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FINAL REPORT

PROMOTING CENTERLINE RUMBLE STRIPS TO INCREASE RURAL, TWO-LANE HIGHWAY SAFETY

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16 Abstract

In the United States, 60 percent of fatal accidents occur on rural roads. Among these, 90 percent occur on two-lane roads, and 20 percent of these accidents involve two vehicles traveling in opposite directions, totaling 4,500 fatal accidents per year. Centerline Rumble Strips (CLRS) are primarily installed on the centerline of undivided, two lane, two-way highways, and their main purpose is reduction of crossover accidents, specifically head-on and opposite direction sideswipe accidents, which are usually caused by driver inattention and/or drowsiness.

Several authors have reported advantages other than reducing accidents in installing CLRS, such as a high benefit-cost ratio, improvement of lateral vehicle position to the right, low interference in passing maneuvers, versatile installation conditions, and public approval. However, some concerns involving CLRS, such as disturbing noise for nearby residents, decreased visibility of the painted strips, faster pavement deterioration, potential driver erratic maneuvers to the left after encountering CLRS, and ice formation in the grooves, have been cited in the current literature.

The objective of this report is to summarize results of three studies conducted by Kansas State University in 2008 and 2009; addressing some of the above mentioned concerns related to the installations of CLRS.Centerline Rumble Strips do increase the levels of external noise.

Based on analysis using a light and medium vehicle, a distance of 200 feet from centerline should be considered. This is the distance where noise from CLRS is no longer greater than smooth pavement.

This study applied three methods of evaluating the visibility of pavement markings. Based only on the limited data collected, it can be concluded that the coverage check method should not substitute the retroreflectometer readings for studies of retroreflectivity, since the correlation of the two methods was not reliable. In addition, the spectrometry method should only be used as a complementary analysis. The spectrometry method revealed that the yellow pavement markings remained within the yellow spectrum over the study period at all three locations.

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PREFACE

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

NOTICE

DISCLAIMER

ABSTRACT

In the United States, 60 percent of fatal accidents occur on rural roads. Among these, 90 percent occur on two-lane roads, and 20 percent of these accidents involve two vehicles traveling in opposite directions, totaling 4,500 fatal accidents per year (Suzman, 1999; cited by Russell and Rys, 2005). Data from 2007 show 21,433 fatal accidents, or 57.5 percent of the total number of fatal accidents, occurred on undivided two-lane highways (NHTSA, 2007). Head-on (HO) and opposite-direction sideswipes (OPP SW) accidents represent 12.5 percent of fatal accidents and 10.3 percent of the total number of accidents (NHTSA, 2007).

In order to reduce the number of accidents, several state departments of transportation have installed rumble strips and other accident countermeasures on U.S. highways. Rumble strips are grooved or raised indentations, placed on the shoulder or on the pavement of a travel lane. The primary purpose of the strips is to prevent accidents by providing noise and vibration when crossed by vehicles, alerting drivers. In the United States (U.S.), four different types of rumble strips have been used: milled, raised, rolled, and formed (Richards and Saito, 2007).

- Milled: Type of rumble strips made by a machine that cuts grooves in the pavement surface. It is the most common type in the U.S.
- Rolled: Type of rumble strips made by a roller machine that presses into hot asphalt surfaces to create grooves. They must be installed during pavement compaction.
- Formed: Type of rumble strips that are formed in concrete pavements during the finishing process.

- Raised: Type of rumble strips installed over pavements by the adherence of various materials.

CENTERLINE RUMBLE STRIPS

Centerline rumble strips (CLRS) are primarily installed on the centerline of undivided, two lane, two-way highways, and their main purpose is reduction of crossover accidents, specifically head-on and opposite direction sideswipe accidents, which are usually caused by driver inattention and/or drowsiness.

After CLRS were accepted as an efficient method for reducing crossover accidents, their use in the United States has been increasing over the years. Chen and Cottrell (2005) reported that 24 states in the U.S. have installed CLRS. In addition, according to Richards and Saito (2007), there are more than 2,400 miles of CLRS installed in the country, and the most common pattern dimensions are length (dimension perpendicular to the travel lane) of 16 inches, width (dimension parallel to the travel lane) of 7 inches, depth of 0.5 inches, and spacing (center to center) of 12 inches. Several authors have reported advantages other than reducing accidents in installing CLRS, such as a high benefit-cost ratio, improvement of lateral vehicle position to the right, low interference in passing maneuvers, versatile installation conditions, and public approval. However, some concerns involving CLRS, such as disturbing noise for nearby residents, decreased visibility of the painted stripes, faster pavement deterioration, potential driver erratic maneuvers to the left after encountering CLRS, and ice formation in the grooves, have been cited in the current literature (Russell and Rys, 2005). For this reason, a better understanding of the balance needed between safety and practical effects of CLRS depends on investigation of these concerns. The objective of this report is to summarize results of three studies conducted by Kansas State University in 2008 and 2009; addressing some of the above mentioned concerns related to the installations of CLRS. This report is divided into the following chapters. The first chapter presents a study of the safety-effectiveness of CLRS. The second chapter focuses on the exterior noise produced by vehicles travelling over the CLRS and their effect on nearby residences. Chapter three includes a study of retro-reflectivity of pavement markings placed over the CLRS. Appendix A contains results from the Motorcycle Riders' Safety survey and Appendix B contains results from the Noise Survey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - EVALUATION OF CENTERLINE RUMBLE STRIPS FOR PREVENTION OF HIGHWAY CROSSOVER ACCIDENTS IN KANSAS

The objective of this study was to investigate the effectiveness of milled-in CLRS in reducing the number of total and targeted crossover accidents in Kansas. The before-and-after Empirical Bayes (EB) method and the Naïve before-and-after method were applied and compared.

1.1 Literature Review

1.1.1 Naïve Before-and-After Method

The Naïve before-and-after method consists of a comparison between the number of accidents on a treated section in the after period and the number of accidents in the same section during the before period. This type of comparison is known to be biased due to the regression to the mean phenomenon, i.e. a section of highway that presented an elevated number of accidents in a period tends to have decreased number of accidents in a future period and vice versa, even with no improvement on the section. Although the Naïve method does not account for the regression to the mean bias, this method has been used in several studies of the effectiveness of CLRS in reducing accidents. Some results of studies that used the Naïve method are listed below:

- Fitzpatrick et al. (2000) reported a 90 percent reduction in fatal head-on accidents and 42 percent reduction in total head-on accidents after the installation of CLRS in a 23 mile section of a two-lane rural highway in California. The total period analyzed was 59 months.

- Outcalt (2001) reported a 34 percent reduction in head-on accidents, and 36.5 percent in sideswipe opposite-direction accidents, after the installation of CLRS in a 17 mile section of a two-lane rural highway in Colorado, even with an increase of 18 percent of annual average daily traffic (AADT). The total period was 44 months.
- Monsere (2002), cited by Russell and Rys (2005), reported an overall 69.5 percent reduction in crossover accidents after the installation of CLRS in two sections of approximately 8.5 miles each, one a four-lane, rural highway and the other a two-lane, rural highway in Oregon. DelDOT (2003) showed a 95 percent reduction in the average number of head-on accidents per year, 60 percent in the average per year of “drove left of the center” type of accident, and eight percent in the average per year of all types of accidents after the installation of CLRS in a 2.9 mile section of a two-lane rural highway in Delaware. However, this study showed a four percent increase in the average per year of total number of accidents involving injuries and 13 percent increase in the average per year number of accidents involving only property damage. The AADT increased four percent from the before to the after period. The total period analyzed was 10 years.
- According to Kar and Weeks (2009), Arizona DOT reported a decrease in the number of fatal and serious injury head-on and opposite- direction

sideswipe accidents, from 18 in the before period (2000 - 2002), to seven in the after period (2003 - 2005). Crashes per million vehicle miles traveled (MVMT) were calculated as follows: MVMT = (number of accidents * 1,000,000) / (AADT * 365 * segment length). In the before period, MVMT was approximately 0.025, and in the after period it was approximately 0.011. Thus, there was approximately a 56 percent reduction of these types of accidents after the installation of CLRS.

1.1.2 Empirical Bayes Method

The Empirical Bayes (EB) method estimates the number of accidents for the after period, based on linear regression analysis, using information from untreated sections with similar characteristics to the treated sections, and on historical crash information. The estimated number of accidents calculated is compared to the actual number of accidents recorded on the treated section in the after period.

Even though the EB method can be considered the most acceptable method to evaluate the characteristics of a treatment in reducing accidents over time, only one study that applied the EB method to investigate the safety-effectiveness of CLRS in reducing accidents was found in the literature. In this study, Persaud et al. (2004) used data from seven states and found an estimated reduction of approximately 21 percent (95 percent CI = 5-37 percent) in frontal and sideswipe opposing-direction types of accidents in treated sections of undivided, two-lane rural highways after the installation of CLRS. When injuries were involved in the same types of accidents, the reported reduction was estimated to be 25 percent (95 percent CI = 5-45 percent). Considering all types of accidents, the authors reported an estimated 14 percent (95 percent CI = 8-

20 percent) reduction of Injury accidents. All types of accidents were reduced by an estimated 15 percent (95 percent CI=15-25 percent). The total length of treated sections was 210 miles at 98 sites.

1.2 METHODOLOGY

The first installation of CLRS in Kansas occurred in June 2003, on approximately 15.2 miles of US-50, between Newton and Hutchinson, in Harvey County. Two different patterns of rectangular CLRS were installed in this location, alternating and continuous, as shown in Figure 1.1. In this report, this section will be referred to as section A. It consists of a two-lane, undivided, rural highway with a lane width of 12 feet, and some passing zones on hills, on a generally straight alignment. Surface type of the lanes and shoulders was bituminous. Width of the shoulders ranged between five to 10 feet, and the AADT on this section ranged from 4000 to 6000. The second section studied in this report had football-shaped CLRS installed in May 2005 in a segment of approximately 10.8 miles on US-40 between Lawrence and Topeka. Figure 1.2 illustrates the football shaped CLRS installed on US-40. In this report, this section will be referred to as section B. It was a two-lane, undivided, rural highway with lane width of 11 feet. It had a high percentage of no-passing zones with many horizontal and vertical curves. Surface type of the lanes was bituminous, and the three-foot shoulders had turf surface.

