effect "distance" was significant in the ANOVA table due to the F-test differences among all levels (15 m vs. 30 m; 15 m vs. 45 m; 30 m vs. 45 m), shown in Table 4.2.

Table 4.1 ANOVA Table - Model without Covariates

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
LP	19	19	23.74	<.0001 [a]
VEH	1	19	57.45	<.0001 [a]
SPD	1	19	269.17	<.0001 [a]
VEH x LP	19	19	1.47	0.2040
SPD x LP	19	19	2.05	0.0629
VEH x SPD	1	19	5.15	0.0351 [a]
DIST	2	38	1102.18	<.0001 [a]
DIST x LP	38	38	2.61	0.0019 [a]
VEH x DIST	2	38	0.44	0.6487
SPD x DIST	2	38	2.63	0.0855
VEH x DIST x LP	38	38	0.47	0.9895
SPD x DIST x LP	38	38	0.51	0.9791
VEH x SPD x DIST	2	38	0.84	0.4413

Note: [a] Statistically significant at 0.05 level

Table 4.2 Orthogonal Contrasts

Contrast #	Label	Numerator DF	Denominator DF	F Value	Pr > F
1	Smooth F[b] vs. Smooth R[c]	1	19	4.07	0.0581
2	CLRS vs. Smooth	1	19	307.70	< 0.0001 [a]
3	Football vs. Rectangular	1	19	0.05	0.8318
4	Smooth F[b] vs. Football CLRS	1	19	132.96	< 0.0001 [a]
5	Smooth R[c] vs. Rectangular CLRS	1	19	176.13	< 0.0001 [a]
6	15 m vs. 30 m = 50 ft vs. 100 ft	1	38	2192.32	< 0.0001 [a]
7	15 m vs. 45 m = 50 ft vs. 150 ft	1	38	390.16	< 0.0001 [a]
8	30 m vs. 45 m = 100 ft vs. 150 ft	1	38	670.62	< 0.0001 [a]

Note: [a] statistically significant at 0.05 level.
Note: [b] Noise levels at locations with football rumble strips, collected over smooth pavement.
Note: [c] Noise levels at locations with rectangular rumble strips, collected over smooth pavement.

Figure 4.5 presents the mean levels of noise, and the differences between rumble strips and baseline runs. Results were compared to the NAC values and the substantial increase criteria presented previously, in order to verify if CLRS produced inacceptable and/or substantial increase in noise levels.

Figure 4.5 Mean Levels of Noise and Differences between Rumble Strips and Baseline Runs

Disaggregated Mean Values of Noise											
Corrected noise (dBA) at:			**15 m**	**30 m**	**45 m**	**Corrected noise (dBA) at:**			**15 m**	**30 m**	**45 m**
Taurus	64 km/h	FRS	67.12	60.26	55.77	Van	64 km/h	FRS	72.49	66.57	60.88
Taurus	64 km/h	Smooth F	64.63	57.8	52.38	Van	64 km/h	Smooth F	65.93	60.00	54.86
Difference			**2.48**	**2.46**	**3.39**	**Difference**			**6.56**	**6.57**	**6.02**
Taurus	64 km/h	RRS	67.45	60.67	55.41	Van	64 km/h	RRS	73.36	67.84	61.82
Taurus	64 km/h	Smooth R	62.81	55.07	50.99	Van	64 km/h	Smooth R	65.4	57.23	56.23
Difference			**4.64**	**5.6**	**4.42**	**Difference**			**7.96**	**10.61**	**5.6**
Taurus	105 km/h	FRS	77.91	72.18	67.26	Van	105 km/h	FRS	82.36	74.87	69.98
Taurus	105 km/h	Smooth F	70.27	63.21	57.75	Van	105 km/h	Smooth F	71.7	64.7	58.64
Difference			**7.64**	**8.97**	**9.51**	**Difference**			**10.66**	**10.16**	**11.34**
Taurus	105 km/h	RRS	78.82	71.59	65.89	Van	105 km/h	RRS	81.46	73.66	67.53
Taurus	105 km/h	Smooth R	69	59.57	55.7	Van	105 km/h	Smooth R	69.59	63.84	58.55
Difference			**9.82**	**12.03**	**10.19**	**Difference**			**11.87**	**9.83**	**8.98**

Aggregated Mean Values of Noise			
Description	**Noise (dBA)**	**Description**	**Noise (dBA)**
Overall Ford Taurus	63.37	Overall Rectangular CLRS	68.83
Overall Chevrolet Express Van	66.71	Overall Smooth R	61.8
Overall 15m	71.27	Overall Football CLRS	68.97
Overall 30m	64.5	Overall Smooth F	61.17
Overall 45m	59.34	Overall CLRS	68.9
Overall 64 km/h	61.42	Overall Smooth	61.17
Overall 105 km/h	68.65		

Note: FRS: Football Rumble Strips.
Smooth F: Runs over smooth pavement at locations with FRS.
RRS: Rectangular Rumble Strips.
Smooth R: Runs over smooth pavement at locations with RRS.

Key Findings

This section summarizes the results found from this study.

- The Taurus mean level of noise (63.37 ± 0.31 dBA) was significantly lower compared to the mean level noise of the Chevrolet van (66.71 ± 0.31 dBA); the P-value of this test was smaller than 0.001 (see F-test of VEH effect in Table 3). However, the highest difference in levels of noise of rumble strips when compared to smooth pavement (12.03 dBA), was measured at 30 m (100 ft) when the Taurus was traveling at 105 km/h or 65 mph (see Figure 4.5).
- Overall, the mean level of noise at 64 km/h or 40 mph (61.42 ± 0.31 dBA) was significantly lower when compared to the mean level of noise at 105 km/h or 65 mph (68.65 ± 0.31 dBA); the P-value of this test was smaller than 0.0001 (see F-test of SPD effect in Table 4.1).
- Overall, the mean level of noise at 15 m or 50 ft (71.27 ± 0.26 dBA) was significantly greater than the noise at 30 m or 100 ft (64.50 ± 0.27 dBA) and 45 m or 150 ft (59.34 ± 0.26 dBA), and they were also different from each other; the P-values of these tests were smaller than 0.0001 (see Table 4.2).
- In general, mean noise levels dropped 9.5% from 15 m to 30 m (50 ft to 100 ft) and 8.0% from 30 m to 45 m (100 ft to 150 ft).
- The mean level of noise generated by smooth pavement at locations with football CLRS (61.17 dBA) was not significantly different from the mean noise level on smooth pavement at locations with rectangular rumble strips (61.80 dBA); the P-value of this test was 0.0581 (see Table 4.2).
- The levels of noise generated by CLRS (68.90 dBA) were significantly greater than the noise generated by smooth pavement (61.17 dBA); the P-value of this test was smaller than 0.0001 (see Table 4.2).
- Assuming that in practice vehicles would hit CLRS more than 10 percent of the time, it is possible to use the criteria of NAC and definitions of "substantial noise increase" from Tables 1.1 and 1.2 to define disturbance as a practical criterion for this study. Hence, noise disturbance would occur if the noise recorded in areas classified as Activity Category "B" (Table 1.1) approaches or is greater than 70 dBA, or if an increase is greater than 10 dBA in the levels of noise due to the installations of CLRS (Table 1.2). By observing Figure 4.5, it is possible that at distances up to 45 m (150 ft) for areas classified as category "B", CLRS would cause noise disturbance. Noise levels recorded when the vehicles were traveling at 105 km/h (65 mph) over CLRS exceeded or approached 70 dBA. In addition, a substantial noise increase (greater than 10 dBA) was detected.
- The interaction between speed and vehicle was significant. The P-value of this test was 0.0351 (See Table 4.1). It means that the levels of noise of the Taurus and the Chevrolet van have different trends depending on the speed of vehicles.
- The interaction between distance and LP was significant (See Table 4.1). This means that the variation of noise per level of distance was different across the locations. Possibly due to differences between types of asphalt, terrain, vegetation, etc.
- There was no significant difference between rectangular (68.83 dBA) and football (68.97 dBA) CLRS; the P-value of this test was 0.8318 (see Table 4.2).

- Semi-trucks traveling at operational speeds (approximately 105 km/h or 65 mph) on smooth pavement produced higher levels of noise compared to the Taurus and the Chevrolet van traveling over rumble strips, as shown in Table 4.3. It is possible (but not measured in this study) that semi-trucks crossing over CLRS could produce even higher levels of noise.

Table 4.3 Comparison to Semi-Trucks

Mean Corrected Noise (dBA)			
Distance	**Taurus over CLRS**	**Van over CLRS**	**Semi-Trucks over smooth pavement**
15 m or 50 ft	78.36	81.91	83.89
30 m or 100 ft	71.89	74.27	76.4
45 m or 150 ft	66.58	68.76	73.14

In order to predict the critical distance at which the levels of noise produced by rumble strips would be at acceptable levels, considering only the vehicles studied, four simple linear regression models were developed. The first model described the variation of noise from the Taurus traveling over rumble strips at 105 km/h (65 mph). The second model had data from the Taurus traveling over smooth pavement at 105 km/h (65 mph). The third model had data from the Chevrolet van traveling over rumble strips at 105 km/h (65 mph), and the forth model had data from the Chevrolet van over smooth pavement at 105 km/h (65 mph). The predictor of each model was distance. Table 4.4 shows the regression analysis results.

Table 4.4 Regression Models Results

Model 1 = Taurus CLRS: Noise = 84.1 – 0.387 * Distance (m). Adj R^2 = 75.04%				Model 2 = Taurus Smooth: Noise = 75.5 – 0.424 * Distance (m) Adj R^2 = 70.10%			
Distance (m)	**Prediction**	**Real Average**	**Residual**	**Distance (m)**	**Prediction**	**Real Average**	**Residual**
15	78.27	78.36	-0.09	15	69.17	69.61	-0.44
30	72.47	71.89	0.58	30	62.82	61.46	1.36
45	66.67	66.58	0.09	45	56.46	56.69	-0.23
60	60.87	*	*	60	50.10	*	*
Model 3 = Van CLRS: Noise = 88.1 – 0.432 * Distance (m). Adj R^2 = 70.50%				**Model 4 = Van Smooth: Noise = 76.6 – 0.396 * Distance (m). Adj R^2 = 62.80%**			
Distance (m)	**Prediction**	**Real Average**	**Residual**	**Distance (m)**	**Prediction**	**Real Average**	**Residual**
15	81.67	81.91	-0.24	15	70.66	70.68	-0.02
30	75.20	74.27	0.93	30	64.72	64.28	0.44
45	68.73	68.76	-0.03	45	58.77	58.60	0.17
60	62.25	*	*	60	52.83	*	*

According to Benekohal et al. (1992) cited by Meyer and Walton (2002), the typical noise levels of common sound events are given in Table 4.5.

Table 4.5 Typical Noise Levels for Common Sounds

Event	Noise (dB)
Soft whisper	30
Refrigerator	40
Normal conversation	50
Television	60
Noisy restaurant	70
Dishwasher	75
Blow dryer	80
Electric razor	85
Lawn mower	90
Power tools	100
Stereo headset	110
Rock concert	120
.22 caliber rifle	130
Jet take-off	140

Source: Meyer and Walton (2002).

The expected rumble strips' noise at 60 m or 200 ft (60.87 dBA for the Taurus and 62.25 dBA for the Van) would be comparable to the noise produced by a television (60 dBA), which should be considered acceptable since it is lower than the NAC value (see Table 1.1). The expected increase from the baseline due to CLRS would be approximately 10 dBA, which is acceptable by two of the three FHWA criteria (see Table 1.2).

Conclusions and Future Work

From the analyses performed, it can be concluded that the external noise depends on the speed (the lower the speed, the lower the noise), type of vehicles (heavier vehicles have a tendency to produce more noise), and distance (the greater the distance, the lower the noise).

Both football and rectangular CLRS substantially increase the levels of external noise. Therefore, before installing CLRS, the distance from houses or businesses should be considered. Based on the linear regression analysis using only one light and one medium vehicle, an estimated distance of up to 60 m (200 ft) from the centerline should be considered as the potential problem area. At this distance the expected noise levels would be in the range of 60 dBA, which is comparable to the noise produced by a television set and lower than the noise abatement criteria proposed by the FHWA.

The authors believe that there is a trade-off between the safety impacts of CLRS and the exterior noise created by them. A qualitative study conducted by Makarla (2009), suggested that the roadside residents were willing to accept the levels of noise generated by the CLRS on US-40 in Kansas due to the increase in safety aspects. Future work can be done using semi-trucks and different models of automobiles to collect data. Additional and more comprehensive interviews of roadside residents along sections of CLRS should be conducted to determine their acceptance and/or tolerance for the external noise.

Chapter 5 - OPERATIONAL USE OF THE TRAVEL LANE

According to the Kansas Department of Transportation (KDOT) 2007 Policy on Longitudinal Milled-in Shoulder and Centerline Rumble Strips, "Centerline rumble strips may be used on two-lane, Class B and C, rural highways with asphalt pavement surfaces 3.81 cm (1.5 inches) or more in depth having paved shoulder width of at least 0.91 m (3 feet)". Unfortunately, there is a good number of two-lane rural roadways in Kansas that does not meet the shoulder width requirement, but could potentially benefit from the installation of CLRS. There is no definitive answer for which situations to technically and economically recommend the installation of CLRS. Based on the literature review, no study was performed to evaluate these criteria.

Reducing overall and injury cross-over crashes on rural two-lane, undivided roadways is always an urgent priority with very high payoff. However, the current KDOT shoulder width policy may eliminate hundreds of kilometers of Kansas rural highways from potential life savings treatment. As previously stated, the assumption made in this chapter regarding the lateral position of cars in the travel lane is that the safest position occurs when drivers position the center of their vehicles near the center on the travel lane (not the center of the roadway). A shift in average position to the left, towards the centerline was assumed to increase the risk of cross-over crashes. On the other hand, a shift to the right, toward the edgeline, was assumed to increase the risk of ROR crashes. Shifts in lateral position were assumed to be practically significant if they were greater than 15 cm (6 inches), as described by Finley et al. (2008).

Thus, the objectives of this analysis were to verify how rumble strips influence the operational use of roadways (in terms of vehicular operating speed and lateral position) with different shoulder widths and to provide recommendations of when CLRS should be installed, based on crash data (Chapter 6).

According to Donnell et al. (2009), vehicles' speeds are often set as indicators of two different transportation performance characteristics, mobility and safety. Higher speeds are usually associated with lower travel times, an indication of good mobility. However, the relationship between speed and safety is complex and unclear. The general accepted relationship is that injury levels increase with speed. The physics explanation is that "a vehicle's kinetic energy is proportional to its velocity squared. When a crash occurs, all or part of the kinetic energy is dissipated, primarily through friction and mass deformation. As kinetic energy increases exponentially with speed, so does the potential for mass deformation, including humans that are inside and outside of the vehicle" (Donnell et al. 2009). In this chapter, a minimum practical significance level for difference in speed was assumed as 8 km/h (5 mph), which is the usual value for changes in speed limits.

A comparison of operating speed, vehicles' lateral position, and safety effectiveness between sections with *CLRS only*, with *SRS only*, with combinations of CLRS and SRS, and without any type of rumble strips on roadways and at different shoulder widths and AADTs was performed. The safety relationships (in Chapter 6) were evaluated by analyzing SPF functions developed using crash data of the 29 sections that received installation of CLRS in Kansas, as described in Chapter 3.

Literature Review

From previous studies performed it is possible to conclude that the operational use of the travel lane is changed by the presence of rumble strips. Five studies indicate that CLRS affect the lateral position of vehicles in the travel lane. According to these studies, the vehicles move to the right, i.e. they traveled further from the center line after the installation of CLRS, avoiding the contact with CLRS (Harder et al. 2002; Porter et al. 2004; Hirasawa et al. 2005; Miles et al. 2005; and Räsänen 2005). However, vehicle speed on highway is not affected by CLRS (Porter et al. 2004; Hirasawa et al. 2005; Räsänen 2005; Briese 2006). One study used driver simulator equipment and 40 volunteers to investigate the lateral placement of vehicles when both CLRS and SRS are installed together. Anund et al. (2005) compared two situations of placement of the rumble stripes: a) wider lane (3.5 m or 11.48 ft) and narrow shoulder, and b) narrow lane (3.25 m or 10.66 ft) and wider shoulder, while keeping the roadway width constant at 9.0 m (29.53 ft). The authors concluded that there was no statistically significant difference in number of departures to the left, and that the number of departures to the right was larger in the case of the narrow lane condition.

The previous investigations of the effects of CLRS on the operational use of the travel lane are detailed below.

Simulation Studies

Harder et al. (2002) used a driving simulator to investigate the effects of centerline treatments on vehicular lateral position and speed. The following centerline treatment conditions were studied.

1. The control condition: 3.6 m (12 ft) lanes and 102 mm (4 in) centerline pavement marking (current US standard), without CLRS;
2. Lane width of 4.3 m (14 ft) with centerline pavement dashes of 102 mm (4 in), without CLRS;
3. Lane width of 4.3 m (14 ft) with centerline pavement dashes of 102 mm (4 in), with CLRS;
4. Lane width of 3.6 m (12 ft) with lanes separated by a 1.2 m (4 ft) central buffer area bounded by 102 mm (4 in) pavement marking dashes, without CLRS.
5. Lane width of 3.6 m (12 ft) with lanes separated by a 1.2 m (4 ft) central buffer area bounded by 102 mm (4 in) pavement marking dashes, with CLRS.

6. Lane width of 3.6 m (12 ft) with lanes separated by a 1.2 m (4 ft) central buffer area bounded by 203 mm (8 in) pavement marking dashes, without CLRS.

There were 18 participants. Each of them drove these six test trials and in each trial the participant encountered several different driving situations, including:

- Cruising with no traffic in the opposing lane;
- Cruising with traffic in the opposing lane;
- Following behavior, when the driver had to adjust to the speed of the car that it was following; and
- Attempts to overtake a car in the same travel lane (i.e., passing maneuver).

Harder et al. (2002) found that participants drove significantly further away from the centerline for conditions 2 and 3 when compared to conditions 1, 4, 5, and 6. Drivers' performance on conditions 2 and 3 were not statistically different. In addition, Harder et al. concluded that the use of 3.6 m (12 ft) lanes with the central buffer area caused participants to shift away from the centerline when compared to the use of wider lanes (4.3 m or 14 ft); that the presence of oncoming traffic on the opposing lane caused participants to shift lateral position away from the centerline, as compared to the cruising condition; and that there was no statistical difference between the wider pavement marking dashes as compared to the narrow dashes.

Harder et al. (2002) concluded that the use of centerline treatments would decrease the likelihood of cross-over crashes and supported the implementation of 4.3 m (14 ft) lane with 102 mm (4 in) pavement marking dashes, with CLRS.

Noyce and Elango (2004) used a driving simulator to verify the effects of CLRS on drivers' reaction response. Overall, there was no statistically significant difference in reaction time between treatments, two-lane roads with or without CLRS. However, on curved sections the reaction time to return to the intended travel lane was significantly greater on sections with CLRS as compared to sections without CLRS. Moreover, the researchers found that 20 to 40 percent of drivers wrongly reacted to the left after encountering centerline rumble strips on two-lane roads.

Anund et al. (2005) investigated the effects of SRS and CLRS installed on roadways narrower than nine meters or 29.5 ft, on fatigued drivers using a moving-base driver simulator. Four different patterns of milled-in rumble strips were studied, as follows: Pennsylvania pattern (length = 50 cm or 19 in., width = 30 cm or 11.8 in., depth = 1.2 cm or 0.47 in., and spacing = 30 cm or 11.8 in.); Swedish pattern (length = 50 cm or 19.7 in., width = 30 cm or 11.8 in., depth = 2 cm or 0.79 in., and spacing = 53 cm or 20.9 in.); Malilla pattern (length = 35 cm or 13.8 in., width = 15 cm or 5.9 in., depth = 1 cm or 0.39 in., and spacing = 120 cm or 47.2 in.); and Finish pattern (length = 17.5 cm or 6.9 in., width = 2 cm or 0.79 in., depth = 1.5 cm or 0.59 in., and spacing = 30 cm or 11.8 in.). Two distinct placements (the lane width and shoulder width were altered) were investigated. Placement “A” had lane width of 3.5 m or 11.48 ft and shoulder width of 1.0 m or 3.28 ft. Placement “B” had lane width of 3.25 m or 10.66 ft and shoulder width of 1.25 m or 4.10 ft. In all cases, the roadway width was kept unaltered as 9.0 m or 29.5 ft.

There were 40 regular night shift workers participating in this study. The participants were asked to drive the simulator on morning hours after an entire night shift of work. Data collected consisted of driving behavior (lateral position, speed, and steering angle) and physiological data (brain activity, eye activity, muscle activity, and level of sleepiness measured at every five minutes). The authors concluded that rumble strips help alerting drivers, despite the pattern or placement. Drivers preferred the placement with wider shoulders and the researchers recommended the Pennsylvania or the Swedish patterns of CLRS. There was no statistically significant difference in the number of departures to the left, and the number of departures to the right was higher in the case of the narrower lane.

Auberlet et al. (2009) used two different types of driver simulators, (a fixed-base and a motion-base), as shown in Figure 5.1, to investigate the effects of CLRS on vehicular lateral position on vertical crest curves in France.