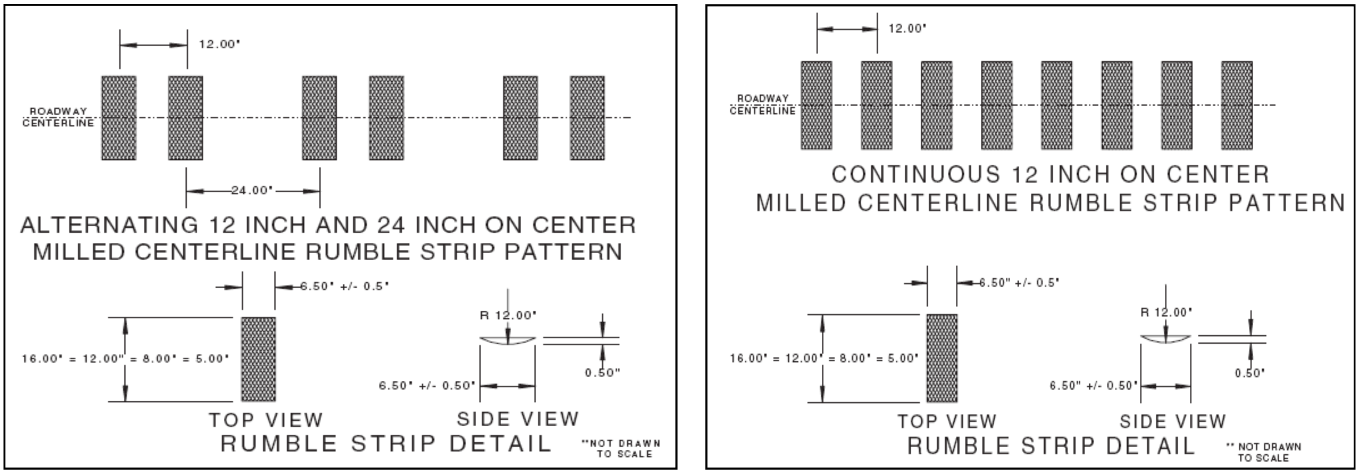


Figure 1.1: Patterns of CLRS installed on US-50. Source: Russell and Rys (2005)

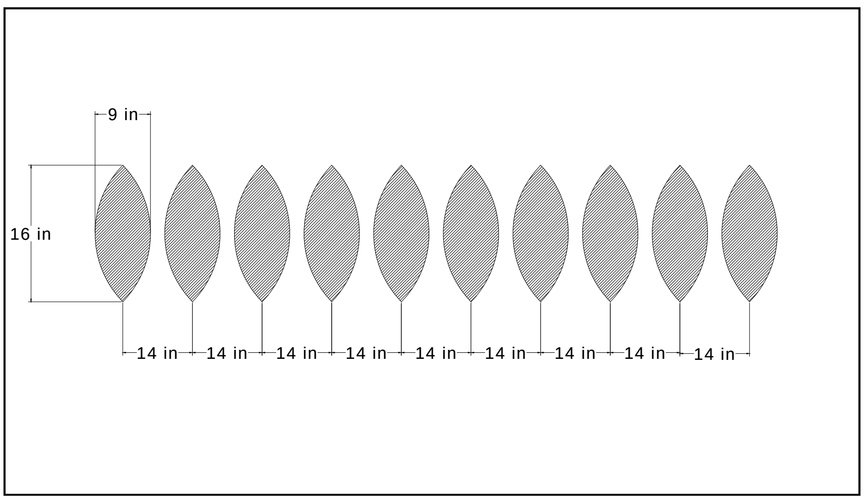


Figure 1.2: Football shaped CLRS installed on US-40. Source: Gardner (2006)

1.2.1 Naïve Before-and-After Method

This method calculates the number of accidents in the after period compared to the before period. For section A on US-50, the before period was from January 1998 to June 2003. The after period considered for this section was from July 2003 to December 2007. For section B, on US-40, the before period was from January 1998 to May 2005. The after period studied for this section was from June 2005 to December 2007.

Since the before and after periods for the two studied sections had different durations, the recorded number of accidents was divided by the duration of the period and by the length of the section. The comparable results were stated in annual accidents per mile.

1.2.2 Empirical Bayes Method

The methodology described in this section was based on Hauer (1997, 2002) and Harwood et al. (2002).

According to Patel *et al.* (2007), the concept of the EB method is to estimate the number of accidents that the sections of interest would have had in the after period if no treatment had been used, and compare this number to the actual number of accidents in the after period on the section submitted to treatment. Therefore, it is possible to estimate the influence of the treatment (CLRS) on the final result. In this report, the expected number of accidents in the after period was corrected due to differences in traffic volume over the periods and also the differences between the duration of the periods.

The estimated number of accidents in the after period if no treatment were used is not only based on historical information (accidents that occurred in the section of interest in the before period), but also uses data from a group of similar sites – highways without treatment with similar characteristics to the treated section (AADT, geometry, rate of accident per year, etc) to calibrate a safety performance function (SPF). 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 bias.

The SPFs can be obtained by performing a regression analysis, generally using a negative binomial distribution. In this report, the regression analyses were done using AADT as the only predictor for the total number of accidents in one mile of a specific group of highways. As a result, the SPF should predict the number of accidents per mile on a highway with determined characteristics, according to the volume of traffic. The most difficult task for a researcher, in order to apply the EB method, is to find sections that are comparable in terms of traffic, number of accidents, and geometry to the sections studied. In this report, the geometry and volume of traffic were the most important factors used to choose the similar sites.

KDOT provided the total number of accidents from sections that were used as potential similar sites to match section A on US-50 and section B on US-40. The AADT were obtained from KDOT traffic count maps, available online (KDOT, 2009).

In order to match section A on US-50, there were three potential similar sites available with the following characteristics: two-lane rural highways, lane width of 12 feet, surface type for lane and shoulder: bituminous, shoulder width ranging from five to 10 feet, AADT ranging from 3800 to 6500, and accident rate ranging from 1.926 to 4.259 accident per 100 MVM (million vehicle-miles of travel). The three locations were as follows:

- First, US-54 in Kiowa County, from the junction of US-54 and US-400 to the Pratt county line, excluding the cities of Greensburg and Haviland. It was divided into two sections, called Kiowa A, from county reference posts 6.443 to 14.410; and Kiowa B, from county reference posts 15.666 to 30.355.

- Second, US-75 in Montgomery County from US-75/US-166 to US-75/US-400. It was divided into three sections, called Montgomery A, from county reference posts 1.697 to 4.695; Montgomery B, from county reference posts 17.980 to 20.664; and Montgomery C, from county reference posts 26.311 to 33.493.
- Third, US-281 in Barton County from RS-981 to the transition 2L/4L undivided, about 1.5 miles north of RS-42. It was divided into three sections, called Barton A, from county reference posts 2.100 to 5.320; Barton B, from county reference posts 8.622 to 10.272; and Barton C, from county reference posts 12.330 to 17.059.

In order to match section B on US-40, four similar sites were available, and they had the following characteristics: two-lane rural highways, lane width of 11 feet, surface type for lane was bituminous, turf shoulder with a width of 3 feet and AADT ranging from 2000 to 5100, and accident rate ranging from 0 to 3.375 accident per 100 MVM (not considering US-24). The four locations were as follows:

- First, herein referred to as Douglas, US-24 from Douglas/Leavenworth County line to Tonganoxie south city limit. County reference posts 0.000 to 8.625.
- Second, herein referred to as Brown, KS-20 in Brown County from the JCT KS-20/RS-1265 to west city limit of Horton.
- Third, herein referred to as Cherokee, KS-7 in Cherokee County from the JCT KS-7/RS-1166 to JCT US-400/KS-7.

- Fourth, herein referred to as Franklin, KS-33 in Franklin County from the JCT I-35/KS-33 to south city limit of Wellsville.

In this study, the GENMOD procedure in the commercial Statistical Analysis System (SAS) software version 9.1 was used to compute the SPF functions. Since SAS 9.1 uses the natural logarithm as a link function in the GENMOD procedure, the model of the SPF function is exponential, as presented by Equation 1.1.

$$ACC = e^{\beta_0} * e^{(AADT_{Before} * \beta_1)} \qquad \text{Equation 1.1}$$

Where:

ACC = expected number of accidents (per mile per year) in a section with the same characteristics to the section of interest;

$AADT_{Before}$ = average AADT for the before period; and

β_0 and β_1= intercept and slope of the regression analysis.

The negative binomial regression analysis also gives the overdispersion parameter (*k*) per mile. It is discussed in more details in Hauer (2001).

The result of the EB method depends on how much “weight” is given to accidents in similar sites (first part of equation 1.2), and to the counted accidents in the treated sections during the before period (second part of Equation 1.2).

$$\text{estimated ACC} = \rho * ACC + (1-\rho) * \text{ACC Before} \qquad \text{Equation 1.2}$$

Where:

estimated ACC = expected number of accidents in a period with the same duration of the before period.

ρ = weight or how much influence is due to historical data or similar sites. This parameter was calculated using Equation 1.3.

$$\rho = \frac{1}{1 + (ACC / k)}$$ Equation 1.3

The standard deviation of e*stimated ACC*, denoted by σ_{EST}, was calculated by Equation 1.4.

$$\sigma_{EST} = \sqrt{\text{estimated ACC} * (1 - \rho)}$$ Equation 1.4

The corrected number of accidents that would have occurred in the after period if no treatment had been made was calculated by Equation 1.5.

$$\mu = \text{estimated ACC} * C_1 * C_2$$ Equation 1.5

Where:

C_1 = ratio between the result of equation 1, using $AADT_{After}$,and the result of the same equation, using $AADT_{Before}$. It is clear that the relation between AADT and the number of accidents in a period is not linear (it follows the function given by equation 1). For this reason, C1 was used to correct e*stimated ACC,* instead of the simple ratio between AADTs.

C_2 = ratio between the duration of the after period and the duration of the before period.

The variance of μ was calculated by Equation 1.6.

$$\text{Var } \mu = C_1^2 * C_2^2 * \sigma_{Est}^2$$ Equation 1.6

An estimate of the safety-effectiveness of the CLRS treatment can be obtained by the ratio between *ACC After* and *μ*. However, Hauer (1997) claims that an estimate like this is biased. A better estimate is obtained using Equation 1.7.

$$\omega = \frac{\text{ACC After}/\mu}{1 + (\text{Var } \mu / \mu^2)}$$ Equation 1.7

Where:

ω = unbiased estimate of safety effectiveness of a treated site, or more than one site (using sums of the terms).

The variance of ω was obtained by Equation 1.8.

$$\text{Var } \omega = \omega^2 * \left[\frac{(\text{Var ACC After}/\text{ACC After}^2) + (\text{Var } \mu/\mu^2)}{1 + (\text{Var } \mu/\mu^2)}\right]^2 \qquad \text{Equation 1.8}$$

where

Var ACC After = Variance of *ACC After* = ∑ *ACC After*.