The authors used three treatment conditions, as follows:

- Condition 1, the control condition that consisted of crest curves on two-lane road without sealed shoulders and without CLRS;
- Condition 2 that consisted of crest curves on two-lane road without sealed shoulders and with CLRS on both sides of the centerline pavement marking; and
- Condition 3 that consisted of crest curves on two-lane road with sealed shoulders and without CLRS.

Figure 5.1 Two Types of Drivers Simulators used by Auberlet et al. (2009)

a) Fixed-based simulator b) Motion-based simulator

The treatment conditions are shown in Figure 5.2.

Figure 5.2 Treatment Conditions used by Auberlet et al. (2009)

a) Condition 1 b) Condition 2 = CLRS c) Condition 3

Auberlet et al. (2009) considered as the response the lateral position (distance measured from the centerline pavement marking) and collected data on a reference point, on a pre-test hill point, on a test hill point, and on a post-test hill point on crest vertical curves. Data was analyzed as repeated measures design. The authors concluded that when treatments were present, drivers tended to position the vehicle closer to the center of the travel lane. There was no statistical difference between condition two and three. The perceptual treatments tended to smooth the trajectory profiles. In addition, there was a statistically significant difference between the two types of simulators.

Field Test Studies

Porter et al. (2004) conducted a before-after study with comparison sites to investigate the effects of CLRS on vehicular lateral position and speed. Data from a control site and four relatively flat, tangent, two-lane rural highways in Pennsylvania were used for the analysis. The lane widths considered were 3.35 m (11 ft) or 3.66 m (12 ft). A statistically significant difference in the lateral position of vehicles along the treatment sites was found when comparing the periods before the installation of CLRS and after the installation of CLRS. Vehicles shifted 13.97 cm (5.5 inches) away from the reference point on the centerline on roads with 3.66 m (12 ft) lanes and 7.62 cm (3.0 inches) on roads with 3.35 m (11 ft) lanes. The variance in the placement of vehicles was significantly smaller on segments with CLRS. In addition there was no statistically significant relationship between speed and the placement of centerline rumble strips.

Briese (2006) investigated the effects of CLRS on vehicular speed at tangent and curve sites, vehicular lateral position at tangent sites, and centerline encroachments on horizontal curves using a before-and-after methodology in Minnesota. There was no statistically significant effect of CLRS on speed and lateral position. Moreover, CLRS reduced centerline encroachments by 40% - 76%.

Hirasawa et al. (2005) investigated the effects of several centerline treatments on driving behavior in Japan. Data were collected by using a video-camera. Vehicular speed and lateral position were compared along different sections of roads with median strips, center poles, chatter bars, rumble strips, and double-yellow centerlines. Results indicate that CLRS did not impact driving speeds. In addition, Hirasawa et al. (2005) regarded CLRS as being effective in reducing head on collisions because they kept vehicles at a proper distance (not defined by the authors) from the centerline.

Miles et al. (2005) conducted a study to determine the effects of CLRS on driver behavior in Texas. Data was collected though videotape when a test car was driven at 8.0, 16.0, and 24.0 km/h (5, 10, and 15 mph) below the posted speed limit of 113 km/h (70 mph). The results revealed the following:

- There was no effect of CLRS on erratic movements, encroachments on the centerline prior to initiating a passing maneuver, or the number of passes made by a driver.
- After the installation of CLRS, passing drivers initiated their passing maneuvers closer to a vehicle that they were passing.
- Drivers took more time to initiate a passing maneuver after the installation of CLRS.
- After installation of CLRS drivers appeared to wait longer before passing a vehicle traveling at 88 km/h (55 mph).
- Drivers moved the lateral position of vehicles away from the centerline after the installation of CLRS.

Overall, Miles et al. (2005) concluded that none of the changes recorded had a practical significance in driving characteristics and that the changes that were considered do not induce unsafe driving practices.

Räsänen (2005) conducted a before-after observational study to evaluate the changes in lane keeping promoted by installation of CLRS on a horizontal curve section on a rural two-lane undivided highway facility in Finland. Four treatment conditions were studied as follows:

1. Worn-out painted centerline pavement markings;
2. Freshly painted centerline pavement markings without CLRS;
3. Resurfaced and freshly painted centerline pavement markings with CLRS; and
4. One-year after installing CLRS.

The data collected consisted of the number of encroachments, vehicular lateral position, and vehicular speed, considered in both directions of travel for various traffic situations. Results indicated that the number of centerline encroachments along the curve decreased for treatment condition two (centerline pavement markings freshly painted) as compared to the treatment condition one (worn-out painted condition). However, there was no difference between treatment conditions two and three. Therefore, Räsänen claimed that the reason for reduction in centerline encroachments may not be necessarily because of centerline rumble strips, but due to the better visibility promoted by fresh painted pavement markings. In addition, there was no effect of CLRS on speed, but drivers moved closer to the edgeline after the installation of centerline rumble strips on horizontal curves. The author recommended the utilization of CLRS, which would potentially enhance safety by preventing unintentional and intentional centerline encroachments because noise and vibration levels produced by them are expected not to degrade as quickly as the visibility or retroreflectivity of pavement markings.

Finley et al. (2008) studied impact of SRS and CLRS on vehicular lateral position on two-way, undivided highways in Texas. The authors used piezoelectric sensors in a "Z" configuration to collect the distance from the right tire of vehicles to the edgeline. The study locations included sites with CLRS only, SRS only, and both CLRS and SRS, lane widths varying from 3.0 m to 3.66 m (10 – 12 ft), shoulder width varying from 0.3 m (1 ft) to widths greater than 3.0 m (10 ft) and placement of SRS was either on the edgeline, 0 to 30 cm (0 to 12 inches) from the edgeline, or farther than 61 cm (24 inches) from the edgeline.

Results indicated that on roads with only CLRS and with both CLRS and edgeline rumble strips (ERS) and on narrow shoulders (0.3 to 0.91 m or 1 to 3 ft), drivers tended to position the center of their vehicle closer to the center of the travel lane as compared to roads without rumble strips. On the other hand, on roads with shoulder width greater than 2.7 m (9 ft), there were no effects of CLRS nor the combination of CLRS and SRS.

The researchers found that SRS located further from the edgeline (89 cm or 35 inches) did not have any practical effect on the lateral position of vehicles in the travel lane. In addition, it seems that the negative effect of SRS close to the edgeline, causing vehicles to move closer to the centerline, can be mitigated by including CLRS. Finley et al. (2008) assumed it took a minimum shift in lateral position of 15.24 cm (6 inches) to be significant in a practical sense and did not perform any statistical comparisons.

Briand et al. (2010) conducted field test studies using a before-and-after CLRS installation methodology to validate the results of a prior experiment conducted by Auberlet et al. (2009) in which two different types of driver simulators, (a fixed-base and a motion-base) where used to investigate the effects of CLRS on vehicular lateral position on vertical crest curves in France. The authors concluded that the trends observed both on driving simulators and on the real site were similar.

Gross et al. (2009) investigated the effects of varying shoulder widths and lane widths on crash departure effectiveness, while keeping the total pavement width constant. Gross et al. used a matched case-control analysis and data of road segments in Pennsylvania and Washington. Geometric, traffic, and crash data were obtained for the entire population of undivided, two-lane, rural road segments in both states. The primary objective of the study was to determine crash modification factors (CMF) for various lane-shoulder width configurations for total paved widths from 7.92 to 10.97 m (26 to 36 ft). The authors concluded that there were crash reductions as pavement, shoulder and lane widths increase, all else being equal.

Furthermore, Gross et al. (2009) found that the crash modification factor (CMF) for a given shoulder width may not be applicable across various lane widths. For total pavement width between 7.92 m and 9.75 m (26 to 32 ft), a 3.66 m (12 ft) lane was recommended for optimal safety benefit, providing a CMF ranging from 0.94 to 0.97 (3 – 6 percent crash reduction as compared with 3.05 m (10 ft) lanes for a fixed paved width).

For a 10.36 m (34 ft) total roadway paved width, 3.35 m (11 ft) lanes provided a CMF of 0.78, which was the optimal safety benefit as compared to the 3.05 m (10 ft) baseline. For a 10.97 m (36 ft) total roadway paved width, both 3.35 m and 3.66 m (11 ft and 12 ft) lanes provided CMF of 0.95, the optimal safety benefit.

In the case of narrow roadways (7.32 m or 24 ft total roadway width), CMFs increased nonlinearly with increasing traffic volumes, indicating a strong relationship between traffic volume and lane and shoulder configuration. The rate of increase was different for each lane and shoulder configuration. Considering AADTs of less than 1,000 vehicles per day, configurations with shoulders performed better than the baseline (3.66 m (12 ft) lanes and no shoulders). On the other hand, for AADTs greater than 1,000 vehicles per day, configurations with shoulders had higher CMFs than the baseline. Therefore, the researchers concluded that for narrow roadway widths, it is beneficial to provide narrower lanes with wider shoulders at low AADTs (less than 1,000 vehicles per day), and 3.66 m (12 ft) lanes and no shoulders for larger AADTs (greater than 1,000 vehicles per day). The authors claimed that changing lane or shoulder widths results in essentially zero cost because it involves only the location of pavement markings.

Stodard and Donnell (2008) conducted a study to determine if considering speed and lateral vehicle position estimated with ordinary least squares (OLS) models separately is inefficient because the error terms of the two equations may be correlated. The researchers considered the hypothesis that an endogenous relationship may exist between the speed and lateral vehicle position. They collected vehicular speed and lateral vehicle position data during nighttime conditions on a closed circuit consisting of a three-mile section of two-lane highway with a posted speed limit of 40 mph in Pennsylvania. Stodard and Donnell concluded that endogeneity did not exist in the speed and lateral vehicle position measured in the experiment. A single-equation, random effects, panel regression model was better than the ordinary least-squares regression model for the change in speed metric. However, the ordinary least-squares regression model, which considered horizontal curve direction, roadside hazard rating, vertical grade, horizontal curve radius, and approach tangent length, was appropriate for the vehicular lateral position model.

Methodology

The objective of this study was to investigate the effects of various shoulder width / rumble strips configurations on drivers' behavior, measured in terms of vehicular lateral position and speed. Data was collected by using pneumatic "road tubes" sensors connected to a traffic counter. When vehicle tires passes over the pneumatic sensors, the tires press the tube and the air inside the tube is pushed away. One end of the tube is connected to the traffic counter that contains a membrane and an electrical switch. The other end of the tube is essentially closed. The air pressure moves the membrane and engages the switch, providing a time data point. The configuration of the sensors used in this study was similar to "Z" configurations used by Finley et al. (2008). Figures 5.3 - 5.5 show the configuration of sensors used in this study. All sensors had the same total length and same dimension L_{tube}, measured from the reference point which was the outside border of the edgeline.

The lateral position denoted by Y was calculated by applying the following equations, which depended on the vehicle's speed. First,

$$V = \frac{L_1 + L_2}{(T_4 - T_1)} \tag{5.1}$$

where V is the vehicle speed, L_1 is the distance from sensor one and sensor two (diagonal sensor), measured along the reference line; L_2 is the distance from sensor two and sensor three, measured along the reference line; T_1 is the time point collected when the frontal tires pass over sensor one; and T_4 is the time point collected when tires pass over sensor three. Second,

$$D_1 = V * (T_2 - T_1) \tag{5.2}$$

where D_1 is the distance from the sensor one and the point at which the frontal tires passed over sensor two (diagonal sensor). Third,

$$\alpha = \text{arc cosine}\left(\frac{L_2 - L_3}{L_{tube}}\right) \tag{5.3}$$

where alpha is the angle formed by sensor two (diagonal sensor) and the reference line (outside border of the edgeline); L_3 is the distance between the end of sensor two and sensor three; and L_{tube} is a measure of the travel lane width, from the outside border of the edgeline to the center of the pavement width. All sensors had the same dimension L_{tube} per location. Forth and fith,

$$X = D_1 - L_1 \tag{5.4}$$

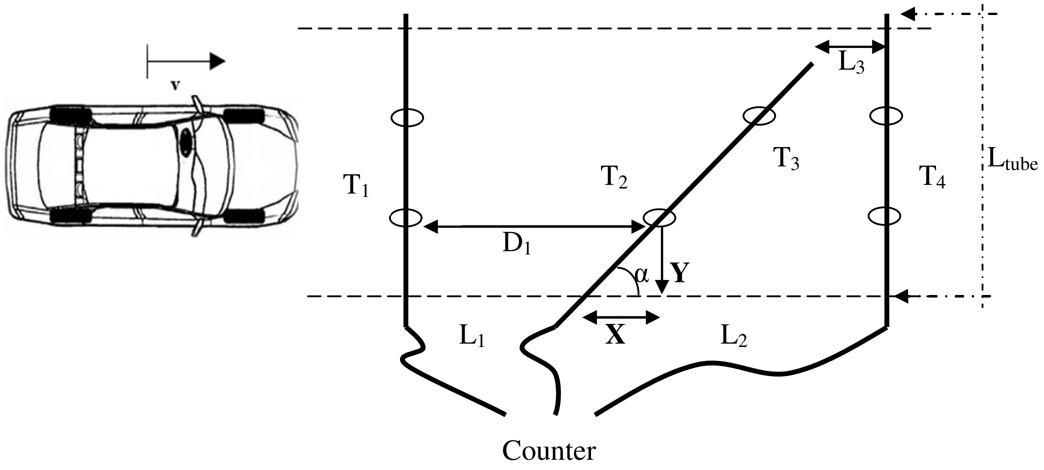
and

$$Y = X * \text{Tangent}(\alpha) \tag{5.5}$$

where Y is a measure of the lateral position from the outside of the edgeline.

The distance between the first sensor and the middle sensor, denoted by L_1 was set to 1.83 m (6 ft) and distance between the middle diagonal sensor and the third sensor, denoted by L_2 was set to 3.048 m (10 ft).

Figure 5.3 Set up of the Sensors in a "Z" Configuration. Modified from Finley et al. (2008)



The Jamar TRAX I Plus traffic counter was used to collect the data. Time stamp points, with a sensitivity of milliseconds were used to provide the times at which vehicles crossed the sensors.

Figure 5.4 Set up of Road Tubes Sensors for Data Collection in section with CLRS

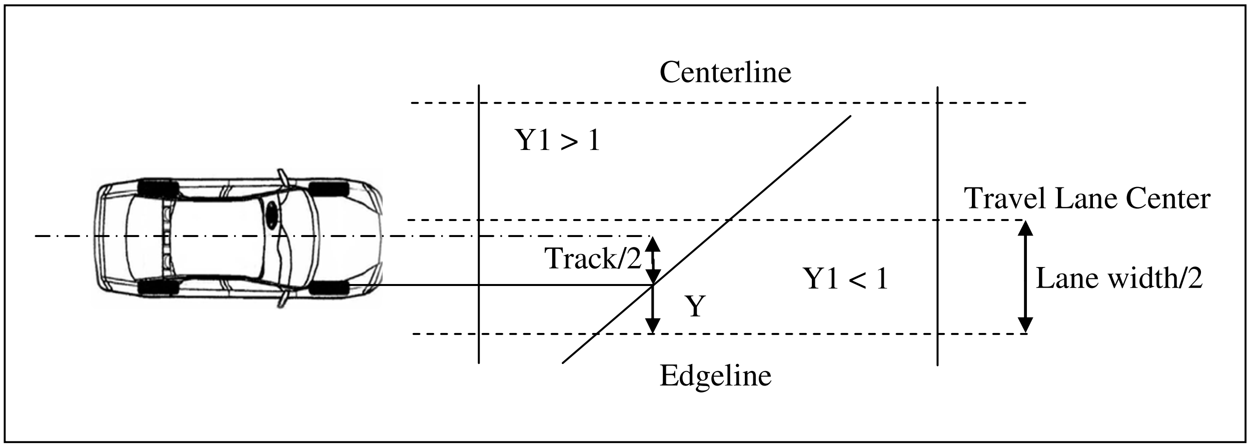
Figure 5.5 "Z" Configuration of Sensors for Data Collection

Lateral position data was coded and the new response denoted by Y_1 expressed a measure of lateral distance from vehicles' center to the center of the travel lane, in order to account for variable lane widths. The data point considered denoted how many percentage points the center of cars (Y + Track/2) were away of the center of the travel lane, and the reference value was the lane width divided by two, as presented by equation 5.6:

$$Y_1 = \frac{Y + Track/2}{Lane\,Width/2} \tag{5.6}$$

Values of the new response Y_1 greater than one indicated a vehicle was traveling closer to the centerline (on left side of the center of the travel lane), while values of Y_1 smaller than one indicated a vehicle was traveling closer to the edgeline (on the right side of the center travel lane center), as shown by Figure 5.6.

Figure 5.6 Diagram for Calculation of Coded Response Y_1



The frontal track value was assumed to be 1.60 m or 63.05 inches, the weighted average of the individual vehicles tracks based on the percentage of national market share for 20 best-selling vehicles in the month of July 2011, as presented in Figure 5.7.

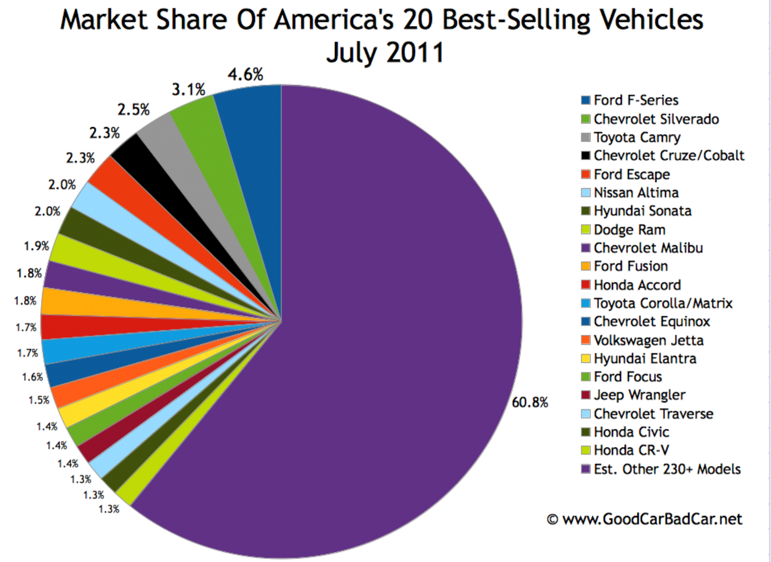
The speed data was coded to express percentage point differences of individual vehicles from the posted speed limit (PSL) of various locations, in order to account for differences in PSL across locations. The coded speed response was denoted as Y_2. Values of Y_2 greater than one indicated that vehicles were traveling at speeds greater than the PSL, while values of Y_2 lower than one indicated that vehicles were traveling below the PSL.

The data was classified by type of vehicle by using the recorded axle configuration, according to the Federal Highway Administration (FHWA) Type F Vehicle Classification Scheme (FHWA website, 2011B). Only vehicles from classes two (passenger cars) and three (pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, carryalls, and minibuses) were considered in this analysis.

Speed and lateral position data were collected during one to four-hour measurements at several locations containing different shoulder width / rumble strip configurations and lane widths (measured from the outside border of the edgeline to the center of the roadway, denoted as L_{tube}) ranging from 3.56 to 3.89 m (11.67 to 12.75 ft). Each vehicle per location was considered as an independent data replication. This study did not account for traffic effects, i.e. the measurements did not consider free flow speeds. One section of highway was selected for each combination of shoulder width / rumble strip configuration and a (one-way) treatment number was assigned to the sections. However, there were cases at which no section was selected (missing levels) due to non-existence of the specific configuration. Table 5.3 shows the matrix of locations where data was collected and the respective treatment numbers. The experiment was conducted on tangent (straight segments) and on flat vertical alignment in all locations.

Figure 5.7 Calculation of the Assumed Frontal Track Dimension

Ranking	Vehicle	Frontal Track Width (m)	Frontal Track Width (in)	Market Share %
1	Ford F-Series	1.7018	67	4.6
2	Chevrolet Silverado	1.72974	68.1	3.1
3	Toyota Camry	1.5748	62	2.5
4	Chevrolet Cruze	1.54178	60.7	2.3
5	Ford Escape	1.54178	60.7	2.3
6	Nissan Altima	1.5494	61	2
7	Hyundai Sonata	1.59766	62.9	2
8	Dodge Ram	1.7272	68	1.9
9	Crevrolet Malibu	1.51384	59.6	1.8
10	Ford Fusion	1.56718	61.7	1.8
11	Honda Accord	1.59004	62.6	1.7
12	Toyota Corolla	1.52908	60.2	1.7
13	Crevrolet Equinox	1.59766	62.9	1.6
14	Volkswagen Jetta	1.54178	60.7	1.5
15	Hyundai Elantra	1.5621	61.5	1.4
16	Ford Focus	1.55448	61.2	1.4
17	Jeep Wrangler	1.57226	61.9	1.4
18	Crevrolet Traverse	1.72212	67.8	1.3
19	Honda Civic	1.4986	59	1.3
20	Honda CR-V	1.56464	61.6	1.3
	Average	1.60	63.05	



Sources: www.edmunds.com and www.goodcarbadcar.com

Table 5.1 Matrix of Locations with Assigned Treatment Number

Shoulder Width Level	Shoulder Width (m ft)	Rumble Strips Configurations			
		CLRS only	SRS only	Both CLRS and SRS	Neither
Narrow	0.6 m or 2 ft	Trt 1	-	-	Trt 2
Medium	1.8 m or 6 ft	Trt 3	Trt 4	-	Trt 5
	2.4 m or 8 ft	Trt 6	Trt 7	Trt 8	Trt 9
Wide	2.7 m or 9 ft	Trt 10	-	Trt 11	Trt 12
	3.0 m or 10 ft	Trt 13	Trt 14	Trt 15	Trt 16

Data was analyzed in an ANOVA framework. The experimental design structure used was a “messy” completely randomized design and the treatment structure was one-way, where the treatment name is given in Table 5.2. Contrasts were built to provide correct statistical tests, which were not possible to achieve by using regular (Type I or Type III Sums of Squares) ANOVA analysis due to the presence of missing levels. In addition to statistical tests, a minimum practical significance shift in lateral position was assumed to be 15.24 cm or 6 inches (based on the value suggested by Finley et al. 2008) and the minimum practical significance change in speed was assumed to be 8 km/h or 5 mph. An approximately 8% deviation in Y_1 would correspond to the 15.24 cm (6 inches) criterion of minimum practical significance value, considering an averaged observed lane width/2 of 1.85 m or 6.06 ft.