Similar sites chosen and used to match section B on US-40 were US-24 in Douglas County and KS-33 in Franklin County. These were the only ones used due to lack of convergence of the SAS algorithm when using the data of other potential similar sites that were available.

Data from all potential similar sites were used to calculate the SPF for section A on US-50, since the algorithm on SAS converged.

Parameters of the regression analysis and goodness-of-fit of the SPF functions are presented in Table 1.1.

Table 1.1: Parameters of regressions and evaluation of goodness-of-fit of the SPF functions

SPF for US-40 - Total Accidents				SPF for US-50 - Total Accidents			
Parameter	**Estimate**	**SE**	**Pr > Chi Sq.**	**Parameter**	**Estimate**	**SE**	**Pr > Chi Sq.**
β_0	-1.2229	0.6328	0.0533	β_0	-1.4019	0.5569	0.0118
β_1	0.0007	0.0001	< 0.0001	β_1	0.0004	0.0001	< 0.0001
K	-0.0793	0.0245		*K*	-0.1475	0.0335	
Criterion	**DF**	**Value**	**Value/DF**	**Criterion**	**DF**	**Value**	**Value/DF**
Deviance	16	17.1240	1.0703	Deviance	62	48.8752	0.7883
Scaled Deviance	16	17.1240	1.0703	Scaled Deviance	62	48.8752	0.7883
Pearson Chi-Square	16	17.0100	1.0631	Pearson Chi-Square	62	48.7775	0.7867
Log Likelihood		92.6221		Log Likelihood		-24.3943	

In order to compute the head-on and opposite-direction sideswipe (HO + OPP SW) accidents that would be corrected by CLRS, all police accident reports for accidents in the treated sections of US-40 and US-50 were analyzed. Police reports of accidents from similar sites were not analyzed because the total number of accidents was used to calibrate SPF's, so it was not necessary to investigate the causes of the these accidents.. The potentially correctable crossover accidents considered occurred on non-intersection zones, due to drivers' inattention, influence of alcohol, and drivers that fell asleep. All accidents that occurred due to other factors were not considered as CLRS correctable, and were not computed in the analysis of HO + OPP SW accidents.

Another analysis was conducted using the total number of accidents, excluding those involving animals, intersections, or related to intersections. The effect of the treatment could be over or under estimated due to the presence of these types of accidents, because the incidence of animals and the number of intersections per mile of highway can be very different from one section to another, and there was no data available to determine these numbers.

In summary, two analyses were conducted. The first used the total number of accidents excluding intersections and animals. The second computed only HO + OPP SW types of accidents. Both analyses had the SPFs generated using total number of accidents (all types) as input data.

1.3 KEY FINDINGS

1.3.1 Naïve Before-and-After Method

Table 1.2 shows results of the Naïve before-and-after method.

Table 1.2: Results of the Naïve before-and-after method

	Section	**Length (miles)**	**Installation**	**Years**		**# Acc Before**	**# Acc After**	**Rate Before**	**Rate After**	**Reduction**
				Before	After					
Total	A on US-50	15.18	June, 2003	5.5	4.5	75	38	0.90	0.56	**38.07%**
	B on US-40	10.76	May, 2005	7.42	2.58	205	32	2.57	1.15	**55.11%**
	Overall	25.94				280	70	3.47	1.71	**50.69%**
	Section	**Length (miles)**	**Installation**	**Years**		**# Acc Before**	**# Acc After**	**Rate Before**	**Rate After**	**Reduction**
				Before	After					
HO + OPP SW	A on US-50	15.18	June, 2003	5.5	4.5	6	1	0.07	0.01	**79.63%**
	B on US-40	10.76	May, 2005	7.42	2.58	9	0	0.11	0.00	**100.00%**
	Overall	25.94				15	1	0.18	0.01	**92.07%**

During the before period on US-50 (section A), there were six HO or OPP SW accidents. Four of these were caused by drivers' inattention, one occurred due to alcohol influence, and one due to a driver falling asleep. During the after period in the same section, there was only one accident, caused by driver's inattention. Considering the section of US-40, nine HO or OPP SW accidents occurred in the before period. Five of these occurred due to drivers' inattention, two due to alcohol influence, and two due to drivers that fell asleep. No HO or OPP SW accident occurred in this section during the after period.

Results of the Naïve method showed that in section A on US-50, the number of total accidents per mile per year (excluding animals and intersections) decreased 38.07 percent in the after period compared to the before period. The number of crossover accidents (head-on and opposite-direction sideswipe) decreased 79.63 percent in this section after the installation of CLRS. In section B on US-40, the number of total accidents per mile per year decreased 55.11 percent. The number of crossover accidents decreased 100 percent, since no crossover accidents occurred in this section after the installation of CLRS. Overall, the number of total accidents per mile per year decreased 50.69 percent. The number of crossover accidents decreased 92.07 percent. It is clear that CLRS are not capable of reducing all types of accidents. However, results of the Naïve method provide evidence that CLRS are potentially effective in reducing total number of accidents, and are particularly effective in reducing head-on and opposite-direction sideswipe accidents.

1.3.2 Empirical Bayes Method

Table 1.3 presents the analysis of safety effectiveness in the sections treated with CLRS, using the EB method.

Table 1.3: Safety effectiveness in sections treated with CLRS – EB method

Section	AADT Before	AADT After	Counted Accidents During After Period with Treatment		Expected Accidents During After Period in case of no Treatment		Reduction	
			Total	HO + OPP SW	Total (σ)	HO + OPP SW (σ)	Total (95% CI)	HO + OPP SW (95% CI)
A on US-50	5524	5036	38	1	53.93 (6.23)	4.22 (1.74)	30.47%	79.75%
							(27.93% - 33.01%)	(68.03% - 91.46%)
B on US-40	4255	4465	52	0	83.83 (5.86)	3.65 (1.22)	62.01%	100.00%
							(61.44% - 62.58%)	
Overall			**90**	**1**	**137.76 (8.55)**	**8.68 (2.21)**	**49.38%**	**89.18%**
							(47.58% - 51.18%)	**(66.70% - 111.67%)**

Section A on US-50 presented a statistically significant reduction, estimated as 30.47 percent, in number of total accidents and 79.75 percent in number of HO+OPP SW accidents. Considering section B, the reduction of total accidents was statistically significant and estimated as 62.01 percent. The targeted crossover accidents were reduced from 3.65 to zero (100 percent of reduction). Section B, treated with football-shaped CLRS, presented a potentially better effect when compared with section A, treated with rectangular CLRS. However, this comparison may have limited validity due to differences in other variables relative to the sections.

Overall, considering both sections, reduction of total accidents (excluding animals and intersections) was significant and estimated as 49.38 percent, and reduction of the targeted crossover (HO + OPP SW) accidents was also statistically significant and estimated as 89.18 percent. Thus, the treatments were effective in decreasing both the number of total and crossover accidents.

Table 1.4 summarizes the results of this report, comparing the two methods.

Table 1.4: Comparison between results of the Naïve and EB methods

Section	Naïve Total	EB Total (95% CI)	Naïve HO + OPP SW	EB HO + OPP SW (95% CI)
A on US-50	38.07%	30.47% (27.93% - 33.01%)	79.63%	79.75% (68.03% - 91.46%)
B on US-40	55.11%	62.01% (61.44% - 62.58%)	100.00%	100.00%
Overall	**50.69%**	**49.38% (47.58% - 51.18%)**	**92.07%**	**89.18% (66.70% - 111.67%)**

The comparison of the results of the two methods reveals that the reduction in the total number of accidents, calculated by the Naïve method, is comparable with the reduction found by the EB method. Considering the targeted crossover accidents, results of the two methods are also comparable.

In summary, both methods showed a significant reduction in accidents after the installation of CLRS. It is concluded that the treatments had a positive effect in reducing both crossover accidents and total accidents in the two analyzed sections.

1.3.3 Comparison to Other States

Although there are a considerable number of studies about the effectiveness of CLRS in reducing accidents in the U.S., types of accidents evaluated in these studies are not consistent. Therefore, in order to achieve a better comparison between the results found in Kansas and other studies, extra calculations were necessary, using the same methodology previously cited for the Naïve and EB methods.

Table 1.5 summarizes the reduction of accidents per state after the installation of CLRS, calculated for various types of accidents.

Table 1.5: Reduction of accidents per state after installation of CLRS

State / Accident type	Naïve Method					EB Method	
	Fatal HO	HO	OPP SW	HO + OPP SW	Fatal and Serious Injuries HO + OPP SW	HO + OPP SW	Total (all types)
Arizona					56%		
California	90%	42%				12%	14%
Colorado		34%	37%			31%	11%
Delaware		95%				81%	23%
Maryland							19%
Minnesota						-12%	0%
Oregon				70%			46%
Washington						21%	25%
Kansas	**80%**	**81%**	**78%**	**80%**	**59%**	**85%**	**33%**

Based on this limited data available from other states, it can be assumed that overall results found in Kansas are comparable to results found by other states, which reinforces the evidence that CLRS are effective in preventing crossover and possibly other types of accidents as well.

1.4 CONCLUSIONS

The results showed that installing CLRS reduced head-on and opposite-direction sideswipe types of accidents in the treated sections of US-50 and US-40. Although the CLRS were not expected to reduce all types of accidents, it appears they may have an effect on decreasing the total number of accidents as well. Results of the EB method were comparable to results found by the Naïve method for the analyses of CLRS correctable head-on, and sideswipe accidents and for the total number of accidents, excluding those involving animals and intersections.

The limitation of this study was the use of SPFs obtained for all types of accidents for predicting the number of the crossover accidents and total number of accidents.

Results of this report are comparable with results found in other states and evidence found in the literature, adding evidence that installing CLRS is an effective way to reduce crossover accidents.

CHAPTER 2 - A STUDY OF EXTERIOR NOISE

The objective of this study was to quantify the level of exterior noise created by CLRS and to discover if the mean level of noise created by CLRS is statistically different than the noise generated by vehicles driving over smooth pavement.