Furthermore, the shoulder width main effect was considered as categorical factor with three levels (narrow = 0.6 m or 2 ft; medium = average of 1.8 and 2.4 m or 6 and 8 ft; and wide = average of 2.7 and 3.0 m or 9 and 10 ft). Therefore, the matrix of treatments was reduced to the form shown by Table 5.2.

Table 5.2 Reduced Matrix of Locations with Assigned Treatment Name

Shoulder Width Level	Shoulder Width (m ft)	Rumble Strips Configurations			
		CLRS only	SRS only	Both CLRS and SRS	Neither
Narrow	0.6 m or 2 ft	Trt A	-	-	Trt B
Medium	1.8 m or 6 ft	Trt C	Trt D	Trt E	Trt F
	2.4 m or 8 ft				
Wide	2.7 m or 9 ft	Trt G	Trt H	Trt I	Trt J
	3.0 m or 10 ft				

The following comparisons were made for both lateral position and vehicles’ speed responses:

- Rumble strip main effect comparison of *CLRS only* versus *SRS only*, averaged across common levels of shoulder widths (considered mean of treatments C + G versus the mean of treatments D + H);
- Rumble strip main effect comparison of *CLRS only* versus *both*, averaged across common levels of shoulder widths (considered mean of treatments C + G versus the mean of treatments E + I);
- Rumble strip main effect comparison of *CLRS only* versus *neither* (considered mean of treatments A +C + G versus the mean of treatments B + F + J);
- Rumble strip main effect comparison of *SRS only* versus *both*, averaged across common levels of shoulder widths (considered mean of treatments D + H versus the mean of treatments E + I);
- Rumble strip main effect comparison of *SRS only* versus *neither*, averaged across common levels of shoulder widths (considered mean of treatments D + H versus the mean of treatments F + J);
- Rumble strip main effect comparison of *both* versus *neither*, averaged across common levels of shoulder widths (considered mean of treatments E + I versus the mean of treatments F + J);
- Shoulder width main effect *narrow* versus *medium* shoulders, averaged across common levels of rumble strips (considered mean of treatments A + B versus the mean of treatments C and F);
- Shoulder width main effect *narrow* versus *wide* shoulders, averaged across common levels of rumble strips (considered mean of treatments A + B versus the mean of treatments G and J);
- Shoulder width main effect *medium* versus *wide* shoulders (considered mean of treatments C + D + E + F versus the mean of treatments G + H + I + J);
- All possible interaction contrasts;
- All possible pairwise comparisons between treatments;

In addition, tests of equal variances (Levene's and Bartlett's tests) were performed in order to verify if treatments presented different variances because the ANOVA analysis assumes equal variance across treatments. However, the Mixed procedure in SAS accounts for differences in variances by using the Repeated / Group statement. In the analysis performed to test the hypothesis of equal means, the treatments were divided by variance groups by the use of the repeated statement where the group factor was the treatment factor.

A further verification of how the shoulder width affects the lateral position was conducted by treating the shoulder width as a numeric variable, in a second step of this analysis. Regression models were built for each level of rumble strip treatment. The dependent variable was the lateral position. The developed models were used to predict a value of shoulder width that would set the response to a value equals to 1.0 (corresponding to the center of the travel lane) or to a safe zone range in the center of the travel lane.

A shoulder width and AADT criteria for installation of CLRS was then determined in Chapter 6, by analyzing constructed SPFs regression models (assuming that crashes follow the negative binomial distribution) using data from the 29 sections that received CLRS in Kansas (as described in Chapter 3). Crashes that occurred in the period after the installation of CLRS were used to fit models for rumble strips configurations *CLRS only* and *both*, based on AADT, shoulder width, and rumble strip configurations. Crashes that occurred in the period before the installation of CLRS were used to fit models for rumble strips configurations *SRS only* and *neither*, based on the same predictors as for the *CLRS only* and *both* configurations. The total correctable crashes, cross-over crashes, run-of-the road crashes, and crashes involving fatalities and injuries were considered as responses, as previously described in Chapter 3. In addition to these types of crashes, other two types were considered, i.e. total correctable crashes that happened during daylight conditions, denoted by *Day* and total correctable crashes that happened during nighttime conditions, without the presence of streetlights, denoted by *Night*.

Results and Discussion

Table 5.3 presents some characteristics of the locations and the mean and standard error values of the two coded responses that represent drivers' behavior (Y_1 for lateral position and Y_2 for speed).

Table 5.3 Mean and Standard Error of Y_1 and Y_2 and Characteristics of all Treatments

Treatment	Configuration	Lane width - LW (meters)	Number of Observations	Posted Speed Limit - PSL (km/h)	Lateral Pos Y_1		Speed Y_2	
					Mean	Std Error	Mean	Std Error
1	CLRS only, SW = 0.6 m (2ft)	3.56	131	88.5	1.1135	0.01985	0.9824	0.007279
2	Neither, SW = 0.6 m (2ft)	3.61	102	96.6	1.0715	0.01855	0.9954	0.008083
3	CLRS only, SW = 1.8 m (6 ft)	3.82	77	104.6	1.0982	0.02245	1.0904	0.008308
4	SRS only, SW = 1.8 m (6ft)	3.70	105	104.6	0.8574	0.0181	0.9784	0.00829
5	Neither, SW = 1.8 m (6 ft)	3.71	40	88.5	1.0904	0.02703	1.1789	0.01636
6	CLRS only, SW = 2.4 m (8 ft)	3.56	58	104.6	1.1082	0.0302	0.9706	0.01192
7	SRS only, SW = 2.4 m (8 ft)	3.68	140	104.6	0.8874	0.01734	1.0268	0.006746
8	Both, SW = 2.4 m (8 ft)	3.87	102	104.6	0.9007	0.01746	1.0124	0.008707
9	Neither, SW = 2.4 m (8 ft)	3.62	72	104.6	1.1865	0.02053	0.9645	0.01013
10	CLRS only, SW = 2.7 m (9 ft)	3.67	29	104.6	1.1293	0.03707	1.0348	0.01196
11	Both, SW = 2.7 m (9 ft)	3.75	142	104.6	0.914	0.01423	1.0229	0.005705
12	Neither, SW = 2.7 m (9 ft)	3.72	160	104.6	0.8634	0.01398	0.9771	0.006073
13	CLRS only, SW = 3.0 m (10 ft)	3.73	102	88.5	0.984	0.02646	1.0871	0.0124
14	SRS only, SW = 3.0 m (10 ft)	3.63	100	104.6	0.9926	0.02499	1.0082	0.006053
15	Both only, SW = 3.0 m (10 ft)	3.67	58	104.6	0.9242	0.02798	0.9893	0.008787
16	Neither, SW = 3.0 m (10 ft)	3.82	51	104.6	1.0141	0.03274	0.9893	0.01382

The analysis of the lateral position and speed results described in Table 5.3 can be done in the following manner. On roads with narrow shoulders and CLRS only (treatment 1), drivers tended to travel 11.35% of lane width/2 closer to the centerline (toward the left side of the travel lane center), which corresponds to a shift of 20.20 cm or 7.95 inches to the left, at speeds 1.76 percentage points (1.55 km/h or 2.5 mph) over the PSL. This shift in lateral position would be practically significant according to the minimum 15.24 cm or 6 inches criterion proposed by Finley et al. (2008), but the change in speed would not be practically significant. The shift in position to the left is perhaps explained by the stronger influence of narrow shoulders over the presence of CLRS. Drivers may had the tendency to correct the mean position to the left to avoid running-off-the-road (due to the presence of narrow shoulders) and in this case the presence of CLRS would be beneficial to provide them with a warning to avoid cross-over departures. The perception that narrow roads are risky is perhaps validated by the results of treatment 2. Drivers on this location (with narrow shoulders and without any rumble strips) had the tendency to travel 7.15 percentage points of Y_1 to the left (equivalent to a shift of 25.81 cm or 10.16 inches), perhaps to avoid the risk of running-off-the-road caused by the presence of narrow shoulders, at mean speeds very similar to the PSL.

Table 5.4 shows the results, considering the reduced matrix of treatments.

Table 5.4 Mean and Standard Errors, Considering the Reduced Matrix of Treatments

Treatment	Configuration SW / RS	Mean Y1	St. Error Y1	Mean Y2	St. Error Y2
A	Narrow / CLRS only	1.1140	0.02000	0.9816	0.007297
B	Narrow / Neither	1.0713	0.01837	0.9962	0.008044
C	Medium / CLRS only	1.1025	0.01816	1.0389	0.008634
D	Medium / SRS only	0.8746	0.01259	1.0061	0.005451
E	Medium / Both	0.9007	0.01746	1.0124	0.008707
F	Medium / Neither	1.1522	0.01685	1.0411	0.01307
G	Wide / CLRS only	1.0161	0.02274	1.0755	0.01017
H	Wide / SRS only	0.9926	0.02499	1.0082	0.006053
I	Wide / Both	0.9170	0.01292	1.0131	0.004894
J	Wide / Neither	0.8998	0.01392	0.9801	0.005683

From the results presented in Table 5.4, at narrow shoulder levels drivers tended to travel closer to the centerline (regardless of the presence of CLRS), perhaps to avoid the risk of running-off-the road, as previously stated. On roadways with medium shoulder widths, drivers tended to drive closer to the centerline if SRS were not present and closer to the edgeline if SRS were present. This behavior may reflect some level of trust in SRS in preventing run-off-the-road. On roadways with wide shoulders, drivers tended to travel closer to the centerline if CLRS were present and closer to the edgeline otherwise. With wider shoulders, drivers tended to shift to the right perhaps because of an increased perception of safety (due to increased perception of available width). Drivers may prefer to avoid the contact with vehicles in the opposite direction by shifting to the right. When CLRS are present, this tendency may be reduced due to the increased perception of safety created by the presence of CLRS as a mechanism of defense against cross-over crashes, so drivers choose to travel closer to the centerline. Another potential explanation for this result is that drivers have a tendency to initiate passing maneuvers closer to other vehicles when CLRS are present (Miles et al. 2005). Thus, drivers may drive closer to the centerline in order to pursue a better sight for passing other vehicles (since locations were usually chosen in passing areas).

ANOVA Analysis for Coded Response Y_1 – Lateral Position

Tables 5.5 and 5.6 show the results of the Levene's and Bartllet's tests of equal variances for the lateral position coded response Y_1.

Table 5.5 Levene's Test for Homogeneity of Y_1 Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
TRT	9	0.8093	0.0899	6.11	<.0001
Error	1459	21.4571	0.0147		

Table 5.6 Bartlett's Test for Homogeneity of Y_1 Variance

Source	DF	Chi-Square	Pr > ChiSq
TRT	9	44.7719	<.0001

Since both tests presented P-values lower than 0.0001, the hypothesis of equal variances across the treatments should be rejected. Thus, the ANOVA analysis was performed to account for this covariance structure. Table 5.7 summarizes the results of the estimate statements of the rumble strip main effect comparisons for the ANOVA analysis of the lateral position coded response Y_1.

The first step on the ANOVA analysis was the test for interaction effects. A contrast considering all possible interaction comparisons simultaneously was built and the result indicated that there is a statistically significant interaction between shoulder width and rumble strip configurations (P-value < 0.0001). Table 5.7 shows the sources of interactions.

Table 5.7 Interaction Comparisons in terms of Y_1

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
interaction (+A -B -C +F)	0.04619	0.01838	469	2.51	0.0123
interaction (+A -B -G +J)	-0.03682	0.01903	457	-1.94	0.0536
interaction (+C -F -G +J)	-0.08301	0.01820	465	-4.56	<.0001
interaction (+C -D -G +H)	0.1022	0.02019	384	5.06	<.0001
interaction (+C -E -G +I)	0.05131	0.01816	443	2.83	0.0049
interaction (+D -E -H +I)	-0.05088	0.01771	309	-2.87	0.0044
interaction (+D -F -H +J)	-0.1852	0.01775	321	-10.43	<.0001
interaction (+E -F -I +J)	-0.1343	0.01541	459	-8.72	<.0001

The statistically significant interaction indicates that the lateral position across rumble strip configurations depends on the level of shoulder width analyzed and vice-versa.

Then, the rumble strip main effect was tested according to the comparisons shown in Table 5.8. A contrast was built using all comparisons shown in Table 5.8 simultaneously, in order to verify whether the main effect *Rumble Strips* was statistically significant or not. The contrast had a P-value smaller than 0.0001, revealing the statistical significance of the main effect *Rumble Strips*.

Table 5.8 Rumble Strips Main Effect Overall Comparisons in terms of Y_1

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
CLRS only vs. *SRS only* averaged over Medium and Wide	0.1257	0.02019	384	6.23	<.0001
CLRS only vs. *Both* averaged over Medium and Wide	0.1505	0.01816	443	8.29	<.0001
CLRS only vs. *Neither*	0.03639	0.01512	694	2.41	0.0164
SRS only vs. *Both* averaged over Medium and Wide	0.02476	0.01771	309	1.40	0.1631
SRS only vs. *Neither* averaged over Medium and Wide	-0.09240	0.01775	321	-5.20	<.0001
Both vs. *Neither* averaged over Medium and Wide	-0.1172	0.01541	459	-7.60	<.0001

From Table 5.8 and by using the mean values of Y_1 given in Table 5.4, it is possible to draw the following conclusions:

- On roads with *CLRS only*, drivers tend to travel 7.75 percentage points of LW/2 further left of the center of the travel lane, i.e. closer to the centerline (a shift of approximately 14.14 cm, or 5.57 in), which is not practically significant, using the 15.24 cm (6 inches) minimum practical value criterion used by Finley et al. (2008).
- On roads with *SRS only*, drivers tend to travel 6.64 percentage points closer to the edgeline, resulting in an average shift to the right of approximately 12.15 cm or 4.78 inches, measured from the center of the travel lane, which is not practically significant.
- On roads with *both* CLRS and SRS, drivers tend to drive 9.12 percentage points closer to the edgeline, resulting in an average shift to the right of approximately 17.30 cm = 6.81 inches, measured from the center of the travel lane, which is practically significant.
- On roads with *neither*, drivers tend to stay 4.11 percentage points closer to the center of the centerline, drifting only 7.56 cm, or 2.98 inches to the left, measured from the center of the travel lane, which is not practically significant.
- The difference between *CLRS only* and *SRS only* was 12.57 percentage points (correspondent to 22.97 cm or 9.04 in.). It is statistically significant (P-value < 0.0001) and practically significant, using the 15.24 cm (6 inches) minimum practical value criterion used by Finley et al. (2008).
- The difference between *CLRS only* and *both* was 15.05 percentage points (correspondent to 28.00 cm or 11.02in.). It is statistically significant (P-value < 0.0001) and practically significant.
- The difference between *CLRS only* and *neither* was 3.64 percentage points (equivalent to 6.68 cm or 2.63 in.). It is statistically significant (P-value = 0.0164), but not practically significant.
- There was no statistically significant difference between roads with *SRS only* and roads with *both* CLRS and SRS (P-value = 0.1631).
- The difference between roads with *SRS only* and *neither* was 9.24 percentage points (equivalent to a distance of 16.96 cm or 6.68 in). It is statistically significant (P-value < 0.0001) and practically significant.

- The difference between roads with *both* and *neither* was 11.72 percentage points (equivalent to a distance of 21.90 cm or 8.62 in). It is statistically significant (P-value < 0.0001) and practically significant.

Table 5.9 summarizes the results of the comparisons made to test the shoulder width main effect, where the tested levels were averaged across common levels of rumble strips.

Table 5.9 Shoulder Width Main Effect Comparisons across Common Levels in terms of Y_1

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
SW: Narrow vs. Medium averaged over CLRS only and Neither	-0.03465	0.01838	469	-1.89	0.0600
SW: Narrow vs. Wide averaged over CLRS only and Neither	0.1347	0.01903	457	7.08	<.0001
SW: Medium vs. Wide	0.05109	0.01270	750	4.02	<.0001

A contrast was built considering overall comparisons of the shoulder width main effect simultaneously. It resulted in a P-value smaller than 0.0001, revealing that the main effect shoulder width was statistically significant, in terms of Y_1.

From Table 5.9 it is possible to draw the following conclusions:

- There are statistically significant differences between the narrow shoulder levels (0.6 m or 2 ft) and the medium shoulder levels (1.8 and 2.4 m or 6 and 8 ft), between the narrow and the wide levels (2.7 and 3.0 m or 9 and 10 ft) and between the medium and the wide shoulder level.
- On roads with narrow shoulder widths (considering only the CLRS and neither rumble strip configurations) drivers tended to travel 9.27 percentage points (shift of approximately 16.59 cm or 6.53 in.) away to the left of the travel lane center (closer to the centerline).
- On roads with medium shoulders (considering all configurations of rumble strips), drivers tended to travel 0.75 percentage points (shift of approximately 1.40 cm or 0.55 in.) away to the left of the travel lane center.
- On roads with wide shoulder (considering all configurations of rumble strips), drivers tended to travel 4.36 percentage points (shift of approximately 8.08 cm or 3.18 in.) away to the right of the travel lane center (closer to the edgeline).

These results indicate that on roadways with narrow shoulders drivers may prefer to avoid the risk of ROR departures, on roads with medium shoulders drivers place the vehicles near the center of the travel lane, and on roadways with wide shoulders drivers may prefer to avoid cross-over departures.

ANOVA Analysis for Coded Response Y_2 – Operating Speeds

Tables 5.10 and 5.11 show the results of the Levene's and Bartllet's tests of equal variances for speed coded response Y_2.

Table 5.10 Levene's Test for Homogeneity of Y_2 Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
TRT	9	0.4819	0.0535	14.95	<.0001
Error	1459	5.2247	0.00358		

Table 5.11 Bartlett's Test for Homogeneity of Y_2 Variance

Source	DF	Chi-Square	Pr > ChiSq
TRT	9	134.2	<.0001

Since both tests presented P-values smaller than 0.0001, the hypothesis of equal variances across the treatments in terms of Y_2 should also be rejected. Thus, as it was done for Y_1, the ANOVA analysis for Y_2 was performed to account for this covariance structure.

The first step on the ANOVA analysis was the test for interaction effects in terms of the speed coded response Y_2. A contrast considering all possible interaction comparisons simultaneously was built and the result indicated that there is a statistically significant interaction between shoulder width and rumble strip configurations (P-value < 0.0001) in terms of speed. Table 5.12 shows the sources of interactions.

Table 5.12 Interaction Comparisons in terms of Y_2

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
interaction (+A -B -C +F)	-0.00619	0.009531	359	-0.65	0.5164
interaction (+A -B -G +J)	-0.05498	0.007963	428	-6.90	<.0001
interaction (+C -F -G +J)	-0.04879	0.009760	371	-5.00	<.0001
interaction (+C -D -G +H)	-0.01723	0.007815	424	-2.20	0.0280
interaction (+C -E -G +I)	-0.01790	0.008332	420	-2.15	0.0322
interaction (+D -E -H +I)	-0.00067	0.006444	359	-0.10	0.9167
interaction (+D -F -H +J)	-0.03156	0.008208	255	-3.85	0.0002
interaction (+E -F -I +J)	-0.03089	0.008702	280	-3.55	0.0005

The statistically significant interaction indicates that the lateral position across rumble strip configurations depends on the level of shoulder width analyzed and vice-versa.

Then, the rumble strip main effect was tested according to the comparisons shown in Table 5.13 and the shoulder width main effect was tested according to comparisons presented in Table 5.14. A contrast was built using all comparisons shown in Table 5.13 simultaneously, in order to verify whether the main effect *Rumble Strips* was statistically significant or not. The contrast had a P-value equals to 0.8024, revealing the non-statistical significance of the main effect *Rumble Strips*. In the same way, a contrast was built considering all comparisons of the shoulder width main effect simultaneously. It resulted in a P-value equals to 0.3595, revealing that the main effect shoulder width was not statistically significant, in terms of Y_2. Because the interaction effect was significant and the main effects were not so, the interpretation of comparisons of one effect was done per level of the other effect.

Table 5.13 Rumble Strips Main Effect Overall Comparisons in terms of Y_2

Label	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
CLRS only vs. *SRS only* averaged over Medium and Wide	0.05008	0.007815	424	6.41	<.0001
CLRS only vs. *Both* averaged over Medium and Wide	0.04447	0.008332	420	5.34	<.0001
CLRS only vs. *Neither*	0.02623	0.007439	548	3.53	0.0005
SRS only vs. *Both* averaged over Medium and Wide	-0.00561	0.006444	359	-0.87	0.3847
SRS only vs. *Neither* averaged over Medium and Wide	-0.00343	0.008208	255	-0.42	0.6764
Both vs. *Neither* averaged over Medium and Wide	0.002180	0.008702	280	0.25	0.8024

From Table 5.13 and by using the mean values of Y_2 given in Table 5.4, it is possible to draw the following conclusions:

- The average PSL observed was 100 km/h or 62.5 mph;
- *CLRS only* was statistically greater than *SRS only*, *both* and *neither*, that were not statistically different from each other in terms of speed.
- On roads with *CLRS only* drivers tended to travel 3.3 percentage points over the PSL (3.07 km/h or 1.92 mph), which is not practically significant, assuming the minimum practical significance value of 8km/h or 5mph;
- On roads with *SRS only*, drivers tended to travel 0.72 percentage points over the PSL (0.74 km/h or 0.46 mph);
- On roads with *both* CLRS and SRS drivers tended to travel 1.28 percentage points over the PSL (1.32 km/h or 0.83 mph);
- On roads with *neither*, and considering all observed rumble strips configurations for this case, drivers tend to travel 0.06 percentage points over the PSL (0.57 km/h or 0.36 mph);

Table 5.14 Shoulder Width Main Effect Comparisons across Common Levels in terms of Y_2

Label	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
SW: Narrow vs. Medium averaged over CLRS only and Neither	-0.05108	0.009531	359	-5.36	<.0001
SW: Narrow vs. Wide averaged over CLRS only and Neither	-0.03889	0.007963	428	-4.88	<.0001
SW: Medium vs. Wide	0.005363	0.005848	639	0.92	0.3595

From Table 5.14, narrow shoulders had statistically lower speeds than medium and wide shoulders, which were not statistically different from each other.

From the analysis of the speed coded response Y_2, it is possible to conclude that rumble strip configurations and shoulder width levels had statistical effects on the response, but the difference between levels in all cases was not practically significant, assuming a 8km/h (5mph) minimum criterion for practical significance, which is used as the minimum value adopted by Departments of Transportation for changes in PSL.

Regression Analysis for Coded Response Y_1 – Lateral Position

Regression models for the dependent variable Y_1 were constructed considering as predictors the rumble strip configuration (denoted by *RS*), the shoulder width in meters, expressed as a numerical variable (denoted by *SW_m*), and the interaction between these two terms (in order to verify if there were different shoulder width slope terms for each rumble strip configuration). The mixed procedure in SAS with the option solution was used to provide the results. Table 5.18 summarizes the results of this analysis.

Table 5.15 Predictor Estimates for Regression Models

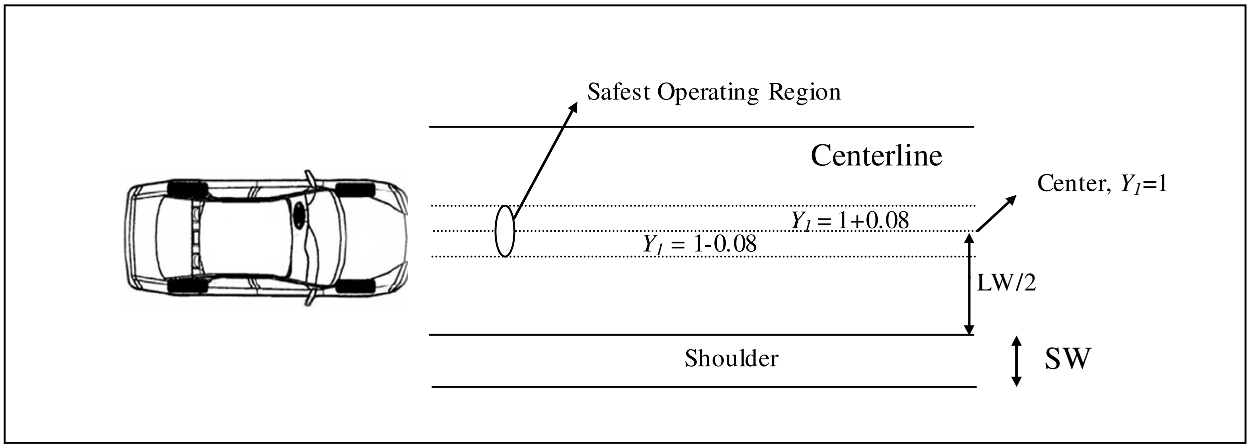
Effect	RS	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.6409	0.06047	1461	10.60	<.0001
RS	Both	0.1645	0.1644	1461	1.00	0.3170
RS	CLRS only	0.5093	0.06473	1461	7.87	<.0001
RS	Neither	0.4934	0.06598	1461	7.48	<.0001
RS	SRS only	0	.	.	.	.
SW_m		0.1120	0.02483	1461	4.51	<.0001
SW_m*RS	Both	-0.07211	0.06250	1461	-1.15	0.2488
SW_m*RS	CLRS only	-0.1509	0.02714	1461	-5.56	<.0001
SW_m*RS	Neither	-0.1725	0.02740	1461	-6.29	<.0001
SW_m*RS	SRS only	0	.	.	.	.

By using the parameter estimates given in Table 5.17, the following equations were developed to predict the coded lateral position Y_1 (the closer to one, the closer to the center of the travel lane, which was assumed to be the safest situation).

- For roadways with CLRS only: $Y_1 = 1.1502 - 0.0389 * SW\_m$;
- For roadways with SRS only: $Y_1 = 0.6409 + 0.112 * SW\_m$;
- For roadways with both CLRS and SRS: $Y_1 = 0.8054 + 0.03989 * SW\_m$; and
- For roadways with neither: $Y_1 = 1.1343 - 0.0605 * SW\_m$;

The equations above were used to predict the minimum shoulder width that would result in vehicles operating in an assumed safe operation region, located on the center of the travel lane ± approximately 8% of travel lane/2 ($Y_1 = 1 \pm 0.08$). The 8% deviation is reasonably equivalent to 15.24 cm or 6 in., the practical significance criterion proposed by Finley et al. (2008). It was not exactly 8% since each rumble strip configuration had a different average lane width /2. This region was considered to be the safest operation region and it is shown in Figure 5.5.

Figure 5.8 Assumed Safest Operating Region



For roadways with *CLRS only*, the shoulder width that would result in predicted Y_1 equals to one is 3.86 m or 12.66 ft (outside the observed shoulder width range), and the predicted minimum value of shoulder width for vehicles to operate in the assumed safest region would be 1.72 m or 5.64 ft.

For roadways with *SRS only*, the shoulder width that would result in predicted Y_1 equals to one is 3.20 m or 10.50 ft (outside the observed shoulder width range), and the predicted minimum value of shoulder width for vehicles to operate in the assumed safest region would be 2.47 m or 8.10 ft.

For roadways with *both* CLRS and SRS, the shoulder width that would result in predicted Y_1 equals to one is 4.88 m or 16.10 ft (outside the observed shoulder width range), and the predicted minimum value of shoulder width for vehicles to operate in the assumed safest region would be 2.79 m or 9.15 ft.

For roadways with *neither* type of rumble strips, the shoulder width that would result in predicted Y_1 equals to one is 2.22 m or 7.28 ft, and the predicted minimum value of shoulder width for vehicles to operate in the assumed safest region would be 0.85 m or 2.79 ft.

It is very important to notice that due to missing levels, the range of observations of shoulder widths was different across rumble strip configurations. The missing levels were more frequent in the narrow category of shoulder widths, which could somehow skew the predicted minimum shoulder widths to a wider value. The range of observed shoulder width for the *CLRS only* and *neither* cases was between 0.6 and 3.0 m (2 and 10 ft). For *both*, the range of observed shoulder widths was between 2.4 and 3.0 m (8 and 10 ft). Finally, the range of observed shoulder widths for *SRS only* was between 1.8 and 3.0 m (6 and 10 ft).

Conclusions

This chapter had the objective of analyzing how rumble strip configurations affect drivers' behavior (measured in terms of lateral position and speed) at several different shoulder width configurations. Vehicular lateral position and operating speed data were collected using pneumatic road tubes in a "Z" configuration. One location per rumble strip / shoulder width combination was selected and a treatment number was assigned to the combinations, but there were several missing treatment levels. Data was statistically analyzed as one-way treatment structure in CRD. The results showed that rumble strips and shoulder width levels have statistically significant effects on vehicular lateral position and speed levels. The interaction between shoulder width and rumble strip configurations was significant in both analyses, indicating that differences across levels of main effects depend on the level of the other analyzed effect. For all analyzed cases, the effects on the speed may be considered not practically significant.

On roadways with narrow shoulders, for both *CLRS only* and *neither*, drivers tended to travel closer to the centerline, which may be attributed to the greater effect of shoulder width over rumble strip configurations. Drivers may prefer to avoid the risk of running-off-the-road in these conditions. The presence of *both* SRS and CLRS at narrow shoulder levels was not observed in this study, but research conducted in Texas concluded that in these conditions, drivers tended to stay closer to the center of the travel lane (Finley et al. 2008).

On roadways with medium shoulder widths, drivers tended to drive closer to the centerline if SRS were not present and closer to the edgeline if SRS were present. This behavior may reflect some level of trust in SRS in preventing run-off-the-road departures.

On roadways with wide shoulders, drivers tended to travel closer to the centerline if CLRS were present and closer to the edgeline otherwise. Drivers tended to shift to the right perhaps because of an increased perception of safety (due to increased perception of available width) with wider shoulders. When CLRS are present, this tendency may be reduced due to the increased perception of safety created by the presence of CLRS as a mechanism of defense against cross-over departures, so drivers choose to travel closer to the centerline. Another potential explanation for this result is that drivers have a tendency to initiate passing maneuvers closer to other vehicles when CLRS are present (Miles et al. 2005). Thus, drivers may drive closer to the centerline in order to pursue a better sight for passing other vehicles (locations observed in this study were usually chosen in passing areas).

An analysis of regression was developed to predict shoulder width levels that would result in vehicles operating in an assumed safe zone located in the center of the travel lane. Different minimum values for shoulder widths were identified, depending on the rumble strip configuration analyzed. The results of this study do not reflect the trends found in the revised literature, perhaps due to differences in methodologies. This study compared the drivers' behavior on several different highway sections, and the majority of the previously conducted studies used a before-and-after methodology.

Chapter 6 - Recommendations and General Conclusions

The objectives of this chapter were to discuss when it is technically and economically beneficial to install rumble strips, by analyzing safety performance functions (SPFs) developed using crash data of highway sections with several shoulder width / rumble strips configurations in Kansas and to provide general conclusions of all the analyses performed. For all SPF models developed in this chapter, the backwards fitting method was used with a level of significance criterion of 0.10, the length of the section in km was used as an offset, and the responses (different types of crashes per km per year) were assumed to be negative binomially distributed. For the rumble strip conditions *SRS only* and *neither*, data from the before period of all 29 sections was used (as explained in Chapter 3). For developing equations for *CLRS only* and *both* conditions, data from the after period of all 29 sections (as explained in Chapter 3) that had received CLRS in Kansas was used.

Table 6.1 summarizes the parameter estimates for all rumble strip configurations.

Table 6.1 Parameter Estimates of SPF models

Parameter		Total Correctable	Day	Night	Cross-over	ROR	Injury FI
Intercept		-1.0399	-2.1382	-2.2437	-4.9226	-0.8728	-1.6718
SW_m		-0.6869	-0.5217	-0.7411	0	-0.8142	-0.7502
RS Config	CLRS only	-1.2154	-1.0756	-0.5478	-1.6713	-0.1565	-1.8071
RS Config	Both	0.5181	0.3912	1.1179	-0.7492	-0.6114	0.633
RS Config	SRS only	-2.1903	0.1091	0.0374	-0.1045	-0.287	-4.3131
RS Config	Neither	0	0	0	0	0	0
AADT		0.0004	0.0004	0.0004	0.0004	0.0003	0.0003
SW_m*RS Config	CLRS only	0.1138	0	0	0	0	0.2746
SW_m*RS Config	Both	0.0023	0	0	0	0	-0.0506
SW_m*RS Config	SRS only	0.7243	0	0	0	0	1.336
SW_m*RS Config	Neither	0	0	0	0	0	0
AADT*RS Config	CLRS only	0.0002	0.0003	0	0	0	0.0003
AADT*RS Config	Both	-0.0002	-0.0002	-0.0003	0	0	-0.0002
AADT*RS Config	SRS only	0	0	-0.0001	0	0	0.0001
AADT*RS Config	Neither	0	0	0	0	0	0
Dispersion Parameter		0.219	0.2498	0.4818	0.2144	0.4284	0.1032

The model equation terms derived from results expressed in Table 6.1 are shown in Table 6.2.

Table 6.2 SPFs - Equations to Predict the Number of Crashes per km per Year

RS Config	Parameter	Total Correctable	Day	Night	Cross-over	ROR	Injury FI
CLRS only	Intercept	-2.2553	-3.2138	-2.7915	-6.5939	-1.0293	-3.4789
	SW_m	-0.5731	-0.5217	-0.7411	0	-0.8142	-0.4756
	AADT	0.0006	0.0007	0.0004	0.0004	0.0003	0.0006
Both	Intercept	-0.5218	-1.747	-1.1258	-5.6718	-1.4842	-1.0388
	SW_m	-0.6846	-0.5217	-0.7411	0	-0.8142	-0.8008
	AADT	0.0002	0.0002	0.0001	0.0004	0.0003	0.0001
SRS only	Intercept	-3.2302	-2.0291	-2.2063	-5.0271	-1.1598	-5.9849
	SW_m	0.0374	-0.5217	-0.7411	0	-0.8142	0.5858
	AADT	0.0004	0.0004	0.0003	0.0004	0.0003	0.0004
Neither	Intercept	-1.0399	-2.1382	-2.2437	-4.9226	-0.8728	-1.6718
	SW_m	-0.6869	-0.5217	-0.7411	0	-0.8142	-0.7502
	AADT	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003

The developed models have an exponential form. For example, the model for Total Correctable crashes and *CLRS only* is: Total Crashes per km per year = exp (-2.2553 - 0.5731 * SW_m + 0.0006 * AADT). By analyzing the results of the SPF models developed, it is possible to conclude that AADT and shoulder width affect the number of all types of crashes (except for cross-over crashes where shoulder width has no effect). In general, increasing the shoulder width would decrease the number of crashes per km per year (with few exceptions) and increasing the AADT would increase the number of crashes per km per year.

The effects of the several configurations of rumble strips on the total correctable crashes are given as follows.

- For *CLRS only*, the predicted total correctable number of crashes per mile per year is very small for small AADTs (less than 1,000 vehicles per day). At this level of AADTs, the shoulder width does not have much impact in the predicted number of total correctable crashes, which provides evidences that CLRS may be applied in roadways with narrow shoulders, depending on the expected traffic volume. As the traffic volume (AADT) increases, the predicted number of total crashes increases considerably, and the effect of shoulder width is also magnified, with the narrowest shoulder conditions being the worst cases, as shown in Figure 6.1.
- For roadways with *SRS only*, the influence of the shoulder width is not as so evident as in the case of *CLRS only*. As the shoulder width increases, the predicted number of crashes per year increases as shown in Figure 6.2, revealing that SRS may be more beneficial for roadways with narrow shoulder widths. This not expected result is perhaps explained by the low number of sections with this condition used to fit the model. Another possible interpretation is that in general, greater shoulder levels are usually installed on highways with greater PSL and greater AADTs, a combination which may result in greater number of crashes not necessarily because of the shoulder width.

Figure 6.1 Predicted number of Total Crashes per Year for the CLRS only Configuration

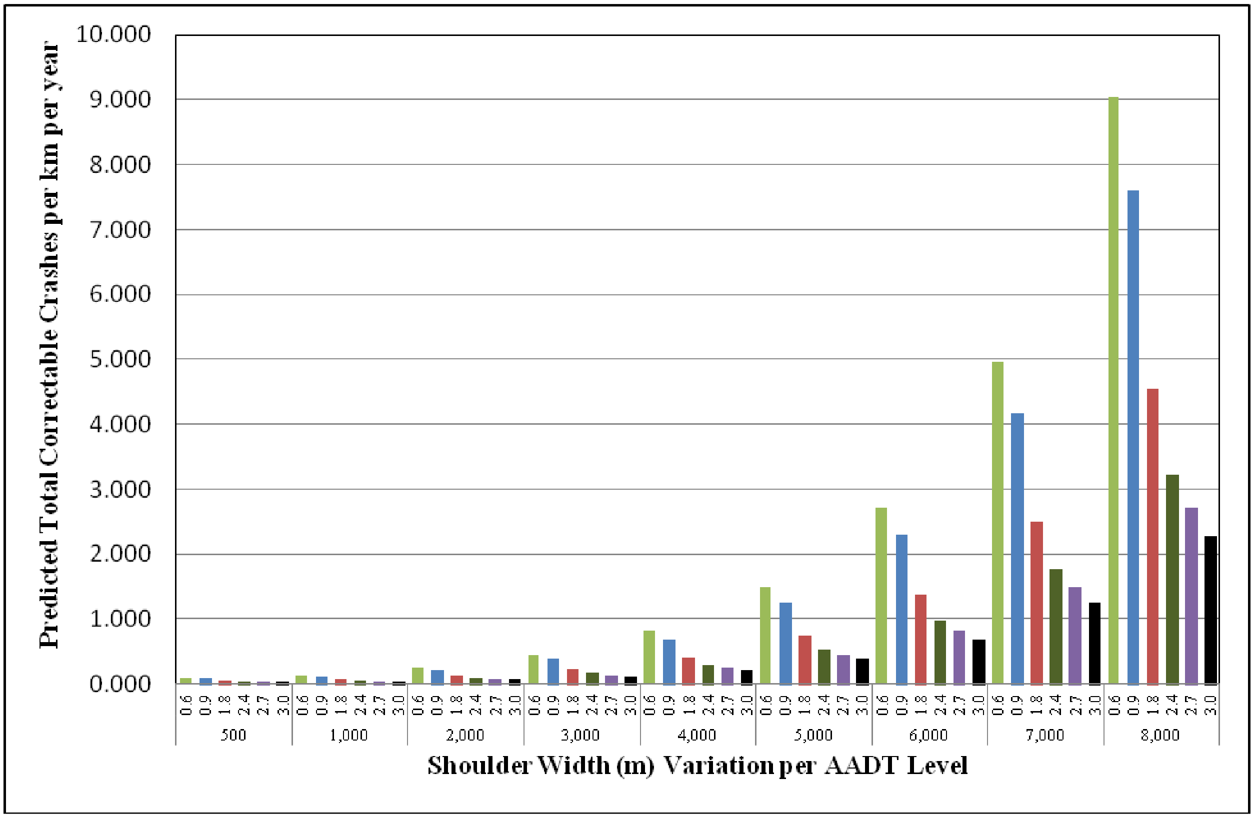


Figure 6.2 Predicted number of Total Crashes per Year for the SRS only Configuration