2.1 Literature review

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

- Higgins and Barbel (1984), tested several configurations of transverse rumble strips (TRS) in Illinois. Results: at 50 feet distance the increase in the noise levels was 7 dB compared to the base noise levels. Different configurations (formed and cut 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 longer duration than the noise associated to cars traveling over TRS.
- Gupta (1993) measured the noise generated by cars and trucks at 10 feet when driven over smooth pavement and over rumble strips in Ohio. Results: rumble strips increased the maximum level of noise in 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 and a truck driven over an asphalt surface without rumble strips in Virginia. Conclusion: at 200 feet 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. Results: at the edge of the pavement, the maximum difference in comparison to the base level noise was 12 dB. At 25 and 50 feet, the difference was 8 and 7dB, respectively. Conclusion: in order for the difference to be zero, the distance would be approximately 200 feet.
- Meyer and Walton (2002) compared “rumbler” (removable) and asphalt rumble strips at two different work zone locations in Kansas. Results: rumbler presented higher levels of noise, 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 strips applications at two different speeds (50 and 70 mph) in Texas. Results: 87 percent of the maximum baseline noise levels for trucks were greater than the peak rumble strips levels. Differences greater than 4 dB, in comparison to baseline conditions, occurred in more than half of rumble strips configurations. Differences were greater at 70 mph and lower for the truck. Pavement type (chip seal vs. hot mix asphalt) had significant effect on the noise levels. 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 (49.7 mph), and the external noise was measured at 25 feet from the center line. Results: the

two tested patterns of sinusoidal strips (shown in Figure 2.1) 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).

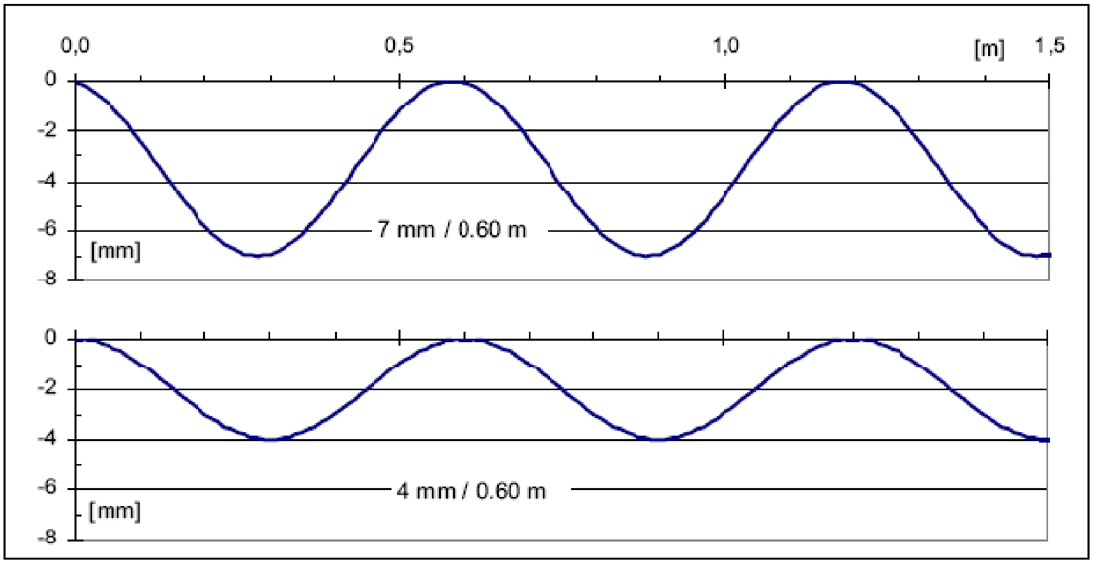


Figure 2.1: Sinusoidal strips. Source: Kragh et al. (2007)

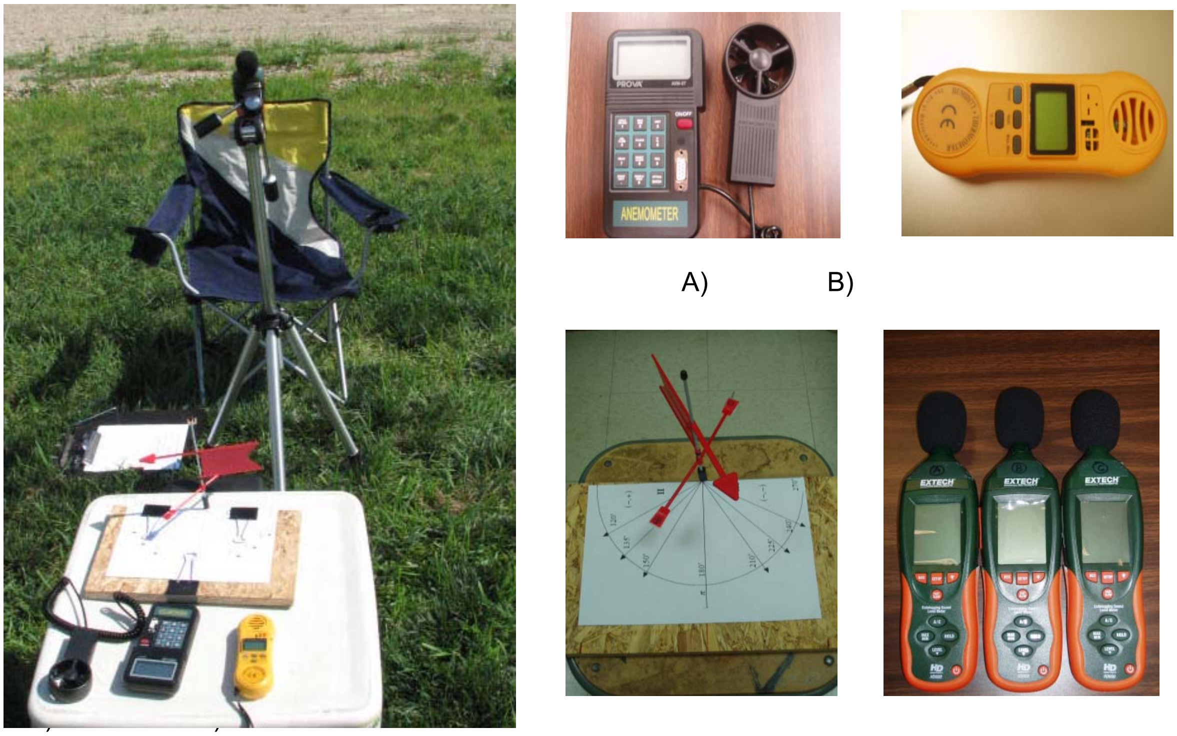
2.2 Methodology

2.2.1 Data Collection

Initially, the study sites presented in Table 2.1 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. The locations had a posted speed limit of 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 50, 100, and 150 feet 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 2.2 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.

Table 2.1: List of study sites selected

Location	County Name	Highway	Rumble Strip Type	Length (Miles)	KDOT Asphalt Classification
1	Chase	US-50	Football	19.0	Overlay 3",Ultrathin Bonded Asp Surf
2	Ellsworth	KS-156	Football	14.9	New Construction (IFD=3)
3	Brown	US-75	Football	13.0	Cold Mill 1", Overlay 1.5"
4	Doniphan	US-36	Football	6.1	Cold Mill .5", Overlay 1.5"
5	Reno	US-50	Football	9.7	Cold Mill 4", Recy Hot 6", Overlay .75"
6	Jefferson	US-24	Rectangular	6.7	Surface Recy 2", Overlay 1"
7	Chase	US-50	Rectangular	7.4	Surf Recy 2",Ultrathin Bonded Asp Surf
8	Osage	US-75	Rectangular	9.6	Surf Recy 2",Ultrathin Bonded Asp Surf
9	Barton	US-56	Rectangular	9.7	Cold Mill 1", Overlay 1.5"
10	Harvey	US-50	Rectangular	17.5	Overlay 1"



A) Prova AVM-07 anemometer. B) CE LM-81HT thermometer / anemometer / humidity meter.
C) Wind vane / angle sheet equipment. D) Extech HD600 noise meters.

Figure 2.2: Equipments used during data collection

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, 40 mph and 65 mph, in a 393 feet (120 meter) straight segment of highway. The rumble strip run had the test vehicles traveling over CLRS at two different speed levels, 40 mph and 65 mph, in a 393 feet straight segment of highway. The segment of highway at which the noise data were collected per location was marked with two traffic cones, as shown in Figures 2.3 and 2.4. Runs that had another vehicle traveling within the 393 feet 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 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.

Figure 2.3: Traffic cones delimiting the experimental unit – 393 feet of highway

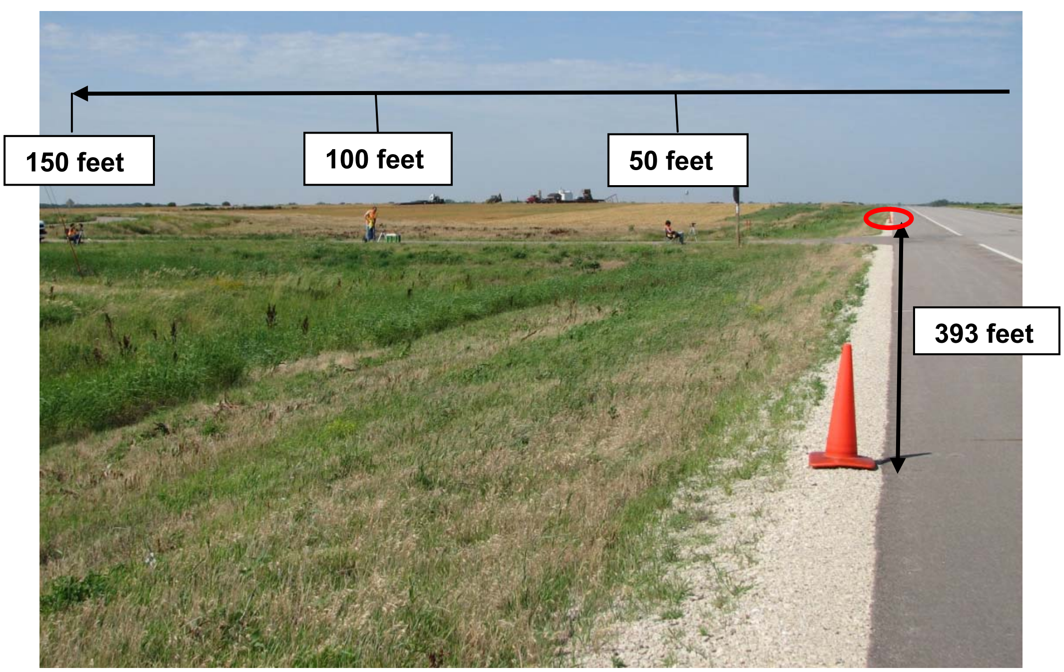


Figure 2.4: Set up of the experiment

The data point associated with each run was the highest noise level recorded at the fast response (125 ms), and using dBA scale, added to the wind contribution factor, to get “corrected noise” values. The wind contribution was calculated using Equation 2.1, given by Cho et. al (2004).