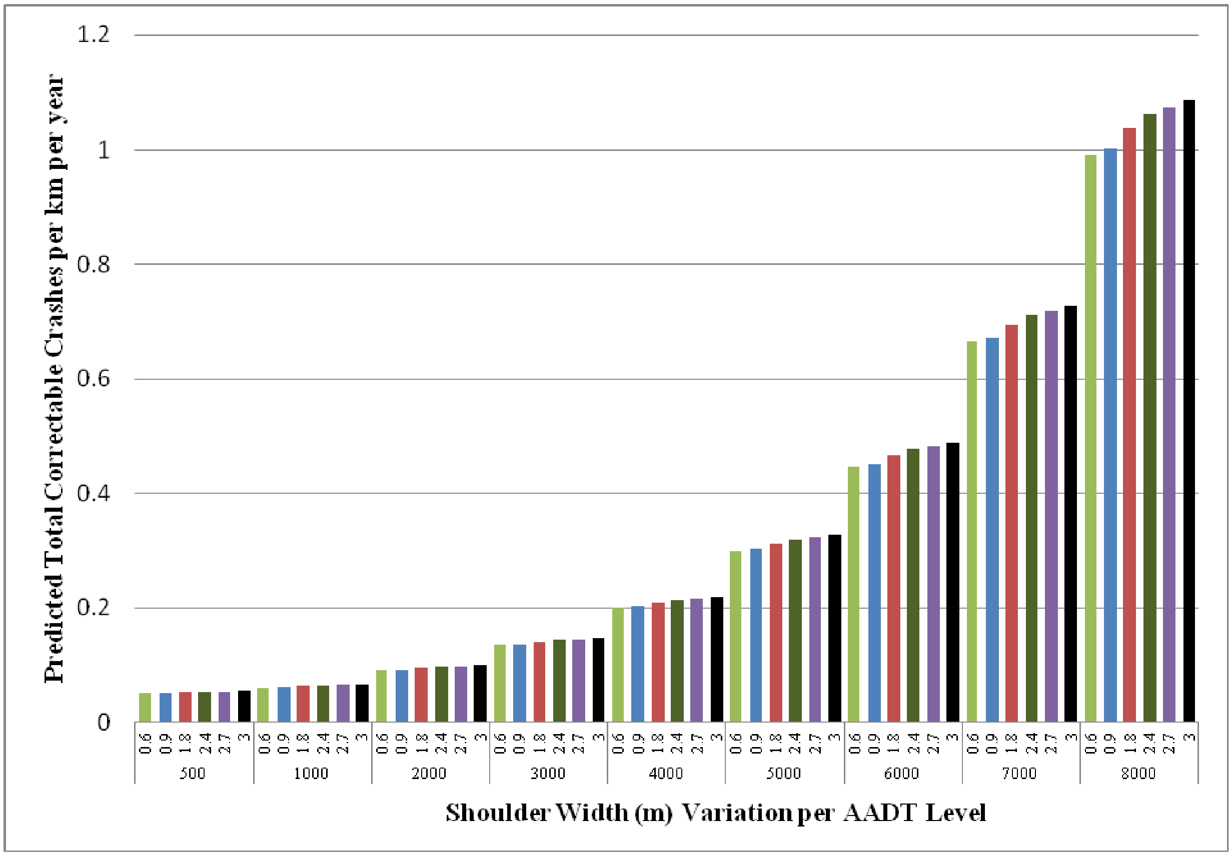
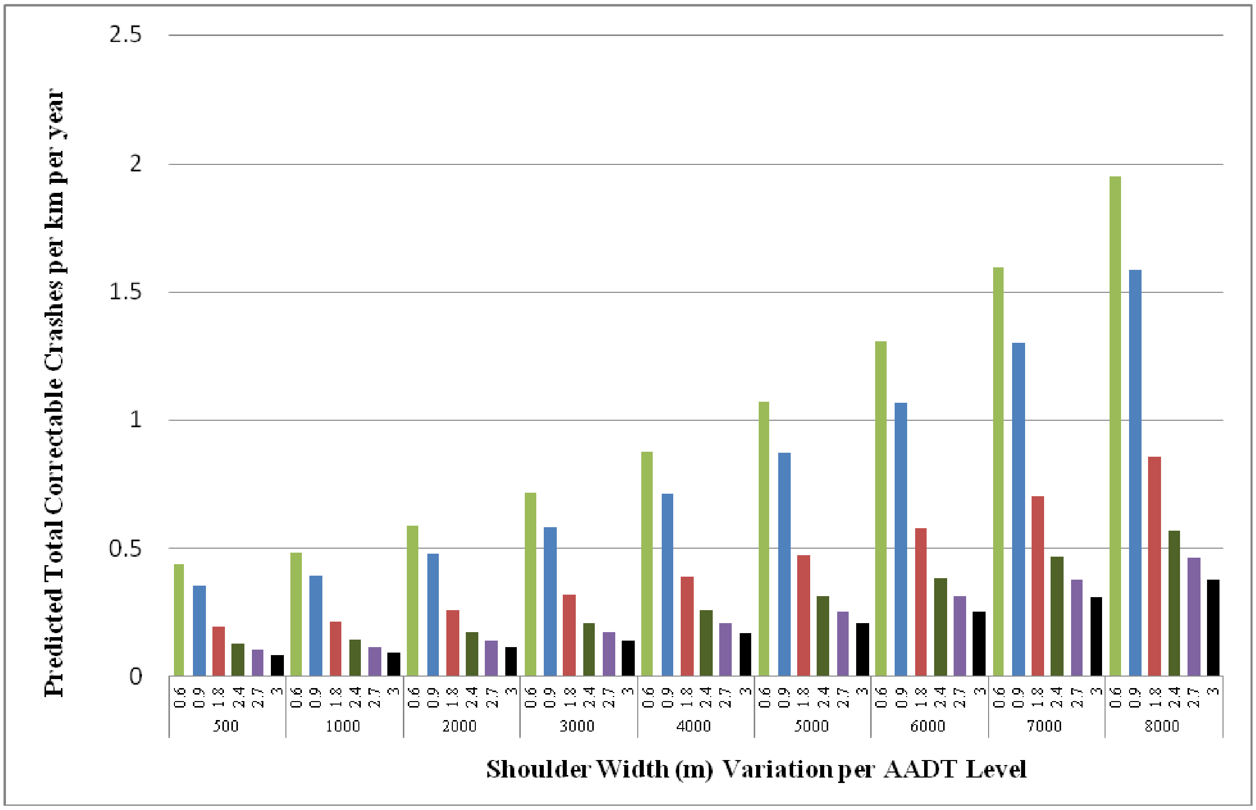


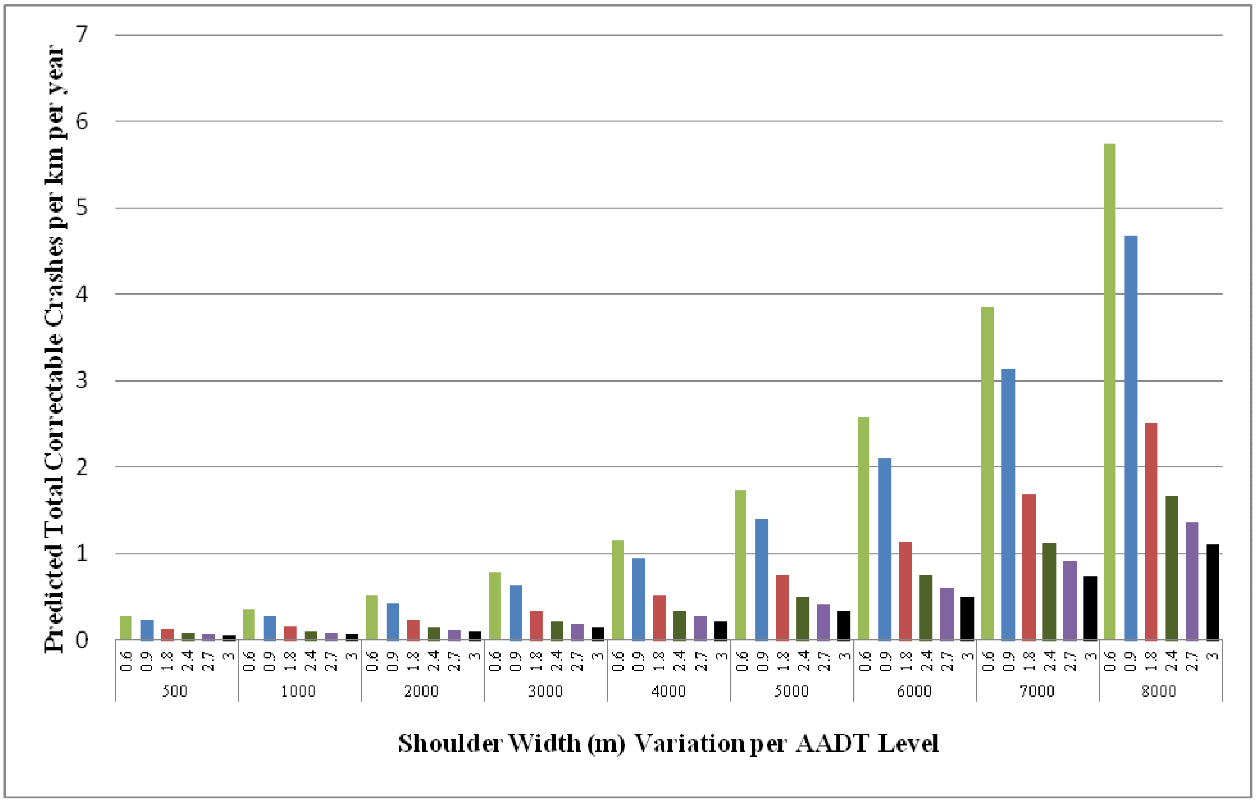
Figure 6.3 Predicted number of Total Crashes per Year for the Both Configuration



- For roadways with both SRS and CLRS, the effect of AADT is not very strong for AADTs up to 3,000 vehicles per day. For AADTs greater than 3,000 vehicles per day, increasing the AADT would result in a strong increase in the number of predicted crashes, especially for narrow shoulder widths, as shown in Figure 6.3.

- For roadways without any kind of rumble strips (*neither* configuration), the impact of AADT is more evident on narrow shoulders and the impact of shoulder width is more evident of higher AADTs (greater than 3,000 vehicles per day), as shown in Figure 6.4.

Figure 6.4 Predicted number of Total Crashes per Year for the Neither Configuration



The predicted number of total correctable crashes per km per year for all rumble strip configurations for several shoulder widths and AADTs are given in Table 6.3. This table also compares the predicted number of crashes with the baseline configuration (*neither*), where negative values express crash reduction, and shows the rumble strip configuration that would result in the minimum predicted crash value as the technical recommendation. An economical recommendation is also given in Table 6.3. This recommendation assumes that the cost of one crash is $19,396.66. This value was arrived at as follows: in 2005 there were 10,700,000 motor vehicle crashes in the country, resulting in an estimated total cost for the society of $166.7 billion (Meyer 2008), so in 2005 money the cost of each crash was 15,579.44, which was capitalized by the averaged annual medical care inflation rate of 3.72% for the period (Bureau of Labor Statistics, 2011), resulting in the $19,396.66 value in 2011 money. The total cost of crashes in

2005 was calculated according to an study that took into consideration expenses with medical treatments, emergency vehicles, policy services, property damage, lost productivity and quality of life (Meyer 2008). Another assumption made is that the cost of installation of SRS or CLRS is \$2,500 per km or \$4,000.00 per mile (based on values presented by Steven Buckley, KDOT in 2008), taking place on the first year of the cash flow. The cost of the *both* configuration per km was assumed to be the double of the cost of only one type of rumble strips. The service life of pavements was assumed to be seven years (after this period of time, pavements with or without rumble strips would be resurfaced). The cost per crash was assumed to increase at a rate of 3.99% per year, the averaged annual medical care inflation rates for the period of 2001 – 2009 (Bureau of Labor Statistics, 2011). The economical recommendation columns in Tables 6.3 – 6.5 show the configuration that would result in the smallest cost per km.

From the results in Table 6.3 based on the total correctable crashes, it is possible to conclude that *CLRS only* provide total correctable crash reductions at AADTs smaller than 5,000 vehicles per day as compared to *neither*; *SRS only* showed technical results better than *neither* for all situations; and the *both* configuration would be better than *neither* for AADTs greater than 3,000 vehicles per day. The economical recommendation showed that for narrow shoulders, the less costly configuration was *SRS only*. For medium and large shoulders, the results are mixed. In these cases, for AADTs lower than 4,000 vehicles per day, the predominant lowest cost configuration was *CLRS only*. For AADTs greater than 4,000 vehicles per day, the *both* configuration is recommended.

Table 6.3 Expected Number to Total Correctable Crashes per km per Year and Recommendations

AADT	SW (m)	CLRS only		Both		SRS only		Neither	Technical Recommendation	Cost per km, neither, over service life = 7 yrs	Cost per km, RS, over service life = 7 yrs	Economical Recommendation
		Expected # Crashes	Relative to Neither	Expected # Crashes	Relative to Neither	Expected # Crashes	Relative to Neither	Expected # Crashes				
500	0.6	0.100	-64.91%	0.435	52.12%	0.049	-82.72%	0.286	SRS only	$45,535.13	$10,329.46	SRS only
	0.9	0.084	-63.69%	0.354	52.22%	0.050	-78.53%	0.233	SRS only	$37,055.40	$10,417.81	SRS only
	1.8	0.050	-59.77%	0.191	52.54%	0.052	-58.79%	0.125	CLRS only	$19,969.46	$10,494.66	CLRS only
	2.4	0.036	-56.93%	0.127	52.75%	0.053	-36.36%	0.083	CLRS only	$13,224.41	$8,168.44	CLRS only
	2.7	0.030	-55.43%	0.103	52.85%	0.053	-20.92%	0.068	CLRS only	$10,761.71	$7,273.04	CLRS only
	3.0	0.025	-53.88%	0.084	52.96%	0.054	-1.72%	0.055	CLRS only	$8,757.62	$6,519.08	CLRS only
1,000	0.6	0.135	-61.21%	0.481	37.64%	0.060	-82.72%	0.349	SRS only	$55,616.74	$12,062.93	SRS only
	0.9	0.114	-59.87%	0.391	37.74%	0.061	-78.53%	0.284	SRS only	$45,259.57	$12,170.83	SRS only
	1.8	0.068	-55.54%	0.211	38.02%	0.063	-58.79%	0.153	SRS only	$24,390.76	$12,501.89	SRS only
	2.4	0.048	-52.40%	0.140	38.21%	0.065	-36.36%	0.101	CLRS only	$16,152.33	$10,151.60	CLRS only
	2.7	0.041	-50.74%	0.114	38.31%	0.065	-20.92%	0.083	CLRS only	$13,144.38	$8,942.93	CLRS only
	3.0	0.034	-49.03%	0.093	38.40%	0.066	-1.72%	0.067	CLRS only	$10,696.58	$7,925.20	CLRS only
2,000	0.6	0.247	-52.63%	0.587	12.69%	0.090	-82.72%	0.521	SRS only	$82,970.42	$16,766.21	SRS only
	0.9	0.208	-50.98%	0.478	12.77%	0.091	-78.53%	0.424	SRS only	$67,519.35	$16,927.18	SRS only
	1.8	0.124	-45.70%	0.258	13.00%	0.094	-58.79%	0.228	SRS only	$36,386.73	$17,421.07	SRS only
	2.4	0.088	-41.86%	0.171	13.16%	0.096	-36.36%	0.151	CLRS only	$24,096.44	$16,442.12	CLRS only
	2.7	0.074	-39.84%	0.139	13.24%	0.097	-20.92%	0.123	CLRS only	$19,609.11	$14,239.79	CLRS only
	3.0	0.062	-37.75%	0.114	13.31%	0.098	-1.72%	0.100	CLRS only	$15,957.42	$12,385.35	CLRS only
3,000	0.6	0.450	-42.14%	0.717	-7.74%	0.134	-82.72%	0.777	SRS only	$123,777.33	$23,782.69	SRS only
	0.9	0.379	-40.13%	0.584	-7.67%	0.136	-78.53%	0.632	SRS only	$100,727.03	$24,022.83	SRS only
	1.8	0.226	-33.67%	0.315	-7.48%	0.140	-58.79%	0.341	SRS only	$54,282.63	$24,759.62	SRS only
	2.4	0.160	-28.99%	0.209	-7.35%	0.144	-36.36%	0.226	SRS only	$35,947.67	$25,264.77	SRS only
	2.7	0.135	-26.52%	0.170	-7.29%	0.145	-20.92%	0.184	CLRS only	$29,253.35	$23,891.30	CLRS only
	3.0	0.114	-23.97%	0.139	-7.23%	0.147	-1.72%	0.149	CLRS only	$23,805.68	$20,512.29	CLRS only
4,000	0.6	0.819	-29.33%	0.876	-24.46%	0.200	-82.72%	1.159	SRS only	$184,654.08	$34,250.05	SRS only
	0.9	0.690	-26.87%	0.713	-24.41%	0.203	-78.53%	0.944	SRS only	$150,267.08	$34,608.29	SRS only
	1.8	0.412	-18.99%	0.385	-24.25%	0.210	-58.79%	0.508	SRS only	$80,980.16	$35,707.45	SRS only
	2.4	0.292	-13.26%	0.255	-24.15%	0.214	-36.36%	0.337	SRS only	$53,627.62	$36,461.05	SRS only
	2.7	0.246	-10.25%	0.208	-24.10%	0.217	-20.92%	0.274	Both	$43,640.88	$37,964.60	Both
	3.0	0.207	-7.13%	0.169	-24.04%	0.219	-1.72%	0.223	Both	$35,513.90	$31,844.32	Both
5,000	0.6	1.493	-13.68%	1.070	-38.15%	0.299	-82.72%	1.730	SRS only	$275,471.51	$49,865.50	SRS only
	0.9	1.257	-10.68%	0.871	-38.11%	0.302	-78.53%	1.408	SRS only	$224,172.13	$50,399.93	SRS only
	1.8	0.751	-1.05%	0.470	-37.98%	0.313	-58.79%	0.759	SRS only	$120,808.21	$52,039.69	SRS only
	2.4	0.532	5.94%	0.312	-37.90%	0.320	-36.36%	0.502	Both	$80,003.01	$54,442.69	Both
	2.7	0.448	9.62%	0.254	-37.85%	0.323	-20.92%	0.409	Both	$65,104.54	$45,263.05	Both
	3.0	0.377	13.43%	0.207	-37.81%	0.327	-1.72%	0.333	Both	$52,980.52	$37,787.72	Both
6,000	0.6	2.721	5.43%	1.307	-49.36%	0.446	-82.72%	2.580	SRS only	$410,955.20	$73,161.02	SRS only
	0.9	2.291	9.09%	1.064	-49.33%	0.451	-78.53%	2.100	SRS only	$334,425.53	$73,958.31	SRS only
	1.8	1.368	20.86%	0.575	-49.22%	0.466	-58.79%	1.132	SRS only	$180,224.67	$76,404.53	SRS only
	2.4	0.970	29.40%	0.381	-49.15%	0.477	-36.36%	0.749	Both	$119,350.46	$65,389.43	Both
	2.7	0.817	33.89%	0.310	-49.12%	0.482	-20.92%	0.610	Both	$97,124.55	$54,177.40	Both
	3.0	0.688	38.54%	0.253	-49.08%	0.488	-1.72%	0.496	Both	$79,037.64	$45,047.02	Both
7,000	0.6	4.957	28.77%	1.596	-58.54%	0.665	-82.72%	3.850	SRS only	$613,073.12	$107,913.86	SRS only
	0.9	4.174	33.25%	1.300	-58.51%	0.673	-78.53%	3.133	SRS only	$498,904.26	$109,103.27	SRS only
	1.8	2.492	47.62%	0.702	-58.43%	0.696	-58.79%	1.688	SRS only	$268,863.61	$112,752.61	SRS only
	2.4	1.767	58.05%	0.465	-58.37%	0.711	-36.36%	1.118	Both	$178,049.97	$78,759.82	Both
	2.7	1.488	63.54%	0.379	-58.34%	0.719	-20.92%	0.910	Both	$144,892.81	$65,065.41	Both
	3.0	1.253	69.22%	0.309	-58.31%	0.728	-1.72%	0.740	Both	$117,910.31	$53,913.53	Both
8,000	0.6	9.033	57.28%	1.949	-66.06%	0.992	-82.72%	5.743	SRS only	$914,597.62	$159,759.00	SRS only
	0.9	7.606	62.75%	1.587	-66.03%	1.003	-78.53%	4.673	SRS only	$744,277.70	$161,533.38	SRS only
	1.8	4.541	80.30%	0.857	-65.96%	1.038	-58.79%	2.519	Both	$401,097.37	$140,853.10	Both
	2.4	3.220	93.04%	0.568	-65.92%	1.061	-36.36%	1.668	Both	$265,619.34	$95,090.45	Both
	2.7	2.711	99.74%	0.463	-65.89%	1.073	-20.92%	1.357	Both	$216,154.67	$78,364.06	Both
	3.0	2.283	106.68%	0.377	-65.87%	1.085	-1.72%	1.105	Both	$175,901.51	$64,743.13	Both

Table 6.4 Expected Number to Cross-over Crashes per km per Year and Recommendations