$A_{wind} = - [0.88 * \log_{10} (L / 15)] * U * \cos \theta$ Equation 2.1

Where:

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 presented in Figure 2.5. They were the 2006 Ford Taurus, and the 2008 Chevrolet Express - 15 passenger van, which weighs approximately 10,000 lbs.

Figure 2.5: Vehicles used in the experiment

2.2.2 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. According to Meyer and Walton, (2002) humans can discern noise differences of at minimum 3dBA. Noise levels from 24 runs per location were taken, and the total number of runs was 240. The data points per run were collected, corresponding to distances of 50, 100, and 150 feet.

This experiment was analyzed as a split-plot design. The whole-plot level had a completely randomized block design with three treatment factors: 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) because the noise levels at different distances in a straight line from the source were assumed to be correlated with each other. The error term for the split plot level was the four-way interaction. Since three replicates of each run were taken, this experiment had a pure error term. The Mixed Procedure in SAS was used to analyze the data.

Four different models were built. The first model had no covariate. The second model had humidity as a covariate, the third had temperature as a covariate, and the fourth had both humidity and temperature as covariates. The best model was without covariates, as shown in Tables 2.2 and 2.3.

Table 2.2: ANOVA Table - Model without covariates

Effect	NUM DF	DEN DF	F Value	Pr > F
LP	19	19	23.74	<.0001 *
VEH	1	19	57.45	<.0001 *
SPD	1	19	269.17	<.0001 *
VEH*LP	19	19	1.47	0.2040
SPD*LP	19	19	2.05	0.0629
VEH*SPD	1	19	5.15	0.0351 *
DIST	2	38	1102.18	<.0001 *
DIST*LP	38	38	2.61	0.0019 *
VEH*DIST	2	38	0.44	0.6487
SPD*DIST	2	38	2.63	0.0855
VEH*DIST*LP	38	38	0.47	0.9895
SPD*DIST*LP	38	38	0.51	0.9791
VEH*SPD*DIST	2	38	0.84	0.4413

*Statistically significant at 0.05 level

Table 2.3: Orthogonal contrasts

Contrast #	Label	Num DF	Den DF	F Value	Pr > F
1	SMOOTH F vs. SMOOTH R	1	19	4.07	0.0581
2	RUMBLE STRIPS vs. SMOOTH	1	19	307.70	< 0.0001 *
3	FOOTBALL vs. RECTANGULAR	1	19	0.05	0.8318
4	SMOOTH F vs. FOOTBALL RS	1	19	132.96	< 0.0001 *
5	SMOOTH R vs. RECTANGULAR RS	1	19	176.13	< 0.0001 *
6	(100VS150) * RUMBLE STRIPS vs. SMOOTH	1	38	5.06	0.0304 *
7	50 feet vs. 100 feet	1	38	2192.32	< 0.0001 *
8	50 feet vs. 150 feet	1	38	390.16	< 0.0001 *
9	100 feet vs. 150 feet	1	38	670.62	< 0.0001 *

*Statistically significant at 0.05 level

Figure 2.6 shows the individual values of corrected noise, according to distances, speed levels, vehicles, and pavement types.

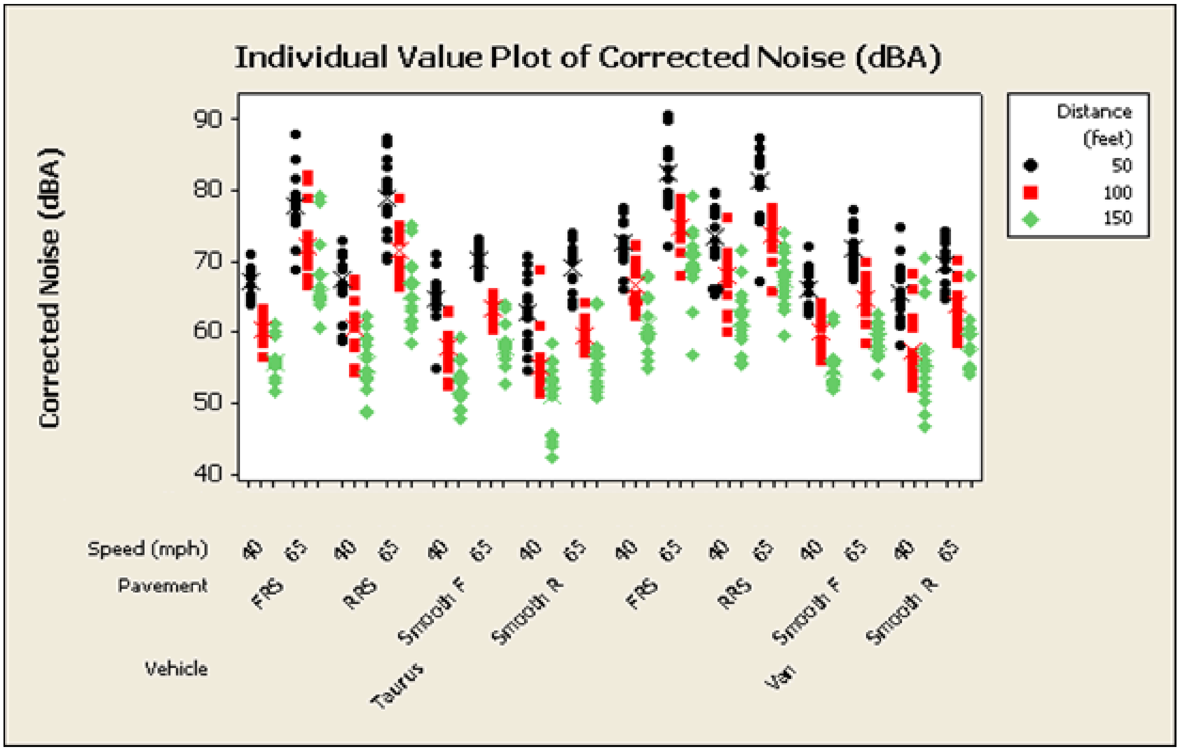


Figure 2.6: Individual values of corrected noise

Table 2.4 presents the mean levels of noise, and the differences between rumble strips and baseline runs.

Table 2.4: Mean levels of noise and differences between rumble strips and baseline runs

Corrected noise (dBA) at:			50 feet	100 feet	150 feet	Corrected noise (dBA) at:				50 feet	100 feet	150 feet
Taurus	40	FRS	67.12	60.26	55.77	Van	40	FRS	50	72.49	66.57	60.88
Taurus	40	Smooth F	64.63	57.8	52.38	Van	40	Smooth F	50	65.93	60	54.86
Difference			**2.48**	**2.46**	**3.39**	**Difference**				**6.56**	**6.57**	**6.02**
Taurus	40	RRS	67.45	60.67	55.41	Van	40	RRS	50	73.36	67.84	61.82
Taurus	40	Smooth R	62.81	55.07	50.99	Van	40	Smooth R	50	65.4	57.23	56.23
Difference			**4.64**	**5.6**	**4.42**	**Difference**				**7.96**	**10.61**	**5.6**
Taurus	65	FRS	77.91	72.18	67.26	Van	65	FRS	50	82.36	74.87	69.98
Taurus	65	Smooth F	70.27	63.21	57.75	Van	65	Smooth F	50	71.7	64.7	58.64
Difference			**7.64**	**8.97**	**9.51**	**Difference**				**10.66**	**10.16**	**11.34**
Taurus	65	RRS	78.82	71.59	65.89	Van	65	RRS	50	81.46	73.66	67.53
Taurus	65	Smooth R	69	59.57	55.7	Van	65	Smooth R	50	69.59	63.84	58.55
Difference			**9.82**	**12.03**	**10.19**	**Difference**				**11.87**	**9.83**	**8.98**

2.3 KEY FINDINGS

- 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. However, the highest difference in levels of noise of rumble strips, in comparison to smooth pavement, was measured at 100 feet when the Taurus was traveling at 65 mph.
- Overall, the mean level of noise at 40 mph (61.42 ± 0.31 dBA) was significantly lower compared to the mean level of noise at 65 mph (68.65 ± 0.31 dBA); the P-value of this test was smaller than 0.0001.
- Overall, the mean level of noise at 50 feet (71.27 ± 0.26 dBA) was significantly higher than the noise at 100 feet (64.50 ± 0.27 dBA) and 150 feet (59.34 ± 0.26 dBA), which were also different from each other; the P-values of these tests were smaller than 0.0001.
- In general, mean noise levels dropped 9.5 percent from 50 to 100 feet and 8.0 percent from 100 to 150 feet.
- The mean level of noise generated by smooth pavement at locations with football CLRS (61.17 dBA) were not significantly different from the noise levels on smooth pavement at locations with rectangular rumble strips (61.80 dBA); the P-value of this test was 0.0581.
- The levels of noise generated by CLRS (68.90 dBA) was significantly greater than the noise generated by smooth pavement (61.17 dBA); the P-value of this test was smaller than 0.0001.

- The interaction between speed and vehicle was significant. The P-value of this test was 0.0351. It means that the levels of noise of the Taurus and the Chevrolet van have different trends, according to the speed, as shown in Figure 2.7.

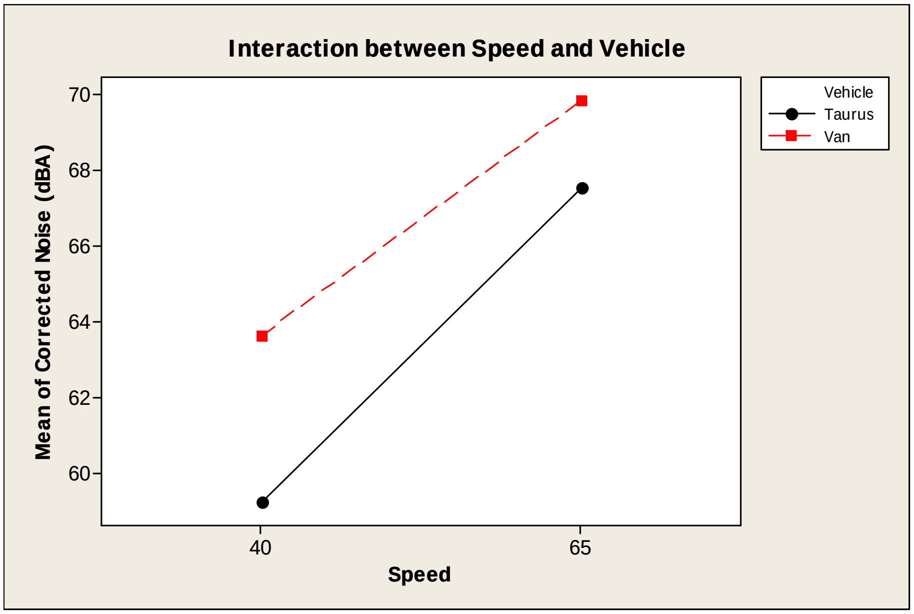


Figure 2.7: Interaction plot between speed and vehicle factors

- The interaction between distance and LP was significant. It means that the variation of noise per level of distance was different across the locations. Probably due to differences between types of asphalt.
- 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.
- Semi-trucks traveling at operational speeds (approximately 65 mph) over smooth pavement produced higher levels of noise compared to the Taurus and the Chevrolet van traveling over rumble strips, as shown in Table 2.5.