AADT	SW (m)	CLRS only		Both		SRS only		Neither	Technical Recommendation	Cost per km, neither, over service life = 7 yrs	Cost per km, RS, over service life = 7 yrs	Economical Recommendation
		Expected # Crashes	Relative to Neither	Expected # Crashes	Relative to Neither	Expected # Crashes	Relative to Neither	Expected # Crashes				
500	0.6	0.002	-81.20%	0.004	-52.73%	0.008	-9.92%	0.009	CLRS only	$1,416.12	$2,764.94	Neither
	0.9	0.002	-81.20%	0.004	-52.73%	0.008	-9.92%	0.009	CLRS only	$1,416.12	$2,764.94	Neither
	1.8	0.002	-81.20%	0.004	-52.73%	0.008	-9.92%	0.009	CLRS only	$1,416.12	$2,764.94	Neither
	2.4	0.002	-81.20%	0.004	-52.73%	0.008	-9.92%	0.009	CLRS only	$1,416.12	$2,764.94	Neither
	2.7	0.002	-81.20%	0.004	-52.73%	0.008	-9.92%	0.009	CLRS only	$1,416.12	$2,764.94	Neither
	3.0	0.002	-81.20%	0.004	-52.73%	0.008	-9.92%	0.009	CLRS only	$1,416.12	$2,764.94	Neither
1,000	0.6	0.002	-81.20%	0.005	-52.73%	0.010	-9.92%	0.011	CLRS only	$1,729.66	$2,823.60	Neither
	0.9	0.002	-81.20%	0.005	-52.73%	0.010	-9.92%	0.011	CLRS only	$1,729.66	$2,823.60	Neither
	1.8	0.002	-81.20%	0.005	-52.73%	0.010	-9.92%	0.011	CLRS only	$1,729.66	$2,823.60	Neither
	2.4	0.002	-81.20%	0.005	-52.73%	0.010	-9.92%	0.011	CLRS only	$1,729.66	$2,823.60	Neither
	2.7	0.002	-81.20%	0.005	-52.73%	0.010	-9.92%	0.011	CLRS only	$1,729.66	$2,823.60	Neither
	3.0	0.002	-81.20%	0.005	-52.73%	0.010	-9.92%	0.011	CLRS only	$1,729.66	$2,823.60	Neither
2,000	0.6	0.003	-81.20%	0.008	-52.73%	0.015	-9.92%	0.016	CLRS only	$2,580.35	$2,982.76	Neither
	0.9	0.003	-81.20%	0.008	-52.73%	0.015	-9.92%	0.016	CLRS only	$2,580.35	$2,982.76	Neither
	1.8	0.003	-81.20%	0.008	-52.73%	0.015	-9.92%	0.016	CLRS only	$2,580.35	$2,982.76	Neither
	2.4	0.003	-81.20%	0.008	-52.73%	0.015	-9.92%	0.016	CLRS only	$2,580.35	$2,982.76	Neither
	2.7	0.003	-81.20%	0.008	-52.73%	0.015	-9.92%	0.016	CLRS only	$2,580.35	$2,982.76	Neither
	3.0	0.003	-81.20%	0.008	-52.73%	0.015	-9.92%	0.016	CLRS only	$2,580.35	$2,982.76	Neither
3,000	0.6	0.005	-81.20%	0.011	-52.73%	0.022	-9.92%	0.024	CLRS only	$3,849.43	$3,220.19	CLRS only
	0.9	0.005	-81.20%	0.011	-52.73%	0.022	-9.92%	0.024	CLRS only	$3,849.43	$3,220.19	CLRS only
	1.8	0.005	-81.20%	0.011	-52.73%	0.022	-9.92%	0.024	CLRS only	$3,849.43	$3,220.19	CLRS only
	2.4	0.005	-81.20%	0.011	-52.73%	0.022	-9.92%	0.024	CLRS only	$3,849.43	$3,220.19	CLRS only
	2.7	0.005	-81.20%	0.011	-52.73%	0.022	-9.92%	0.024	CLRS only	$3,849.43	$3,220.19	CLRS only
	3.0	0.005	-81.20%	0.011	-52.73%	0.022	-9.92%	0.024	CLRS only	$3,849.43	$3,220.19	CLRS only
4,000	0.6	0.007	-81.20%	0.017	-52.73%	0.032	-9.92%	0.036	CLRS only	$5,742.67	$3,574.39	CLRS only
	0.9	0.007	-81.20%	0.017	-52.73%	0.032	-9.92%	0.036	CLRS only	$5,742.67	$3,574.39	CLRS only
	1.8	0.007	-81.20%	0.017	-52.73%	0.032	-9.92%	0.036	CLRS only	$5,742.67	$3,574.39	CLRS only
	2.4	0.007	-81.20%	0.017	-52.73%	0.032	-9.92%	0.036	CLRS only	$5,742.67	$3,574.39	CLRS only
	2.7	0.007	-81.20%	0.017	-52.73%	0.032	-9.92%	0.036	CLRS only	$5,742.67	$3,574.39	CLRS only
	3.0	0.007	-81.20%	0.017	-52.73%	0.032	-9.92%	0.036	CLRS only	$5,742.67	$3,574.39	CLRS only
5,000	0.6	0.010	-81.20%	0.025	-52.73%	0.048	-9.92%	0.054	CLRS only	$8,567.06	$4,102.80	CLRS only
	0.9	0.010	-81.20%	0.025	-52.73%	0.048	-9.92%	0.054	CLRS only	$8,567.06	$4,102.80	CLRS only
	1.8	0.010	-81.20%	0.025	-52.73%	0.048	-9.92%	0.054	CLRS only	$8,567.06	$4,102.80	CLRS only
	2.4	0.010	-81.20%	0.025	-52.73%	0.048	-9.92%	0.054	CLRS only	$8,567.06	$4,102.80	CLRS only
	2.7	0.010	-81.20%	0.025	-52.73%	0.048	-9.92%	0.054	CLRS only	$8,567.06	$4,102.80	CLRS only
	3.0	0.010	-81.20%	0.025	-52.73%	0.048	-9.92%	0.054	CLRS only	$8,567.06	$4,102.80	CLRS only
6,000	0.6	0.015	-81.20%	0.038	-52.73%	0.072	-9.92%	0.080	CLRS only	$12,780.55	$4,891.10	CLRS only
	0.9	0.015	-81.20%	0.038	-52.73%	0.072	-9.92%	0.080	CLRS only	$12,780.55	$4,891.10	CLRS only
	1.8	0.015	-81.20%	0.038	-52.73%	0.072	-9.92%	0.080	CLRS only	$12,780.55	$4,891.10	CLRS only
	2.4	0.015	-81.20%	0.038	-52.73%	0.072	-9.92%	0.080	CLRS only	$12,780.55	$4,891.10	CLRS only
	2.7	0.015	-81.20%	0.038	-52.73%	0.072	-9.92%	0.080	CLRS only	$12,780.55	$4,891.10	CLRS only
	3.0	0.015	-81.20%	0.038	-52.73%	0.072	-9.92%	0.080	CLRS only	$12,780.55	$4,891.10	CLRS only
7,000	0.6	0.023	-81.20%	0.057	-52.73%	0.108	-9.92%	0.120	CLRS only	$19,066.33	$6,067.10	CLRS only
	0.9	0.023	-81.20%	0.057	-52.73%	0.108	-9.92%	0.120	CLRS only	$19,066.33	$6,067.10	CLRS only
	1.8	0.023	-81.20%	0.057	-52.73%	0.108	-9.92%	0.120	CLRS only	$19,066.33	$6,067.10	CLRS only
	2.4	0.023	-81.20%	0.057	-52.73%	0.108	-9.92%	0.120	CLRS only	$19,066.33	$6,067.10	CLRS only
	2.7	0.023	-81.20%	0.057	-52.73%	0.108	-9.92%	0.120	CLRS only	$19,066.33	$6,067.10	CLRS only
	3.0	0.023	-81.20%	0.057	-52.73%	0.108	-9.92%	0.120	CLRS only	$19,066.33	$6,067.10	CLRS only
8,000	0.6	0.034	-81.20%	0.084	-52.73%	0.161	-9.92%	0.179	CLRS only	$28,443.63	$7,821.49	CLRS only
	0.9	0.034	-81.20%	0.084	-52.73%	0.161	-9.92%	0.179	CLRS only	$28,443.63	$7,821.49	CLRS only
	1.8	0.034	-81.20%	0.084	-52.73%	0.161	-9.92%	0.179	CLRS only	$28,443.63	$7,821.49	CLRS only
	2.4	0.034	-81.20%	0.084	-52.73%	0.161	-9.92%	0.179	CLRS only	$28,443.63	$7,821.49	CLRS only
	2.7	0.034	-81.20%	0.084	-52.73%	0.161	-9.92%	0.179	CLRS only	$28,443.63	$7,821.49	CLRS only
	3.0	0.034	-81.20%	0.084	-52.73%	0.161	-9.92%	0.179	CLRS only	$28,443.63	$7,821.49	CLRS only

Table 6.5 Expected Number to ROR Crashes per km per Year and Recommendations

AADT	SW (m)	CLRS only		Both		SRS only		Neither	Technical Recommendation	Cost per km, neither, over service life = 7 yrs	Cost per km, RS, over service life = 7 yrs	Economical Recommendation
		Expected # Crashes	Relative to Neither	Expected # Crashes	Relative to Neither	Expected # Crashes	Relative to Neither	Expected # Crashes				
500	0.6	0.255	-14.49%	0.162	-45.74%	0.224	-24.95%	0.298	Both	$47,427.59	$30,608.75	Both
	0.9	0.199	-14.49%	0.127	-45.74%	0.175	-24.95%	0.233	Both	$37,149.27	$25,058.92	Both
	1.8	0.096	-14.49%	0.061	-45.74%	0.084	-24.95%	0.112	Both	$17,852.87	$14,639.74	Both
	2.4	0.059	-14.49%	0.037	-45.74%	0.052	-24.95%	0.069	Both	$10,953.34	$10,914.31	Both
	2.7	0.046	-14.49%	0.029	-45.74%	0.040	-24.95%	0.054	Both	$8,579.57	$9,632.58	Neither
	3.0	0.036	-14.49%	0.023	-45.74%	0.032	-24.95%	0.042	Both	$6,720.24	$8,628.63	Neither
1,000	0.6	0.296	-14.49%	0.188	-45.74%	0.260	-24.95%	0.346	Both	$55,103.00	$34,753.12	Both
	0.9	0.232	-14.49%	0.147	-45.74%	0.203	-24.95%	0.271	Both	$43,161.30	$28,305.14	Both
	1.8	0.111	-14.49%	0.071	-45.74%	0.098	-24.95%	0.130	Both	$20,742.07	$16,199.78	Both
	2.4	0.068	-14.49%	0.043	-45.74%	0.060	-24.95%	0.080	Both	$12,725.96	$11,871.44	Both
	2.7	0.054	-14.49%	0.034	-45.74%	0.047	-24.95%	0.063	Both	$9,968.04	$10,382.29	Neither
	3.0	0.042	-14.49%	0.027	-45.74%	0.037	-24.95%	0.049	Both	$7,807.81	$9,215.86	Neither
2,000	0.6	0.399	-14.49%	0.253	-45.74%	0.351	-24.95%	0.467	Both	$74,381.27	$45,162.52	Both
	0.9	0.313	-14.49%	0.198	-45.74%	0.275	-24.95%	0.366	Both	$58,261.66	$36,458.65	Both
	1.8	0.150	-14.49%	0.095	-45.74%	0.132	-24.95%	0.176	Both	$27,998.87	$20,118.12	Both
	2.4	0.092	-14.49%	0.059	-45.74%	0.081	-24.95%	0.108	Both	$17,178.25	$14,275.48	Both
	2.7	0.072	-14.49%	0.046	-45.74%	0.063	-24.95%	0.084	Both	$13,455.45	$12,265.33	Both
	3.0	0.057	-14.49%	0.036	-45.74%	0.050	-24.95%	0.066	Both	$10,539.44	$10,690.82	Neither
3,000	0.6	0.539	-14.49%	0.342	-45.74%	0.473	-24.95%	0.630	Both	$100,404.22	$59,213.73	Both
	0.9	0.422	-14.49%	0.268	-45.74%	0.371	-24.95%	0.494	Both	$78,645.01	$47,464.74	Both
	1.8	0.203	-14.49%	0.129	-45.74%	0.178	-24.95%	0.237	Both	$37,794.52	$25,407.33	Both
	2.4	0.125	-14.49%	0.079	-45.74%	0.109	-24.95%	0.146	Both	$23,188.22	$17,520.59	Both
	2.7	0.098	-14.49%	0.062	-45.74%	0.086	-24.95%	0.114	Both	$18,162.96	$14,807.17	Both
	3.0	0.076	-14.49%	0.048	-45.74%	0.067	-24.95%	0.089	Both	$14,226.75	$12,681.80	Both
4,000	0.6	0.728	-14.49%	0.462	-45.74%	0.639	-24.95%	0.851	Both	$135,531.52	$78,180.88	Both
	0.9	0.570	-14.49%	0.362	-45.74%	0.500	-24.95%	0.667	Both	$106,159.66	$62,321.41	Both
	1.8	0.274	-14.49%	0.174	-45.74%	0.240	-24.95%	0.320	Both	$51,017.27	$32,547.01	Both
	2.4	0.168	-14.49%	0.107	-45.74%	0.148	-24.95%	0.197	Both	$31,300.82	$21,901.02	Both
	2.7	0.132	-14.49%	0.084	-45.74%	0.116	-24.95%	0.154	Both	$24,517.43	$18,238.30	Both
	3.0	0.103	-14.49%	0.065	-45.74%	0.091	-24.95%	0.121	Both	$19,204.11	$15,369.35	Both
5,000	0.6	0.982	-14.49%	0.623	-45.74%	0.862	-24.95%	1.149	Both	$182,948.41	$103,783.85	Both
	0.9	0.769	-14.49%	0.488	-45.74%	0.675	-24.95%	0.900	Both	$143,300.56	$82,375.81	Both
	1.8	0.370	-14.49%	0.235	-45.74%	0.325	-24.95%	0.432	Both	$68,866.11	$42,184.58	Both
	2.4	0.227	-14.49%	0.144	-45.74%	0.199	-24.95%	0.265	Both	$42,251.68	$27,813.99	Both
	2.7	0.178	-14.49%	0.113	-45.74%	0.156	-24.95%	0.208	Both	$33,095.07	$22,869.84	Both
	3.0	0.139	-14.49%	0.088	-45.74%	0.122	-24.95%	0.163	Both	$25,922.83	$18,997.16	Both
6,000	0.6	1.326	-14.49%	0.841	-45.74%	1.164	-24.95%	1.551	Both	$246,954.53	$138,344.25	Both
	0.9	1.039	-14.49%	0.659	-45.74%	0.912	-24.95%	1.215	Both	$193,435.52	$109,446.41	Both
	1.8	0.499	-14.49%	0.317	-45.74%	0.438	-24.95%	0.584	Both	$92,959.53	$55,193.93	Both
	2.4	0.306	-14.49%	0.194	-45.74%	0.269	-24.95%	0.358	Both	$57,033.81	$35,795.67	Both
	2.7	0.240	-14.49%	0.152	-45.74%	0.211	-24.95%	0.281	Both	$44,673.67	$29,121.76	Both
	3.0	0.188	-14.49%	0.119	-45.74%	0.165	-24.95%	0.220	Both	$34,992.17	$23,894.18	Both
7,000	0.6	1.790	-14.49%	1.136	-45.74%	1.571	-24.95%	2.093	Both	$333,353.74	$184,995.91	Both
	0.9	1.402	-14.49%	0.890	-45.74%	1.230	-24.95%	1.640	Both	$261,110.64	$145,987.91	Both
	1.8	0.674	-14.49%	0.428	-45.74%	0.591	-24.95%	0.788	Both	$125,482.24	$72,754.72	Both
	2.4	0.413	-14.49%	0.262	-45.74%	0.363	-24.95%	0.483	Both	$76,987.59	$46,569.81	Both
	2.7	0.324	-14.49%	0.205	-45.74%	0.284	-24.95%	0.379	Both	$60,303.14	$37,560.96	Both
	3.0	0.254	-14.49%	0.161	-45.74%	0.223	-24.95%	0.297	Both	$47,234.48	$30,504.48	Both
8,000	0.6	2.416	-14.49%	1.533	-45.74%	2.121	-24.95%	2.825	Both	$449,980.48	$247,969.07	Both
	0.9	1.893	-14.49%	1.201	-45.74%	1.661	-24.95%	2.213	Both	$352,462.49	$195,313.77	Both
	1.8	0.910	-14.49%	0.577	-45.74%	0.798	-24.95%	1.064	Both	$169,383.30	$96,459.31	Both
	2.4	0.558	-14.49%	0.354	-45.74%	0.490	-24.95%	0.653	Both	$103,922.37	$61,113.37	Both
	2.7	0.437	-14.49%	0.277	-45.74%	0.384	-24.95%	0.511	Both	$81,400.73	$48,952.70	Both
	3.0	0.342	-14.49%	0.217	-45.74%	0.300	-24.95%	0.400	Both	$63,759.88	$39,427.45	Both

From results in Table 6.4 based only on the predicted number of cross-over crashes per km per year crashes, it is possible to conclude that *CLRS only* showed technical results better than *neither* for all situations. The economical recommendation showed that AADTs lower than 2,000 vehicles per day, the predominant best configuration was *neither*. For AADTs greater than 2,000 vehicles per day, the *CLRS only* configuration is recommended. Although the lateral position study showed that drivers positioned vehicles closer to the centerline with the presence of CLRS only configuration, this position would not affect the expected crash benefits provided by the CLRS, based on the predicted crash values. A case study was performed using both drivers' behavior data and crash analysis from a section treated with *CLRS only* and narrow shoulders (shoulder width = 0.6 m or 2 ft). This section was numbered as "treated section 15" in Chapter 3 and as "Treatment 1 or A" in Chapter 5. Based on the results of the drivers' behavior experiment, on this section drivers operated 11.35 percentage points (20 cm or 7.95 in) closer to the centerline (which indicates that drivers were perhaps trying to avoid the risk of ROR due to the presence of narrow shoulders), and speeds were similar to the posted speed limit (PSL). Even with this drivers' behavior data, the crash analysis showed a reduction in the number of cross-over crashes per km per year (from 1.5 crashes per km per year in the before period to zero in the after period, or 100 % reduction), which indicated that drivers may choose to operate closer to the centerline due to a level of trust on CLRS in preventing cross-over departures. The installation of CLRS on roadways with narrow shoulders is beneficial, which was verified by the crash analysis. The very rare nature of occurrence of these types of crashes may not be related to the average lateral position of vehicles in the travel lane, but associated with other non-observed causes (for instance driver's inattention or drowsiness).

From results in Table 6.5 based only on the predicted number of ROR crashes per km per year, it is possible to conclude that the *both* configuration would provide the best technical results for all situations. The economical recommendation showed that at AADTs lower than 2,000 vehicles per day and shoulder width greater than 2.7 m, the predominant lowest cost configuration was *neither*. For AADTs greater than 2,000 vehicles per day, the *both* configuration is recommended. Even though the lateral position study showed that on locations with both SRS and CLRS, vehicles would have the tendency to move closer to the edgeline, the crash analysis showed that the installation of the both configuration would be the best in terms of ROR crashes. By performing a validation using results of a section that was numbered as "treated section 15" in Chapter 3 and as "Treatment 1 or A" in Chapter 5, drivers operated 11.35 percentage points (20 cm or 7.95 in) closer to the centerline, and speeds were similar to the PSL. The crash analysis showed reduction in the number of ROR crashes per mile per year (from 20.00 crashes per km per year in the before period to 11.40 in the after period, or a Naïve estimated reduction of 43%). These results are in agreement, since it was assumed that if the average lateral position of vehicles is shifted to the left, a low number of ROR crashes was expected.

Overall, the observed averaged lateral position may not be a good indicator for the number of expected crashes per km per year, perhaps because crashes are a rare event, and the potential causes may have not been observed in the relatively small sample sized measurements of lateral positions.

Overall Conclusions

This dissertation quantified the safety benefits of installing CLRS in Kansas. The presence of CLRS on Kansas rural two-lane highways promoted substantial crash reductions.

This is the main advantage of this roadway treatment. A problem addressed by this dissertation was how and why Centerline Rumble Strips (CLRS) may cause disadvantages for highway users and non-users. Several Departments of Transportation (DOTs) reported concerns from the public about CLRS. Concerns generally included levels of exterior noise created by the patterns, the decrease in visibility of the pavement markings installed over CLRS and their influence on operational use of the travel lane. These disadvantages may reduce the applicability of CLRS to a limited number of undivided two-lane highways in the United States, a factor that may decrease their major advantage i.e. reduction of roadways departure crashes, more specifically cross-over crashes.

Thus, the primary goal of this research was to provide guidance on future installations of CLRS for policy makers, based on current good practices and on specific investigations of exterior noise, safety effectiveness and operational use of the travel lane.

From the state-of-the-art study, it is possible to conclude that the use of CLRS has grown over the years increasing of about 372% over five years (from 2005 to 2010). Currently there are 36 states using CLRS and 17 states have written policies or guidelines for installation of CLRS. According to survey results, the milled type of CLRS construction is the predominant type, and the CLRS predominant pattern dimensions are: length = 40.6 cm or 16 in., width = 17.78 cm or seven in., depth = 1.27 cm or 0.5 in. and spacing = 30.48 cm or 12 in., continuous. Guidelines for installation of CLRS included crash history, AADT levels, pavement structural condition, lane and shoulder widths, and posted speed limit. The combination of CLRS and shoulder rumble strips (or rumble stripes) is rarely used on sections of highways with narrow or no shoulder.

From the study of the before-and-after safety effectiveness of CLRS in Kansas, it is possible to conclude that CLRS are efficient to prevent all types of crashes that were considered in the study. The results showed that following the installation of CLRS in several roads in Kansas, total correctable crashes were reduced by 29.21%, with 95% CI of (-10.00%, -48.42%). The correctable crashes involving fatalities and injuries were reduced by 34.05%, with 95% CI of (-6.34%, -61.76). The number of cross-over crashes was reduced by 67.19%, with 95% CI of (-37.56%, -96.82%). And the number of run-off-the-road crashes showed a not statistically significance reduction of 19.19%, with 95% CI of (-46.91%, +8.52%). The two methods applied (Naïve and Empirical Bayes) presented statistically similar results and there was no statistical difference between football shaped and rectangular shaped CLRS, based on EB crash reductions.

From the exterior noise study performed, it can be concluded that the external noise depends on the speed (the lower the speed, the lower the noise), type of vehicles (heavier vehicles have a tendency to produce more noise), and distance (the greater the distance, the lower the noise). In addition, both football and rectangular CLRS substantially increased the levels of external noise at distances up to 45 m or 150 ft (there was no statistical difference between the patterns, in terms of exterior noise). Therefore, before installing CLRS, the distance from houses or businesses should be considered. A distance of 60 m (200 ft), measured from the center of the roadway was determined as the limit of the potential exterior noise problem area.

From the study of drivers' behavior, it is possible to conclude that the analyzed configurations of rumble strips and shoulder width levels affect vehicular lateral position and speed levels, although speed deviations were not practically significant. On roadways with narrow shoulders, for both *CLRS only* and neither rumble strip conditions, drivers operated closer to the centerline, perhaps to avoid the risk of running-off-the-road in these conditions. The presence of *both* SRS and CLRS at narrow shoulder levels was not observed in this study, but research conducted in Texas concluded that in these conditions, drivers tended to stay closer to the center of the travel lane (Finley et al. 2008).

On roadways with medium shoulder widths, drivers tended to drive closer to the centerline if SRS were not present and closer to the edgeline if SRS were present. This behavior may reflect some level of trust in SRS in preventing run-off-the-road departures. On roadways with wide shoulders, drivers tended to travel closer to the centerline if CLRS were present and closer to the edgeline otherwise. Drivers tended to shift to the right perhaps because of an increased perception of safety (due to increased perception of available width) with wider shoulders. This tendency may be reduced due to the increased perception of safety created by the presence of CLRS as a mechanism of defense against cross-over departures, so drivers choose to travel closer to the centerline. Another potential explanation for this result is that drivers have a tendency to initiate passing maneuvers closer to other vehicles when CLRS are present (Miles et al. 2005). Thus, drivers may drive closer to the centerline in order to pursue a better sight for passing other vehicles (locations observed in this study were usually chosen in passing areas).

From the SPF models developed with data of 29 highway sections that received installation of CLRS in Kansas and considering the total correctable crashes, it is possible to conclude that *CLRS only* provided total correctable crash reductions at AADTs smaller than 5,000 vehicles per day as compared to *neither*. The configuration *SRS only* showed technical results based on total correctable crashes better than *neither* for all situations, and the *both* configuration would be better than *neither* for AADTs greater than 3,000 vehicles per day, considering total correctable crashes. The economical recommendation based on total correctable crashes showed that for narrow shoulders, the less costly configuration was *SRS only*. For medium and large shoulders, the results were mixed. In these cases, for AADTs lower than 4,000 vehicles per day, the predominant lowest cost configuration was *CLRS only*. For AADTs greater than 4,000 vehicles per day, the *both* configuration performed better.

Considering only the predicted number of cross-over crashes per km per year crashes, it is possible to conclude that *CLRS only* showed technical results better than *neither* for all situations. The economical recommendation showed that AADTs lower than 2,000 vehicles per day, the predominant lowest cost configuration was *neither*. For AADTs greater than 2,000 vehicles per day, the *CLRS only* configuration is recommended.

Based only on the predicted number of ROR crashes per km per year, the *both* configuration would provide the best technical results for all situations. The economical recommendation showed that AADTs lower than 2,000 vehicles per day and shoulder width greater than 2.7 m, the predominant lowest cost configuration was *neither*. For AADTs greater than 2,000 vehicles per day, the *both* configuration is recommended.

Overall, this study recommends the installation of CLRS in rural, two-lane, undivided rural roads in Kansas. Both patterns currently installed in Kansas have provided crash reductions, which have reflected in economic benefits for society. Shoulder width and traffic volume should be considered as crash predictors for enhancement of the benefits. General guidelines are summarized below for future better applications of CLRS.

Technical Recommendations

From the list of good practices obtained from the experience of other states using CLRS, and from the literature review, recommendations included:

- For practical reasons and for enhancing the safety effectiveness of CLRS: adopt a minimum AADT (DOTs responses ranged between 1500 and 3000), a minimum speed (DOTs responses ranged between 64.4 and 88.5 km/h or 40 and 55 mph), a minimum crash rate for the installation of CLRS, a minimum lane width (DOTs responses ranged between 3.0 and 3.66 m or 10 and 12 feet), and a minimum shoulder width (DOTs reported two to four feet). In addition, install CLRS in roadways continuously in no-passing and passing zones, but discontinue the use of CLRS at intersections and at bridge decks, and adopt a pattern that is able to generate approximately 10 dBA above the ambient in-vehicle sound level. The predominant pattern in the country (length=40.6 cm or 16 in., width = 17.78 cm or seven in., depth = 1.27 cm or 0.5 in. and spacing = 30.48 cm or 12 in.) has this characteristic (Miles and Finley 2007). Thus, this pattern is recommended. A study conducted in Kansas concluded that the football shaped and the rectangular shaped patterns used in Kansas would promote driver awareness, based on vehicle's internal noise and vibration (Rys et al. 2008).

- To avoid potential pavement deterioration caused by CLRS, good practices included: install CLRS only on new construction or overlays; adopt a minimum pavement depth to install CLRS (DOTs responses ranged between 3.81 to 6.35 cm or 1.5 and 2.5 in.). Do not install CLRS if the center joint is not in good condition (use engineering judgment).
- A widely applied practice to reduce the impact of CLRS on winter maintenance activities is to avoid the raised type of CLRS in areas where snow is frequent.
- Bicyclists are not expected to hit CLRS very often. However, an intermittent gap in the spacing of CLRS may help bicyclists to cross the travel lane when needed.
- To reduce the potential impact of CLRS on vehicles' position on the travel lane, good practices include: adopt a minimum shoulder and lane width for installation of CLRS (DOTs reported lane widths ranging from 3.0 to 3.66 m or 10 to 12 feet and shoulder widths ranging from two to four feet). Utilize CLRS in conjunction with "rumble stripes", when technically feasible, since one study showed that CLRS in conjunction with "rumble stripes" resulted in drivers positioning the vehicle closer to the center of lanes (assumed safer condition) at locations with lane widths as narrow as 3.35 m (11 ft) and shoulder widths of 0.91 m or three feet (Finley et al. 2008).
- In order to avoid potential drivers' mistakes on initial reactions after hitting CLRS, when CLRS are installed in conjunction with shoulder rumble strips (SRS) on the same roadway, different patterns of CLRS and SRS should be used.
- Other factors suggested for inclusion in CLRS installation guidance found in the reviewed literature were: type of roadway, location of roadway, local and regional conditions, roadway alignment, consistency within a state, and experience of others (Russell and Rys 2005). Furthermore, Carlson and Miles (2003) recommended that CRLS may be installed along the edge line delineating pavement stripes for two-way left turn lanes.

From the experiments conducted in this research project, the installation of CLRS is recommended to follow a minimum distance from residences or businesses to avoid exterior noise disturbance. The minimum distance guideline suggested by this study is 60 m (200 ft).

The football and rectangular pattern were not statistically different from each other in terms of crash reductions and exterior noise levels, thus both patterns are recommended.

This study has shown that for applications of *CLRS only*, the predicted number of total correctable crashes per km per year is very small for small AADTs (less than 1,000 vehicles per day). At this level of AADTs, the shoulder width does not have much impact in the predicted number of total correctable crashes, which provides evidence that CLRS may be applied in roadways with narrow shoulders, depending on the expected traffic volume. As the traffic volume (AADT) increases, the predicted number of total crashes increases considerably, and the effect of shoulder width is also magnified, with the narrowest shoulder conditions being the worst cases. Therefore, at narrow shoulder widths (less than 0.9 m or 2 ft) the application of *CLRS only* is recommended for roadways with AADTs less than 1,000 vehicles per day. Even with the small number of crashes, the application of *CLRS only* would be economically feasible, considering a treatment lifetime of seven years. In general, *CLRS only* are recommended for roadways with AADTs lower than 5,000 vehicles per day to prevent total correctable crashes and for AADTs in the range of 500 – 8,000 to prevent cross-over crashes.

Based on the analysis of SPFs for total correctable crashes, the best expected technical and economical treatment, thus recommended for roadways with narrow shoulders and low AADTs is *SRS only*. For medium and large shoulders, the results were mixed. In these cases, for AADTs lower than 4,000 vehicles per day, the predominant expected best configuration was *CLRS only*. Therefore, this configuration is recommended for medium and large shoulders and AADTs lower than 4,000 vehicles per day. For AADTs greater than 4,000 vehicles per day, the *both* configuration is expected to perform better, thus it is recommended.

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Appendix A - A Study of Visibility of Pavement Markings

The objective of this pilot study was to have preliminary conclusions regarding the effects of CLRS on the nighttime visibility of pavement markings at dry and wet conditions. Two rural, undivided two-lane highways with CLRS were selected to provide the data. Both highways had the same type of pavement (asphalt), the same type of pavement marking paint (epoxy) installed on the same year (2008). The main difference between these two sections was the type of CLRS installed in each road. The first had rectangular CLRS and the second had football shaped CLRS. The visibility of pavement markings was expressed in terms of retroreflectivity, measured in millicandelas per square meter per lux (mcd/lx*m^2). Retroreflectivity data was collected by using the Delta LTLX hand-held retroreflectometer (showed in Figure A1.1), which has the depth ability of 14 mm. Data on dry and standard wet conditions were collected according to the ASTM E1710-05 and E2177-01, respectively.

Figure A1.1 Delta LTLX Retroreflectometer

Source: http://www.ara.com

The standard condition of wetness mimics conditions where the pavement markings are wet from humidity or dew, or after a rainfall has ended and the pavement markings are still wet. The standard wet test condition was achieved by pouring two liters of water over the markings' region to be tested and taking the measurements after 45 ± 5s from the moment the water was poured. In all cases (wet or dry conditions), readings were taken at every five cm in order to include measured areas over flat and (approximately four) rumble strip indentations. The average of six to 10 readings was considered as a data point. The hand-held retroreflectometer had a measurement geometry that mimics a viewing distance of 30 m, with a headlight mounting height of 65 cm and observer's eye height of 1.2 m. The measurements were conducted by placing the instrument directly over the markings, during day time with clear weather conditions and temperatures between 40º F and 108º F. A location per road without any rumble strip was selected in order to match the location with CLRS. Data was collected at three independent spots per location and the same spots were observed in every one of the three visits.

The data was analyzed as a repeated measures experiment, since data was collected in three visits per site, and the order of the visits was not randomized. Initially, four visits were performed, but in the first visit it was not possible to collect data in the dry condition, so this visit was not considered in the analysis. Table A1.1 shows the data collected in the two locations.

The first step of the statistical analysis was to determine the covariance structure that best fitted the data. It was achieved by using the repeated statement, varying the covariance type, in the Mixed procedure of SAS. Five different covariance structures were tested and evaluated according to three statistical goodness of fit criteria, AIC, AICC, and BIC.

Table A1.2 shows the goodness of fit results for the five covariance structures tested.

Table A1.1 Retroreflectivity Data

Visit	Date	CLRS Shape (75 = Football, 24 = Rectangular)	Spot	CLRS Presence	Wetness	**Average Readings (mcd/lx*m2)**
2	5-May-11	75	1	Yes	Dry	**107.88**
2	5-May-11	75	2	Yes	Dry	**97.43**
2	5-May-11	75	3	Yes	Dry	**118.88**
2	5-May-11	75	1	Yes	Wet	**32.86**
2	5-May-11	75	2	Yes	Wet	**29.00**
2	5-May-11	75	3	Yes	Wet	**43.22**
2	5-May-11	75	1	No	Dry	**101.38**
2	5-May-11	75	2	No	Dry	**86.00**
2	5-May-11	75	3	No	Dry	**77.13**
2	5-May-11	75	1	No	Wet	**24.50**
2	5-May-11	75	2	No	Wet	**6.71**
2	5-May-11	75	3	No	Wet	**19.50**
2	5-May-11	24	1	Yes	Dry	**69.86**
2	5-May-11	24	2	Yes	Dry	**45.13**
2	5-May-11	24	3	Yes	Dry	**52.00**
2	5-May-11	24	1	Yes	Wet	**31.57**
2	5-May-11	24	2	Yes	Wet	**16.50**
2	5-May-11	24	3	Yes	Wet	**20.14**
2	5-May-11	24	1	No	Dry	**28.00**
2	5-May-11	24	2	No	Dry	**38.57**
2	5-May-11	24	3	No	Dry	**36.50**
2	5-May-11	24	1	No	Wet	**0.71**
2	5-May-11	24	2	No	Wet	**3.57**
2	5-May-11	24	3	No	Wet	**4.38**
3	13-Jun-11	75	1	Yes	Dry	**78.89**
3	13-Jun-11	75	2	Yes	Dry	**75.38**
3	13-Jun-11	75	3	Yes	Dry	**115.75**
3	13-Jun-11	75	1	Yes	Wet	**29.71**
3	13-Jun-11	75	2	Yes	Wet	**34.25**
3	13-Jun-11	75	3	Yes	Wet	**31.38**
3	13-Jun-11	75	1	No	Dry	**135.33**
3	13-Jun-11	75	2	No	Dry	**173.78**
3	13-Jun-11	75	3	No	Dry	**190.75**
3	13-Jun-11	75	1	No	Wet	**19.60**
3	13-Jun-11	75	2	No	Wet	**53.67**
3	13-Jun-11	75	3	No	Wet	**41.38**

Visit	Date	Road = CLRS Shape (75 = Football, 24 = Rectangular)	Spot	CLRS Presence	Wetness	**Average Readings (mcd/lx*m2)**
3	13-Jun-11	24	1	Yes	Dry	**82.50**
3	13-Jun-11	24	2	Yes	Dry	**95.67**
3	13-Jun-11	24	3	Yes	Dry	**139.00**
3	13-Jun-11	24	1	Yes	Wet	**25.38**
3	13-Jun-11	24	2	Yes	Wet	**25.29**
3	13-Jun-11	24	3	Yes	Wet	**38.57**
3	13-Jun-11	24	1	No	Dry	**50.38**
3	13-Jun-11	24	2	No	Dry	**23.63**
3	13-Jun-11	24	3	No	Dry	**98.88**
3	13-Jun-11	24	1	No	Wet	**14.25**
3	13-Jun-11	24	2	No	Wet	**1.50**
3	13-Jun-11	24	3	No	Wet	**17.50**
4	19-Jul-11	75	1	Yes	Dry	**92.33**
4	19-Jul-11	75	2	Yes	Dry	**91.29**
4	19-Jul-11	75	3	Yes	Dry	**95.57**
4	19-Jul-11	75	1	Yes	Wet	**21.86**
4	19-Jul-11	75	2	Yes	Wet	**41.71**
4	19-Jul-11	75	3	Yes	Wet	**26.29**
4	19-Jul-11	75	1	No	Dry	**99.00**
4	19-Jul-11	75	2	No	Dry	**159.86**
4	19-Jul-11	75	3	No	Dry	**223.00**
4	19-Jul-11	75	1	No	Wet	**27.14**
4	19-Jul-11	75	2	No	Wet	**49.14**
4	19-Jul-11	75	3	No	Wet	**82.71**
4	19-Jul-11	24	1	Yes	Dry	**79.38**
4	19-Jul-11	24	2	Yes	Dry	**21.57**
4	19-Jul-11	24	3	Yes	Dry	**88.57**
4	19-Jul-11	24	1	Yes	Wet	**17.63**
4	19-Jul-11	24	2	Yes	Wet	**79.71**
4	19-Jul-11	24	3	Yes	Wet	**28.38**
4	19-Jul-11	24	1	No	Dry	**48.50**
4	19-Jul-11	24	2	No	Dry	**24.43**
4	19-Jul-11	24	3	No	Dry	**43.67**
4	19-Jul-11	24	1	No	Wet	**6.17**
4	19-Jul-11	24	2	No	Wet	**0.43**
4	19-Jul-11	24	3	No	Wet	**7.33**

Table A1.2 Goodness of Fit tests, according to Covariance Structures

Fit Statistics	Covariance Type				
	CS	AR(1)	HCS	HAR(1)	HF
AIC (smaller is better)	361.6	362.4	361.4	361.9	361.8
AICC (smaller is better)	362.0	362.7	362.6	363.2	363.0
BIC (smaller is better)	364.0	364.7	366.1	366.6	366.5

Since the compound symmetry (CS) structure presented the smallest results for two of the criteria, it was selected. An ANOVA analysis was conducted as a split-plot design. There were two error terms. The first error term, to test the whole plot effects, was the combination of two-way and three-way interactions involving the term spot within road. The second error term, to test the split-plot effects, was the combination of the three-way and four way interactions involving the terms visit and spot within road. Tables A1.3 to A1.5 present the results of the ANOVA analysis.

Table A1.3 ANOVA Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Road	1	12	38.19	<.0001
Spot(Road)	4	12	2.95	0.0651
Wetness	1	12	93.81	<.0001
CLRS	1	12	1.70	0.2162
Wetness*CLRS	1	12	2.32	0.1535
Road*Water	1	12	8.39	0.0134
Road*CLRS	1	12	34.89	<.0001
Road*Wetness*CLRS	1	12	7.25	0.0196
Visit	2	24	7.31	0.0033
Road*Visit	2	24	4.14	0.0286
Spot*Visit(Road)	8	24	0.66	0.7203
Wetness*Visit	2	24	3.40	0.0501
CLRS*Visit	2	24	1.01	0.3797
Wetness*CLRS*Visit	2	24	0.16	0.8562
Road*Wetness*Visit	2	24	0.90	0.4181
Road*CLRS*Visit	2	24	2.04	0.1516
Road*Wetness*CLRS*Visit	2	24	2.20	0.1327

Table A1.4 Least Square Means

Effect	Wetness	CLRS	Road	Spot	Visit	Estimate	Standard Error	DF	t Value	Pr > |t|	95% CI Lower	95% CI Upper
Road			24			45.9448	5.2101	12	8.82	<.0001	34.5930	57.2966
Road			75			91.4778	5.2101	12	17.56	<.0001	80.1260	102.83
Spot(Road)			24	1		40.6210	9.0241	12	4.50	0.0007	20.9592	60.2829
Spot(Road)			24	2		35.8621	9.0241	12	3.97	0.0018	16.2002	55.5240
Spot(Road)			24	3		61.3512	9.0241	12	6.80	<.0001	41.6893	81.0131
Spot(Road)			75	1		73.4872	9.0241	12	8.14	<.0001	53.8253	93.1490
Spot(Road)			75	2		93.0861	9.0241	12	10.32	<.0001	73.4243	112.75
Spot(Road)			75	3		107.86	9.0241	12	11.95	<.0001	88.1982	127.52
Wetness	Dry					104.39	5.2101	12	20.04	<.0001	93.0416	115.75
Wetness	Wet					33.0292	5.2101	12	6.34	<.0001	21.6774	44.3810
CLRS		No				73.5211	5.2101	12	14.11	<.0001	62.1693	84.8729
CLRS		Yes				63.9015	5.2101	12	12.26	<.0001	52.5497	75.2533
Wetness*CLRS	Dry	No				114.82	7.3682	12	15.58	<.0001	98.7632	130.87
Wetness*CLRS	Dry	Yes				93.9697	7.3682	12	12.75	<.0001	77.9158	110.02
Wetness*CLRS	Wet	No				32.2251	7.3682	12	4.37	0.0009	16.1713	48.2790
Wetness*CLRS	Wet	Yes				33.8333	7.3682	12	4.59	0.0006	17.7795	49.8872
Road*Wetness	Dry		24			70.9570	7.3682	12	9.63	<.0001	54.9032	87.0109
Road*Wetness	Wet		24			20.9325	7.3682	12	2.84	0.0149	4.8787	36.9864
Road*Wetness	Dry		75			137.83	7.3682	12	18.71	<.0001	121.78	153.88
Road*Wetness	Wet		75			45.1259	7.3682	12	6.12	<.0001	29.0721	61.1798
Road*CLRS		No	24			28.9934	7.3682	12	3.93	0.0020	12.9395	45.0472
Road*CLRS		Yes	24			62.8962	7.3682	12	8.54	<.0001	46.8423	78.9500
Road*CLRS		No	75			118.05	7.3682	12	16.02	<.0001	101.99	134.10
Road*CLRS		Yes	75			64.9069	7.3682	12	8.81	<.0001	48.8530	80.9607
Road*Wetness*CLRS	Dry	No	24			49.7030	10.4202	12	4.77	0.0005	26.9995	72.4066
Road*Wetness*CLRS	Dry	Yes	24			92.2110	10.4202	12	8.85	<.0001	69.5074	114.91
Road*Wetness*CLRS	Wet	No	24			8.2837	10.4202	12	0.79	0.4421	-14.4198	30.9873
Road*Wetness*CLRS	Wet	Yes	24			33.5813	10.4202	12	3.22	0.0073	10.8778	56.2849
Road*Wetness*CLRS	Dry	No	75			179.93	10.4202	12	17.27	<.0001	157.23	202.63
Road*Wetness*CLRS	Dry	Yes	75			95.7284	10.4202	12	9.19	<.0001	73.0248	118.43
Road*Wetness*CLRS	Wet	No	75			56.1665	10.4202	12	5.39	0.0002	33.4630	78.8701
Road*Wetness*CLRS	Wet	Yes	75			34.0853	10.4202	12	3.27	0.0067	11.3817	56.7889
Visit					2	66.3492	4.6629	24	14.23	<.0001	56.7253	75.9730
Visit					3	60.6525	4.6629	24	13.01	<.0001	51.0287	70.2764
Visit					4	79.1322	4.6629	24	16.97	<.0001	69.5083	88.7560
Road*Visit			24		2	51.0437	6.5944	24	7.74	<.0001	37.4335	64.6538
Road*Visit			24		3	37.1463	6.5944	24	5.63	<.0001	23.5362	50.7565
Road*Visit			24		4	49.6443	6.5944	24	7.53	<.0001	36.0342	63.2545
Road*Visit			75		2	81.6547	6.5944	24	12.38	<.0001	68.0445	95.2648
Road*Visit			75		3	84.1587	6.5944	24	12.76	<.0001	70.5486	97.7689
Road*Visit			75		4	108.62	6.5944	24	16.47	<.0001	95.0099	122.23
Spot*Visit(Road)			24	1	2	43.1250	11.4218	24	3.78	0.0009	19.5515	66.6985
Spot*Visit(Road)			24	1	3	37.9167	11.4218	24	3.32	0.0029	14.3432	61.4902
Spot*Visit(Road)			24	1	4	40.8214	11.4218	24	3.57	0.0015	17.2479	64.3949
Spot*Visit(Road)			24	2	2	36.5193	11.4218	24	3.20	0.0039	12.9458	60.0929
Spot*Visit(Road)			24	2	3	31.5357	11.4218	24	2.76	0.0109	7.9622	55.1092
Spot*Visit(Road)			24	2	4	39.5312	11.4218	24	3.46	0.0020	15.9577	63.1048