Table 2.5: Comparison to semi-trucks

Mean Corrected Noise (dBA)			
Distance (feet)	Taurus RS	Van RS	**Semi-Trucks**
50	78.36	81.91	**83.89**
100	71.89	74.27	**76.4**
150	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, four regression models were built. The first model described the variation of noise for the Taurus traveling over rumble strips at 65mph. The second model had data from the Taurus traveling over smooth pavement at 65 mph. The third model had data of the Chevrolet van traveling over rumble strips at 65 mph, and the forth model had data from the Chevrolet van over smooth pavement at 65 mph. The predictor of each model was distance. Table 2.6 shows the regression analysis results.

Table 2.6: Regression models results

Model 1: Noise = 84.1 - 0.118 * Distance				**Model 2: Noise = 75.5 - 0.129 * Distance**			
Distance	**Prediction**	**Real Average**	**Difference**	**Distance**	**Prediction**	**Real Average**	**Difference**
50	78.17	78.36	-0.19	50	69.07	69.61	-0.54
100	72.28	71.89	0.40	100	62.61	61.46	1.15
150	66.40	66.58	-0.18	150	56.15	56.69	-0.54
200	60.51	*	*	200	49.69	*	*
Model 1: Noise = 84.1 - 0.118 * Distance				**Model 2: Noise = 75.5 - 0.129 * Distance**			
Distance	**Prediction**	**Real Average**	**Difference**	**Distance**	**Prediction**	**Real Average**	**Difference**
50	81.57	81.91	-0.34	50	70.56	70.68	-0.12
100	74.99	74.27	0.73	100	64.52	64.28	0.24
150	68.42	68.76	-0.34	150	58.48	58.60	-0.12
200	61.84	*	*	200	52.44	*	*

Table 2.7: 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
Roar of crowd	95
Power tools	100
Stereo headset	110
Rock concert	120
.22 caliber rifle	130
Jet take-off	140

- According to Benekohal et al (1992) cited by Meyer (2002), the typical noise levels of common sound events are given by Table 2.7.The noise produced by rumble strips at 200 ft is comparable to the noise produced by a television, which should be considered acceptable.

2.4 CONCLUSIONS

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 do increase the levels of external noise. Therefore, before installing CLRS, the distance from houses or businesses should be measured. Based on the analysis using only one light and one medium vehicle, a distance of 200 ft from the centerline should be considered. This is the distance where noise from CLRS is no greater than smooth pavement.

CHAPTER 3 - EVALUATION OF RETROREFLECTIVITY OF PAVEMENT MARKINGS

Painted, retroreflective pavement markings (RRPMs) on the centerline and edge-line rumble strips play a major role in providing visual warning to drivers. Pavement markings play a major role in preventing centerline and shoulder incursions. The primary objective of this study was to develop a standardized method for evaluating the retroreflectivity of the RRPMs placed over CLRS and to study the various factors affecting their deterioration. To accomplish this objective, a methodology was developed for studying different factors affecting retroreflectivity of the RRPMs. Field data measurements were taken from US-24, US-50 and US-40 and the results are summarized in this chapter.

3.1 LITERATURE REVIEW

A Texas Transportation Institute (TTI) study focused on evaluation of the visibility of pavement marking in wet-night, rainy conditions and the appropriateness of associated measurement techniques (Pike et al., 2007). In this study, the researchers tested the performance of eighteen pavement marking types in wet-night conditions. They measured the wet-night detection distance of a wide range of pavement markings under typical rainfall rates. They also measured the retroreflectivity of the pavement markings under a wide range of continuous wetting rates. Additionally, they measured the luminance of the marking at a fixed 98.42 feet (30-meter) distance under the same rainfall rate of the detection distance measurements. Retroreflectivity was measured using a portable 98.42 feet pavement marking reflectometer and continuous wetting spray apparatus. The study results showed that the rate of continuous wetting influenced the measured retroreflectivity of the markings. The higher the rate of continuous wetting, the lower the retroreflectivity was observed.

The TTI research team also measured detection distances of pavement markings under simulated rainfall conditions. The measurements were conducted at night with the research participants driving an instrumented vehicle at a constant speed of 30 mph. The vehicle was equipped with a calibrated distance measuring instrument (DMI). Detection distance study results showed that the detection distance is influenced by the intensity of rainfall. Detection distance is reduced with the increase in intensity of rainfall. This study also focused on measuring the luminance of pavement markings. Luminance of the pavement marking was measured using a Radiant Imaging CCD (Charge Coupled Device) photometer. The photometer records a digital picture of the scene for analysis. The photometer was mounted on a tripod in the test vehicle at driver eye height. The measurements were taken with the test vehicle positioned 98.42 feet from the pavement markings. Results of this study showed that the luminance intensity of the pavement marking decreases with the increase in intensity of rainfall. Another important finding in the TTI paper is that the luminance measurement had a high correlation with retroreflectivity.

Concordia University, Montreal, Quebec, created a synthesis of practice of sustainable pavement markings in Canada (Shahata et al., 2008). The objective of this study was to summarize the best practices of managing pavement marking systems in Canada. This study collected data from Canadian provinces, including current management strategies, material types and re-striping criteria. Pavement marking maintenance practices in five provinces (Alberta, British Colombia, Ontario, Quebec, and Saskatchewan) were summarized in this study. This study results are summarized in Table 3.1.

Table 3.1: Current practices for managing pavement marking system in Canadian Provinces. (Shahata et al., 2008)

Activity/Province	Highway/ Roadway System Pavement Markings	Urban/Lateral System Pavement Marking	Re-stripe Practice Service Life
Alberta	Waterborne base paint Alkyd base paint	MMA Epoxy Thermoplastics	Service Life (1-5) years for durable markings Roadway lane lines are painted once per year. On lower volume highways one edge line and centerline are painted. The edge lines are alternated yearly and the centerline is painted every year. On higher volume roadways painted several times a year (up to 3 times)
British Colombia	Alkyd base paint	Waterborne base paint Thermoplastics	Paint is renewed every 1-2 years on the average. Centerline is typically re-striped on a yearly basis. Try to get two years out of Edge Line, but in high snowfall areas where there is lots of salting and sanding, it may have to be repainted yearly. Thermoplastic is renewed every 3 years while some need touching up annually.
Ontario	Waterborne base paint Alkyd base paint	Waterborne base paint Thermoplastics	Paint all longitudinal lines once per year. Paint main arterial roads, twice per year.
Quebec	Waterborne base paint Alkyd base paint Resins Epoxy	Resins Epoxy Marking tape Thermoplastic Methyl Methacrylate (MMA)	Service life: Alkyd base paint and Waterborne base paint; 6-8 months Resin Epoxy; 2-4 years Methyl Methacrylate (MMA); 6 months to 6-years New application luminance: Yellow lines 140 $mcd/m^2/lux$. White lines 200 $mcd/m^2/lux$. If the retroreflectivity drops below 60(white)/50 (yellow) $mcd/m^2/lux$, re-stripe.
Saskatchewan	Waterborne base paint Alkyd base paint	Waterborne base paint Alkyd base paint	Service life for applied pavement marking: 10 – 12 months New application luminance: Yellow lines 200/250 $mcd/m^2/lux$. White lines 290/350 $mcd/m^2/lux$. If the reflectivity drops below 100 $mcd/m^2/lux$, re-stripe

A Civil engineering research team for cold regions in Hiragishi, Japan conducted a study on development of recessed pavement markings that incorporates rumble strips (Hirasawa et al., 2008). In this study the research team proposed a new design of pavement markings whose recessed design prevents scraping damage from snowplows. This design also incorporates rumble strips which increases driving safety. This new design of pavement markings was designed with the intention of improving durability and reducing costs by eliminating the cost for annual repainting of pavement markings. In this design, the markings were installed by milling a shallow longitudinal recess into the pavement while simultaneously milling recessed transverse grooves (the rumble strips) more deeply, and then applying paint. In this study to determine the optimum design for recessed pavement markings, two trial installations were made using two intervals or spacing between grooves. A questionnaire survey was conducted on test drivers to determine the difference in noise and vibration generated by the two patterns. The survey results did not reveal any difference between the two patterns. Field studies were also conducted to determine the sound and vibration from trial installations with different spacing. Field study results showed that recessed markings with long spacing generate more noise and vibration than recessed markings with short spacing, making the former more noticeable than the latter. Therefore, recessed markings with long spacing were selected for installation on roads in service. This study also found that waterborne paints are not durable enough to be used on recessed pavement markings and suggests that thermoplastic paint should be used.

Iowa State University conducted a study on safety effectiveness of pavement marking retroreflectivity. This study focused on analyzing the correlation between longitudinal pavement marking retroreflectivity and safety performance. In this study, when data records showing low retroreflectivity were analyzed (≤200 mcd/m^2/lux), a negative correlation was found to be statistically significant. This study showed that as retroreflectivity decreases, crash probability increases. This study helped the concerned agencies to develop a better pavement marking management program to reduce nighttime crashes where low pavement marking retroreflective values are a contributing factor.

The Kansas Department of Transportation (KDOT) adapted a new replacement policy in 2000 (Migletz et al., 2002), which includes the following conditions in replacing pavement markings:

> “[Replaced when]Average reading of retroreflectivity falls below 150 mcd/m^2/lux for white and 100 mcd/m^2/lux for yellow, marker detached from the roadway due to adhesive failure, or ineffective daytime lane delineation due to loss of pigment.”

The Federal Aviation Administration (FAA) conducted a study on evaluating airport pavement marking effectiveness (Cyrus 2003). This study was conducted for replacement of an ineffective, subjective method of pavement marking evaluation. In the subjective method, paint performance was evaluated by visual inspection marking of segments. The subjective method did not provide confidence in the validity of the evaluation and it lacked the consistency an objective method would provide. Thus they developed an objective method, measuring three important factors of the pavement marking: 1) retroreflectivity, 2) chromaticity and 3) coverage of paint material. For measuring retroreflectivity they developed both a manual and automated method using hand held and vehicle mounted retro reflectometers. For Chromaticity measurements a hand held, point detection spectrometer was used. This measured the spectral coverage of the paint material. For measuring the coverage of paint material they used a glass grid. This objective method was found to be effective and it was adopted by FAA as a standard method.