Effect	Wetness	CLRS	Road	Spot	Visit	Estimate	Standard Error	DF	t Value	Pr > |t|	95% CI Lower	95% CI Upper
Spot*Visit(Road)			24	3	2	73.4866	11.4218	24	6.43	<.0001	49.9131	97.0601
Spot*Visit(Road)			24	3	3	41.9866	11.4218	24	3.68	0.0012	18.4131	65.5601
Spot*Visit(Road)			24	3	4	68.5804	11.4218	24	6.00	<.0001	45.0068	92.1539
Spot*Visit(Road)			75	1	2	65.8841	11.4218	24	5.77	<.0001	42.3106	89.4576
Spot*Visit(Road)			75	1	3	60.0833	11.4218	24	5.26	<.0001	36.5098	83.6568
Spot*Visit(Road)			75	1	4	94.4940	11.4218	24	8.27	<.0001	70.9205	118.07
Spot*Visit(Road)			75	2	2	84.2674	11.4218	24	7.38	<.0001	60.6938	107.84
Spot*Visit(Road)			75	2	3	85.5000	11.4218	24	7.49	<.0001	61.9265	109.07
Spot*Visit(Road)			75	2	4	109.49	11.4218	24	9.59	<.0001	85.9176	133.06
Spot*Visit(Road)			75	3	2	94.8125	11.4218	24	8.30	<.0001	71.2390	118.39
Spot*Visit(Road)			75	3	3	106.89	11.4218	24	9.36	<.0001	83.3193	130.47
Spot*Visit(Road)			75	3	4	121.88	11.4218	24	10.67	<.0001	98.3015	145.45
Wetness*Visit	Dry				2	104.99	6.5944	24	15.92	<.0001	91.3829	118.60
Wetness*Visit	Dry				3	88.9301	6.5944	24	13.49	<.0001	75.3199	102.54
Wetness*Visit	Dry				4	119.26	6.5944	24	18.08	<.0001	105.65	132.87
Wetness*Visit	Wet				2	27.7053	6.5944	24	4.20	0.0003	14.0951	41.3154
Wetness*Visit	Wet				3	32.3750	6.5944	24	4.91	<.0001	18.7648	45.9852
Wetness*Visit	Wet				4	39.0074	6.5944	24	5.92	<.0001	25.3973	52.6176
CLRS*Visit		No			2	68.3856	6.5944	24	10.37	<.0001	54.7755	81.9958
CLRS*Visit		No			3	64.2817	6.5944	24	9.75	<.0001	50.6716	77.8919
CLRS*Visit		No			4	87.8958	6.5944	24	13.33	<.0001	74.2857	101.51
CLRS*Visit		Yes			2	64.3127	6.5944	24	9.75	<.0001	50.7025	77.9228
CLRS*Visit		Yes			3	57.0233	6.5944	24	8.65	<.0001	43.4131	70.6335
CLRS*Visit		Yes			4	70.3686	6.5944	24	10.67	<.0001	56.7584	83.9787
Wetness*CLRS*Visit	Dry	No			2	112.12	9.3259	24	12.02	<.0001	92.8750	131.37
Wetness*CLRS*Visit	Dry	No			3	99.7421	9.3259	24	10.70	<.0001	80.4944	118.99
Wetness*CLRS*Visit	Dry	No			4	132.59	9.3259	24	14.22	<.0001	113.34	151.83
Wetness*CLRS*Visit	Dry	Yes			2	97.8634	9.3259	24	10.49	<.0001	78.6157	117.11
Wetness*CLRS*Visit	Dry	Yes			3	78.1181	9.3259	24	8.38	<.0001	58.8704	97.3657
Wetness*CLRS*Visit	Dry	Yes			4	105.93	9.3259	24	11.36	<.0001	86.6799	125.18
Wetness*CLRS*Visit	Wet	No			2	24.6486	9.3259	24	2.64	0.0142	5.4009	43.8963
Wetness*CLRS*Visit	Wet	No			3	28.8214	9.3259	24	3.09	0.0050	9.5737	48.0691
Wetness*CLRS*Visit	Wet	No			4	43.2054	9.3259	24	4.63	0.0001	23.9577	62.4531
Wetness*CLRS*Visit	Wet	Yes			2	30.7619	9.3259	24	3.30	0.0030	11.5142	50.0096
Wetness*CLRS*Visit	Wet	Yes			3	35.9286	9.3259	24	3.85	0.0008	16.6809	55.1763
Wetness*CLRS*Visit	Wet	Yes			4	34.8095	9.3259	24	3.73	0.0010	15.5618	54.0572
Road*Wetness*Visit	Dry		24		2	81.6736	9.3259	24	8.76	<.0001	62.4259	100.92
Road*Wetness*Visit	Dry		24		3	51.0188	9.3259	24	5.47	<.0001	31.7712	70.2665
Road*Wetness*Visit	Dry		24		4	80.1786	9.3259	24	8.60	<.0001	60.9309	99.4263
Road*Wetness*Visit	Wet		24		2	20.4137	9.3259	24	2.19	0.0386	1.1660	39.6614
Road*Wetness*Visit	Wet		24		3	23.2738	9.3259	24	2.50	0.0198	4.0261	42.5215
Road*Wetness*Visit	Wet		24		4	19.1101	9.3259	24	2.05	0.0515	-0.1376	38.3578
Road*Wetness*Visit	Dry		75		2	128.31	9.3259	24	13.76	<.0001	109.06	147.56
Road*Wetness*Visit	Dry		75		3	126.84	9.3259	24	13.60	<.0001	107.59	146.09
Road*Wetness*Visit	Dry		75		4	158.34	9.3259	24	16.98	<.0001	139.09	177.58
Road*Wetness*Visit	Wet		75		2	34.9968	9.3259	24	3.75	0.0010	15.7491	54.2445
Road*Wetness*Visit	Wet		75		3	41.4762	9.3259	24	4.45	0.0002	22.2285	60.7239
Road*Wetness*Visit	Wet		75		4	58.9048	9.3259	24	6.32	<.0001	39.6571	78.1525
Road*CLRS*Visit		No	24		2	34.3542	9.3259	24	3.68	0.0012	15.1065	53.6019

Effect	Wetness	CLRS	Road	Spot	Visit	Estimate	Standard Error	DF	t Value	Pr > |t|	95% CI Lower	95% CI Upper
Road*CLRS*Visit		No	24		3	21.7540	9.3259	24	2.33	0.0284	2.5063	41.0017
Road*CLRS*Visit		No	24		4	30.8720	9.3259	24	3.31	0.0029	11.6243	50.1197
Road*CLRS*Visit		Yes	24		2	67.7331	9.3259	24	7.26	<.0001	48.4854	86.9808
Road*CLRS*Visit		Yes	24		3	52.5387	9.3259	24	5.63	<.0001	33.2910	71.7864
Road*CLRS*Visit		Yes	24		4	68.4167	9.3259	24	7.34	<.0001	49.1690	87.6644
Road*CLRS*Visit		No	75		2	102.42	9.3259	24	10.98	<.0001	83.1694	121.66
Road*CLRS*Visit		No	75		3	106.81	9.3259	24	11.45	<.0001	87.5618	126.06
Road*CLRS*Visit		No	75		4	144.92	9.3259	24	15.54	<.0001	125.67	164.17
Road*CLRS*Visit		Yes	75		2	60.8922	9.3259	24	6.53	<.0001	41.6445	80.1399
Road*CLRS*Visit		Yes	75		3	61.5079	9.3259	24	6.60	<.0001	42.2602	80.7556
Road*CLRS*Visit		Yes	75		4	72.3204	9.3259	24	7.75	<.0001	53.0727	91.5681
Road*Wetn*CLRS*Visit	Dry	No	24		2	57.6250	13.1888	24	4.37	0.0002	30.4047	84.8453
Road*Wetn*CLRS*Visit	Dry	No	24		3	38.8651	13.1888	24	2.95	0.0070	11.6447	66.0854
Road*Wetn*CLRS*Visit	Dry	No	24		4	52.6190	13.1888	24	3.99	0.0005	25.3987	79.8394
Road*Wetn*CLRS*Visit	Dry	Yes	24		2	105.72	13.1888	24	8.02	<.0001	78.5019	132.94
Road*Wetn*CLRS*Visit	Dry	Yes	24		3	63.1726	13.1888	24	4.79	<.0001	35.9523	90.3930
Road*Wetn*CLRS*Visit	Dry	Yes	24		4	107.74	13.1888	24	8.17	<.0001	80.5177	134.96
Road*Wetn*CLRS*Visit	Wet	No	24		2	11.0833	13.1888	24	0.84	0.4090	-16.1370	38.3037
Road*Wetn*CLRS*Visit	Wet	No	24		3	4.6429	13.1888	24	0.35	0.7279	-22.5775	31.8632
Road*Wetn*CLRS*Visit	Wet	No	24		4	9.1250	13.1888	24	0.69	0.4957	-18.0953	36.3453
Road*Wetn*CLRS*Visit	Wet	Yes	24		2	29.7440	13.1888	24	2.26	0.0335	2.5237	56.9644
Road*Wetn*CLRS*Visit	Wet	Yes	24		3	41.9048	13.1888	24	3.18	0.0041	14.6844	69.1251
Road*Wetn*CLRS*Visit	Wet	Yes	24		4	29.0952	13.1888	24	2.21	0.0372	1.8749	56.3156
Road*Wetn*CLRS*Visit	Dry	No	75		2	166.62	13.1888	24	12.63	<.0001	139.40	193.84
Road*Wetn*CLRS*Visit	Dry	No	75		3	160.62	13.1888	24	12.18	<.0001	133.40	187.84
Road*Wetn*CLRS*Visit	Dry	No	75		4	212.55	13.1888	24	16.12	<.0001	185.33	239.77
Road*Wetn*CLRS*Visit	Dry	Yes	75		2	90.0046	13.1888	24	6.82	<.0001	62.7843	117.22
Road*Wetn*CLRS*Visit	Dry	Yes	75		3	93.0635	13.1888	24	7.06	<.0001	65.8431	120.28
Road*Wetn*CLRS*Visit	Dry	Yes	75		4	104.12	13.1888	24	7.89	<.0001	76.8967	131.34
Road*Wetn*CLRS*Visit	Wet	No	75		2	38.2139	13.1888	24	2.90	0.0079	10.9935	65.4342
Road*Wetn*CLRS*Visit	Wet	No	75		3	53.0000	13.1888	24	4.02	0.0005	25.7797	80.2203
Road*Wetn*CLRS*Visit	Wet	No	75		4	77.2857	13.1888	24	5.86	<.0001	50.0654	104.51
Road*Wetn*CLRS*Visit	Wet	Yes	75		2	31.7798	13.1888	24	2.41	0.0240	4.5594	59.0001
Road*Wetn*CLRS*Visit	Wet	Yes	75		3	29.9524	13.1888	24	2.27	0.0324	2.7320	57.1727
Road*Wetn*CLRS*Visit	Wet	Yes	75		4	40.5238	13.1888	24	3.07	0.0052	13.3035	67.7442

Table A1.5 Differences of Least Square Means

Effect	Wetness	CLRS	Road	Visit	_Wetness	_CLRS	_Road	_Visit	Estimate	St Error	DF	t Value	Pr > |t|
Road			24				75		-45.5330	7.3682	12	-6.18	<.0001
Wetness	Dry				Wet				71.3641	7.3682	12	9.69	<.0001
CLRS		No				Yes			9.6196	7.3682	12	1.31	0.2162
Wetness*CLRS	Dry	No			Dry	Yes			20.8473	10.4202	12	2.00	0.0686
Wetness*CLRS	Dry	No			Wet	No			82.5919	10.4202	12	7.93	<.0001
Wetness*CLRS	Dry	No			Wet	Yes			80.9837	10.4202	12	7.77	<.0001
Wetness*CLRS	Dry	Yes			Wet	No			61.7446	10.4202	12	5.93	<.0001
Wetness*CLRS	Dry	Yes			Wet	Yes			60.1364	10.4202	12	5.77	<.0001
Wetness*CLRS	Wet	No			Wet	Yes			-1.6082	10.4202	12	-0.15	0.8799
Road*Wetness	Dry		24		Wet		24		50.0245	10.4202	12	4.80	0.0004
Road*Wetness	Dry		24		Dry		75		-66.8727	10.4202	12	-6.42	<.0001
Road*Wetness	Dry		24		Wet		75		25.8311	10.4202	12	2.48	0.0290
Road*Wetness	Wet		24		Dry		75		-116.90	10.4202	12	-11.22	<.0001
Road*Wetness	Wet		24		Wet		75		-24.1934	10.4202	12	-2.32	0.0386
Road*Wetness	Dry		75		Wet		75		92.7038	10.4202	12	8.90	<.0001
Road*CLRS		No	24			Yes	24		-33.9028	10.4202	12	-3.25	0.0069
Road*CLRS		No	24			No	75		-89.0554	10.4202	12	-8.55	<.0001
Road*CLRS		No	24			Yes	75		-35.9135	10.4202	12	-3.45	0.0048
Road*CLRS		Yes	24			No	75		-55.1526	10.4202	12	-5.29	0.0002
Road*CLRS		Yes	24			Yes	75		-2.0107	10.4202	12	-0.19	0.8502
Road*CLRS		No	75			Yes	75		53.1419	10.4202	12	5.10	0.0003
Road*Wetness*CLRS	Dry	No	24		Dry	Yes	24		-42.5079	14.7363	12	-2.88	0.0137
Road*Wetness*CLRS	Dry	No	24		Wet	No	24		41.4193	14.7363	12	2.81	0.0157
Road*Wetness*CLRS	Dry	No	24		Dry	No	75		-130.23	14.7363	12	-8.84	<.0001
Road*Wetness*CLRS	Dry	Yes	24		Wet	Yes	24		58.6296	14.7363	12	3.98	0.0018
Road*Wetness*CLRS	Dry	Yes	24		Dry	Yes	75		-3.5174	14.7363	12	-0.24	0.8154
Road*Wetness*CLRS	Dry	Yes	24		Wet	Yes	75		58.1257	14.7363	12	3.94	0.0019
Road*Wetness*CLRS	Wet	No	24		Wet	Yes	24		-25.2976	14.7363	12	-1.72	0.1117
Road*Wetness*CLRS	Wet	No	24		Wet	No	75		-47.8828	14.7363	12	-3.25	0.0070
Road*Wetness*CLRS	Wet	No	24		Wet	Yes	75		-25.8016	14.7363	12	-1.75	0.1055
Road*Wetness*CLRS	Wet	Yes	24		Wet	Yes	75		-0.5040	14.7363	12	-0.03	0.9733
Road*Wetness*CLRS	Dry	No	75		Dry	Yes	75		84.2026	14.7363	12	5.71	<.0001
Road*Wetness*CLRS	Dry	No	75		Wet	No	75		123.76	14.7363	12	8.40	<.0001
Road*Wetness*CLRS	Dry	Yes	75		Wet	Yes	75		61.6431	14.7363	12	4.18	0.0013
Road*Wetness*CLRS	Wet	No	75		Wet	Yes	75		22.0812	14.7363	12	1.50	0.1599
Visit				2				3	5.6966	4.9509	24	1.15	0.2612
Visit				2				4	-12.7830	4.9509	24	-2.58	0.0164
Visit				3				4	-18.4797	4.9509	24	-3.73	0.0010
Road*Visit			24	2			24	3	13.8973	7.0017	24	1.98	0.0587
Road*Visit			24	2			24	4	1.3993	7.0017	24	0.20	0.8433
Road*Visit			24	2			75	2	-30.6110	9.3259	24	-3.28	0.0031
Road*Visit			24	2			75	3	-33.1151	9.3259	24	-3.55	0.0016
Road*Visit			24	2			75	4	-57.5764	9.3259	24	-6.17	<.0001
Road*Visit			24	3			24	4	-12.4980	7.0017	24	-1.79	0.0869
Road*Visit			24	3			75	2	-44.5083	9.3259	24	-4.77	<.0001
Road*Visit			24	3			75	3	-47.0124	9.3259	24	-5.04	<.0001
Road*Visit			24	3			75	4	-71.4737	9.3259	24	-7.66	<.0001
Road*Visit			24	4			75	2	-32.0103	9.3259	24	-3.43	0.0022
Road*Visit			24	4			75	3	-34.5144	9.3259	24	-3.70	0.0011

Effect	Wetness	CLRS	Road	Visit	_Wetness	_CLRS	_Road	_Visit	Estimate	St Error	DF	t Value	Pr > |t|
Road*Visit			24	4			75	4	-58.9757	9.3259	24	-6.32	<.0001
Road*Visit			75	2			75	3	-2.5041	7.0017	24	-0.36	0.7237
Road*Visit			75	2			75	4	-26.9654	7.0017	24	-3.85	0.0008
Road*Visit			75	3			75	4	-24.4613	7.0017	24	-3.49	0.0019
Wetness*Visit	Dry			2	Dry			3	16.0630	7.0017	24	2.29	0.0308
Wetness*Visit	Dry			2	Dry			4	-14.2639	7.0017	24	-2.04	0.0528
Wetness*Visit	Dry			2	Wet			2	77.2878	9.3259	24	8.29	<.0001
Wetness*Visit	Dry			2	Wet			3	72.6181	9.3259	24	7.79	<.0001
Wetness*Visit	Dry			2	Wet			4	65.9856	9.3259	24	7.08	<.0001
Wetness*Visit	Dry			3	Dry			4	-30.3269	7.0017	24	-4.33	0.0002
Wetness*Visit	Dry			3	Wet			2	61.2248	9.3259	24	6.57	<.0001
Wetness*Visit	Dry			3	Wet			3	56.5551	9.3259	24	6.06	<.0001
Wetness*Visit	Dry			3	Wet			4	49.9226	9.3259	24	5.35	<.0001
Wetness*Visit	Dry			4	Wet			2	91.5517	9.3259	24	9.82	<.0001
Wetness*Visit	Dry			4	Wet			3	86.8819	9.3259	24	9.32	<.0001
Wetness*Visit	Dry			4	Wet			4	80.2495	9.3259	24	8.61	<.0001
Wetness*Visit	Wet			2	Wet			3	-4.6697	7.0017	24	-0.67	0.5112
Wetness*Visit	Wet			2	Wet			4	-11.3022	7.0017	24	-1.61	0.1196
Wetness*Visit	Wet			3	Wet			4	-6.6324	7.0017	24	-0.95	0.3529

This study was performed to provide preliminary information to answer the question:

how CLRS affect the visibility of pavement markings over time for dry and wet conditions?

From the results shown in Tables A1.3 – A1.5, it is possible to conclude the following:

- The interval of time (about 40 days) used between visits perhaps was not sufficient to reveal expected changes in retroreflectivity, since results of visit four showed greater retroreflectivity levels, followed by the second and then by the third visit (results of visit one were disregarded since the dry condition was not observed). The expected results would be that retroreflectivity levels decrease over time (see Table 1.3 for factors influencing the pavement marking performance). The non-expected results may reflect an effect of ambient temperature, which could have caused condensation on the retroreflectometer glass lenses.
- The three-way interaction involving road, wetness conditions, and CLRS presence was significant. It means that the differences between dry and standard wet conditions depended on the CLRS presence and shape, that the differences between CLRS shapes depended on the wetness condition, and that the differences between the presence or not of CLRS (smooth vs. CLRS results) depended on the wetness condition and on the CLRS shape, as shown in Table A.5.
- There was a statistically significant difference between dry and wet conditions. Overall, the dry condition presented higher levels of retroreflectivity than the standard wet condition, but it depended on CLRS shape and CLRS presence levels.
- There was a statistically significant difference in the interaction between road (factor confounded with rumble strip shape) and the presence of CLRS. At the location with the football shaped CLRS, the presence of CLRS decreased the retroreflectivity

levels, while at the location with rectangular CLRS, the presence of CLRS increased the results. It can be explained by the fact that the section without CLRS that matched the rectangular shaped section was located on a busy intersection and the pavement markings had suffered elevated wear damage due to high traffic volumes crossing the markings.

- It is suggested that future work should be conducted at more roads, with different types of pavement marking materials and at longer intervals of time between data collection visits.