McGinnis collected data from various highway agencies on minimum initial and minimum accepted retroreflectivity for different pavement marking materials (McGinnis, 2001). Initial and minimum accepted retroreflectivity values are shown in Tables 3.2 and 3.3, respectively. The initial retroreflectivity reading is the retroreflectivity reading taken from pavement markings from 0-14 days of installation. The minimum accepted retroreflectivity reading is the reading from a pavement marking within 180 days of installation.

Table 3.2: Summary of minimum <u>initial</u> retroreflectivity values for selected highway agencies (McGinnis, 2001)

Type of Material	Marking Color	Minimum Retroreflectivity (mcd/m²/lux)									
		KS		KY		MD		NC		PA	
		Initial		Initial		Initial		Initial		Initial	
		Min. RR	Period of Days	Min. RR	Period of Days	Min. RR	Period of Days	Min. RR	Period of Days	Min. RR	Period of Days
Waterborne Paint	White					250	0				
	Yellow					150	0				
Epoxy	White	300	0-14			275	0	375	0-30	300	0-60
	Yellow	225	0-14			200	0	250	0-30	250	0-60
Thermoplastic	White	300	0-14			250	0	375	0-30	300	0-60
	Yellow	225	0-14			150	0	250	0-30	250	0-60
Preformed Thermoplastic	White	300	0-14	700	0	250	0				
	Yellow	225	0-14	500	0	150	0				
Spray Thermoplastic	White	300	0-14								
	Yellow	225	0-14								
Cold Plastic	White	250	0-14								
	Yellow	175	0-14								
Patterned Cold Plastic	White	475	0-14			350	0-30			300	0-60
	Yellow	375	0-14			250	0-30			250	0-60
High Durability Tape	White	225	0-14							300	0-60
	Yellow	175	0-14							250	0-60
Modified Urethane	White	300	0-14								
	Yellow	225	0-14								
Polymer-Modified Cementitious	White	300	0-14								
	Yellow	225	0-14								

Table 3.3: Summary of minimum <u>acceptable</u> retroreflectivity values for selected highway agencies (McGinnis, 2001)

Type of Material	Color	Minimum Retroreflectivity (mcd/m^2/lux)									
		KS		KY		MD		NC		PA	
		Acceptable		Acceptable		Acceptable		Acceptable		Acceptable	
		Min RR	Period of Days	Min RR	Period of Days	Min RR	Period of Days	Min RR	Period of Days	Min RR	Period of Days
Waterborne Paint	White			175	30-60						
	Yellow			150	30-60						
Epoxy	White	250	180					325	150-180	125	1095
	Yellow	175	180					200	150-180	100	1095
Thermoplastic	White	250	180	300	150-210			325	150-180	125	1095
	Yellow	175	180	175	150-210			200	150-180	100	1095
Preformed Thermoplastic	White	250	180	200	1440	300	180				
	Yellow	175	180	150	1440	220	180				
Spray Thermoplastic	White	250	180								
	Yellow	175	180								
Cold Plastic	White	200	180								
	Yellow	125	180								
Patterned Cold Plastic	White	425	180			300	180			125	1095
	Yellow	325	180			220	180			100	1095
High Durability Tape	White	200	180							125	1095
	Yellow	150	180							100	1095
Modified Urethane	White	250	180								
	Yellow	175	180								
Polymer-Modified Cementitious	White	250	180								
	Yellow	175	180								

From Table 3.2 it can be seen that minimum *initial* retroreflectivity for thermoplastic paint in Kansas is 225 mcd/m^2/lux (for yellow) and 300 mcd/m^2/lux (for white). From Table 3.3 it can be seen that minimum *accepted* retroreflectivity of thermoplastic paint in Kansas is 175 mcd/m^2/lux (for yellow) and 250 mcd/m^2/lux (for white).

3.2 METHODOLOGY

3.2.1 Description of Locations

The study was conducted on three Kansas State Highways. They were:

1. Kansas Highway US-24 (Jefferson County). Section with rectangular CLRS with dimensions of L=16 inches, W=7 inches and D= 0.6 inch (L-Length, W-Width, D-Depth) and RRPM of 4 inch width were installed on October 2nd 2008. The AADT (Average Annual Daily Traffic) of this section was 5,040 vpd (2009 Traffic flow map).
2. Kansas Highway US-50 (Chase County). Here rectangular CLRS with dimensions of L=16 inches, W=7 inches and D= 0.6 inches and RRPM of 4 inches width were installed on June 3rd 2008. AADT of section under study was 4085 vpd (2009 Traffic flow map).
3. Kansas Highway US-40 (Douglas County). Section with football CLRS with dimensions of L=16 inches, W=9 inches and D= 0.5 inch, where 0.5 inch D is the depth at the center of the depression. Here RRPM of 4 inches width were installed on May 5th 2005. The AADT of this section was 3,320 vpd (2009 Traffic flow map).

3.2.2 Retroreflectometer Evaluation

Retroreflectivity is the ability of a surface to return back light to its source. Retroreflective pavement markings bounce light from vehicle headlights back towards the vehicle and the drivers' eyes, making signs and pavement markings visible to the driver at night. Retroreflectivity is measured using a retroreflectometer.

A 30-meter geometry handheld retroreflectometer (LTL 2000), manufactured by Delta Light & Optics was used for this evaluation. LTL 2000 is a handheld retroreflectometer that is able to measure ability of a RRPM surface to reflect light from car headlight back to the driver. LTL 2000 measures the retroreflectivity values of pavement markings as seen in the vehicle headlight illumination. The 98.42 feet geometry retroreflectivity (which is the horizontal viewing distance from a headlight to the pavement markings) is the standard used by US highway departments (Figure 3.1).

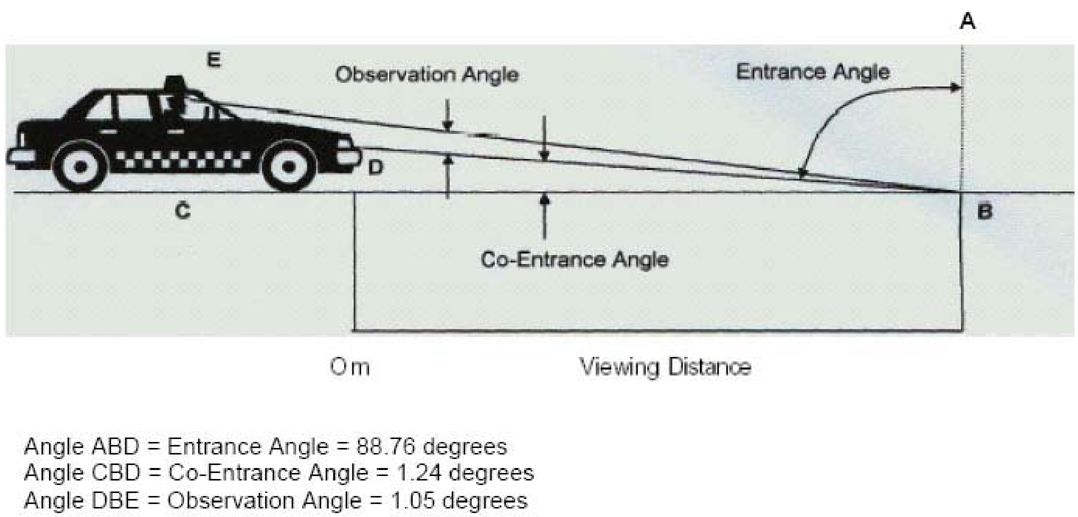


Figure 3.1: Thirty meter geometry measurement for retroreflectivity (Cyrus, 2007)

For measuring retroreflectivity of pavement markings on CLRS, a hardboard was fabricated with a central rectangular hole. This central rectangular hole was cut on the board to match exactly with the reading head opening of the LTL 2000 retroreflectometer and it prevented other light sources from falling on the reflectometer reading head. After each reading the equipment prints out the measured reading in mcd/m^2/lux, which is the standard unit of retroreflectivity values. The retroreflectometer was placed on the pavement marking as shown in Figure 3.2 and readings were taken. Six measurements were taken on a 7-foot 7-inch section of RRPM.

Figure 3.2: Retroreflectivity measurement on CLRS using reflectometer LTL 2000

For taking wet RRPM measurements, water was poured into the depression of a rumble strip (see Figure 3.3) in such a way that the depression is filled up to approximately eighty percent. The rumble strip was not filled up to the pavement ground level because doing so would have interfered with the reading head of the reflectometer.

Figure 3.3: Wetting rumble depression up to approximately eighty percent

Tables 3.4 to 3.6 show the retroreflectivity data collected in sections of US-24, US-50, and US-40 respectively. Reflectivity readings were collected on asphalt pavement with and without CLRS, with dry and wet conditions. Some of the data points are averages of three to five measurements.

The first visit was on October 31st 2008, the second visit was on March 12th 2009 and the third visit was on May 4th 2009. These visit dates were 30, 162 and 215 days from the installation date on US-24 (October 2nd 2008); 144, 283 and 336 days from the installation date of US-50 (June 3rd 2008); and 1269, 1408 and 1461 days from the installation date (May 5th 2005) on US-40.

The minimum acceptable retroreflectivity value for yellow retroreflective paint material is 175 mcd/m^2/lux (McGinnis, 2001). Taking this into consideration, for US-24 the dry retroreflectivity measurements taken on October 31st 2008 were above the acceptance level and measurements taken on March 12th 2009 and May 4th 2009 were below the acceptance level for sections with and without CLRS.

For US-50, considering the section with CLRS, the retroreflectivity in the wet condition was lower than the acceptance level. Under dry condition, the retroreflectivity was above the acceptance level. For the section without CLRS, the wet and the dry conditions gave retroreflectivity values above the acceptance level.

For US-40, the dry retroreflectivity of RRPMs in the location without CLRS was all below the acceptance level. Considering the section without CLRS, the dry retroreflectivity of RRPMs were all below the acceptance level. The results are summarized in tables below.

Table 3.4: Retroreflectivity Data collected on US-24

Visit	Marking's Age (Days)	Water	CLRS	Retroreflectivity ($mcd/m^2/lux$)	Acceptable? Min. 175 $mcd/m^2/lux$
1	30	Dry	Yes	282	Yes
1	30	Dry	Yes	237	Yes
1	30	Dry	No	401	Yes
2	162	Dry	Yes	162	No
2	162	Dry	Yes	119	No
2	162	Wet	Yes	98	No
2	162	Wet	Yes	65	No
2	162	Dry	No	127	No
3	215	Dry	Yes	155	No
3	215	Dry	Yes	137	No
3	215	Wet	Yes	77	No
3	215	Wet	Yes	105	No
3	215	Dry	No	84	No
3	215	Wet	No	234	Yes

Table 3.5: Retroreflectivity Data collected on US-50

Visit	Marking's Age (Days)	Water	CLRS	Retroreflectivity (mcd/m^2/lux)	Acceptable? Min. 175 mcd/m^2/lux
1	144	Dry	Yes	231	Yes
1	144	Dry	Yes	219	Yes
1	144	Dry	No	270	Yes
2	283	Dry	Yes	193	Yes
2	283	Dry	Yes	207	Yes
2	283	Wet	Yes	83	No
2	283	Wet	Yes	118	No
2	283	Dry	No	210	Yes
3	336	Dry	Yes	201	Yes
3	336	Dry	Yes	146	No
3	336	Wet	Yes	62	No
3	336	Wet	Yes	78	No
3	336	Dry	No	206	Yes
3	336	Wet	No	278	Yes

Table 3.6: Retroreflectivity Data collected on US-40

Visit	Marking's Age (Days)	Water	CLRS	Retroreflectivity (mcd/m^2/lux)	Acceptable? Min. 175 mcd/m^2/lux
1	1269	Dry	Yes	125	No
1	1269	Dry	Yes	142	No
1	1269	Dry	No	51.25	No
2	1408	Dry	Yes	107	No
2	1408	Dry	Yes	197	Yes
2	1408	Wet	Yes	16	No
2	1408	Wet	Yes	28	No
2	1408	Dry	No	39.75	No
3	1461	Dry	Yes	93	No
3	1461	Dry	Yes	129	No
3	1461	Wet	Yes	14	No
3	1461	Wet	Yes	25	No
3	1461	Dry	No	35.5	No
3	1461	Wet	No	198.25	Yes

3.2.3 Spectrophotometer Evaluation

The international board that sets color standards is the International Commission of Illumination (CIE) (Cyrus 2006 & 2007). This commission developed the methodology for describing the color in a numerical system that is based upon a standard observer. A standard observer is defined as a small group of individuals (about 20-30) that have normal, human color vision. This technique matches color to an equivalent red, green and blue (RBG) tristimulus value. Chromaticity is expressed in terms of a coordinate system adopted by the CIE. This methodology reduces the spectral emission characteristics of a source to a three letter designation with associated numbers, i.e. CIE *Yxy*. Where *Y* is the absolute measure of the visual luminance of the source and *x* and *y* are the coordinates. The chromaticity evaluation was performed by using a Minolta CL-100 spectrophotometer, shown in Figure 3.4. The data measurement taken was displayed on a Minolta CL-100 spectrophotometer as chromaticity coordinates. The meter was calibrated before each reading was taken. The spectral data was plotted on a chromaticity chart, as shown in Figure 3.5.

Figure 3.4: Minolta CL 100 spectrophotometer

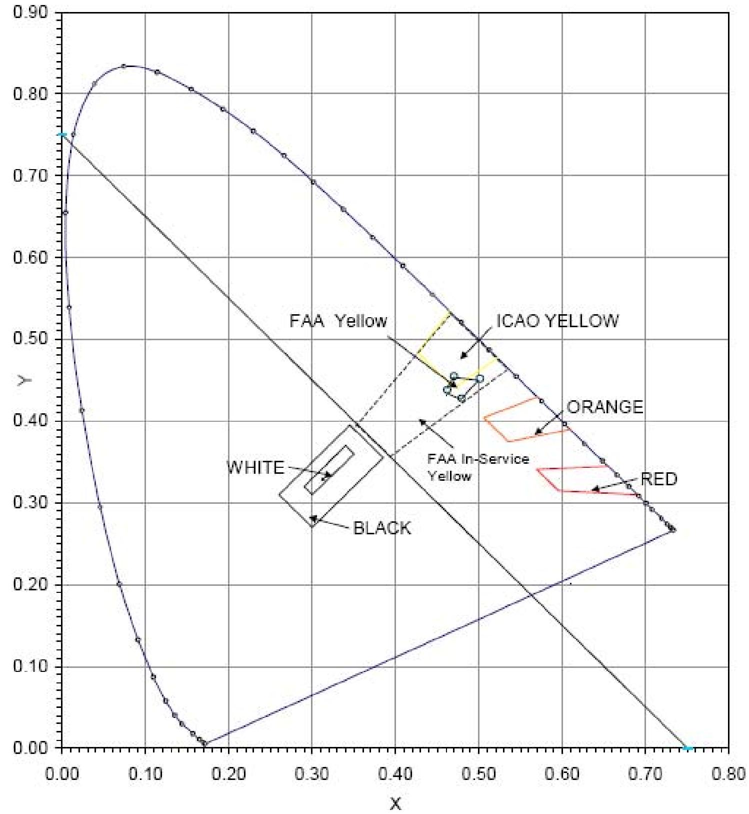


Figure 3.5: CIE standard illuminant D_{65} chromaticity chart for beaded retroreflective paint (Cyrus, 2007)

For taking readings, the spectrophometer was kept at a distance of approximately two inches and aimed at the pavement marking in the rumble strip depression. Chromaticity measurements were taken on all study locations with CLRS. Measurements were taken at the center of all rumble depressions on an entire section of RRPM of 7-foot 7-inch length. These reading were plotted on CIE standard illuminant, D_{65} chromaticity chart for beaded retroreflective paint material using MATLAB R2007 software.

3.2.4 Coverage Check

A coverage check evaluation shows the uniformity of coverage of the paint stripe, such as paint cracking, peeling, and whether or not the marking has adequate coverage. A flexible grid fabricated from vinyl fabric having 80 equal squares was used as a tool for a quantitative measure of a specified percentage of coverage. The flexible fabric was used as grid material because it fits well in rumble strip groves. This grid concept was adopted by the Air Force who uses it for measuring rubber coverage on pavement (www.airtech.tc.faa.gov/safety) (2008).

On Kansas state highways the width of a centerline retroreflective pavement marking is 4 inches; hence, a grid of 4 by 20 equal squares of size 4 by 24 inches was used, as shown in Figure 3.6. The grid was placed on the pavement marking and a picture was taken. This picture was used for visual inspection performed by counting the squares having no paint. For example: 4 out of 80 squares without coverage represent five percent of the paint gone, so the coverage is 95 percent.

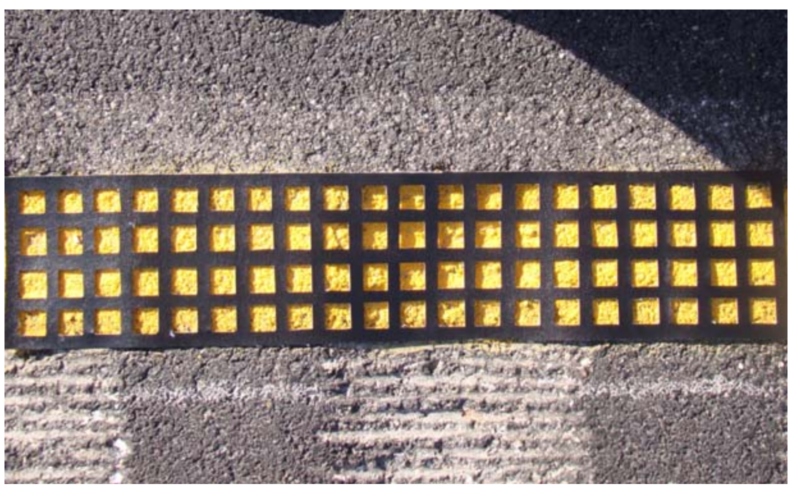


Figure 3.6: Coverage measurement on CLRS using flexible 4 by 24 inch grid

An analysis of correlation was conducted in order to verify that the coverage measurements agree with the reflectivity readings obtained by using the retroreflectometer. The results are given as follows:

- For US-24, the Pearson correlation of retroreflectivity and paint coverage (%) = 0.197 with a P-Value = 0.433;

- For US-50, the Pearson correlation of retroreflectivity and paint coverage (%) = 0.370 with a P-Value = 0.075;
- For US-40, the Pearson correlation of retroreflectivity and paint coverage (%) = 0.842 with a P-Value = 0.004;

The Pearson correlation measures if the two variables have a linear relationship. Statistically significant P-values indicate the existence of linear relationship between the considered variables, and the Pearson coefficient value measures the strength of this linear relationship. Based on the results found in this study, it is possible to conclude that paint coverage measurements are not strongly correlated with retroreflectivity measurements obtained by using the retroreflectometer. Based on the limited data collected in this study, the results indicate that coverage check should not be used as an alternative method to evaluate retroreflectivity values.

3.2.5 Data Analysis

3.2.5.1 Spectrometry

Spectrometry data was collected from US-24, US-50 and US-40 using the procedure previously explained. Spectrometry measurements were taken from US-24 and US-40 on October 31st 2008 and on US-50 on October 24th 2008. Measurements on US-24 were from markings that were 30 days old and those on US-50 and US-40 were 151 days old and 1,279 days old, respectively, from the date of installation. These measurements were taken with the intention of obtaining the regions where new and old yellow retroreflective, beaded paint fall in a CIE standard illuminant, D_{65} chromaticity chart.

The measurements were obtained as chromaticity coordinates from the Minolta CL 100 spectrometer described earlier. The data points obtained were plotted on a CIE standard illuminant, D_{65} (beaded retroreflective paint) chromaticity chart using MATLAB R2007 program. Chromaticity measurements from US-24, US-50 and US-40 were plotted as three different colored regions in the chromaticity chart. Highway US-24 measurements are shown in the blue colored region, US-50 in the green colored region and US-40 in the red colored region. The chromaticity plot is shown in Figure 3.7.

From Figure 3.7 it is seen that all data coordinates lie in the yellow region of the D_{65} chromaticity chart. Again, it can be seen that in the chart, the US-24 measurements, which are in green, lie in the upper plane of the yellow region, US-40 measurements, which are in red, lie in the lower plane of the yellow region and the US-50 measurements, which are in yellow, lie in between the red and green regions.

Based on the spectrometry measurements, it can be concluded that the painting color did not change over the time on which measurements were taken. The beads may lose the ability to reflect the light, but the color remains within the yellow spectrum.

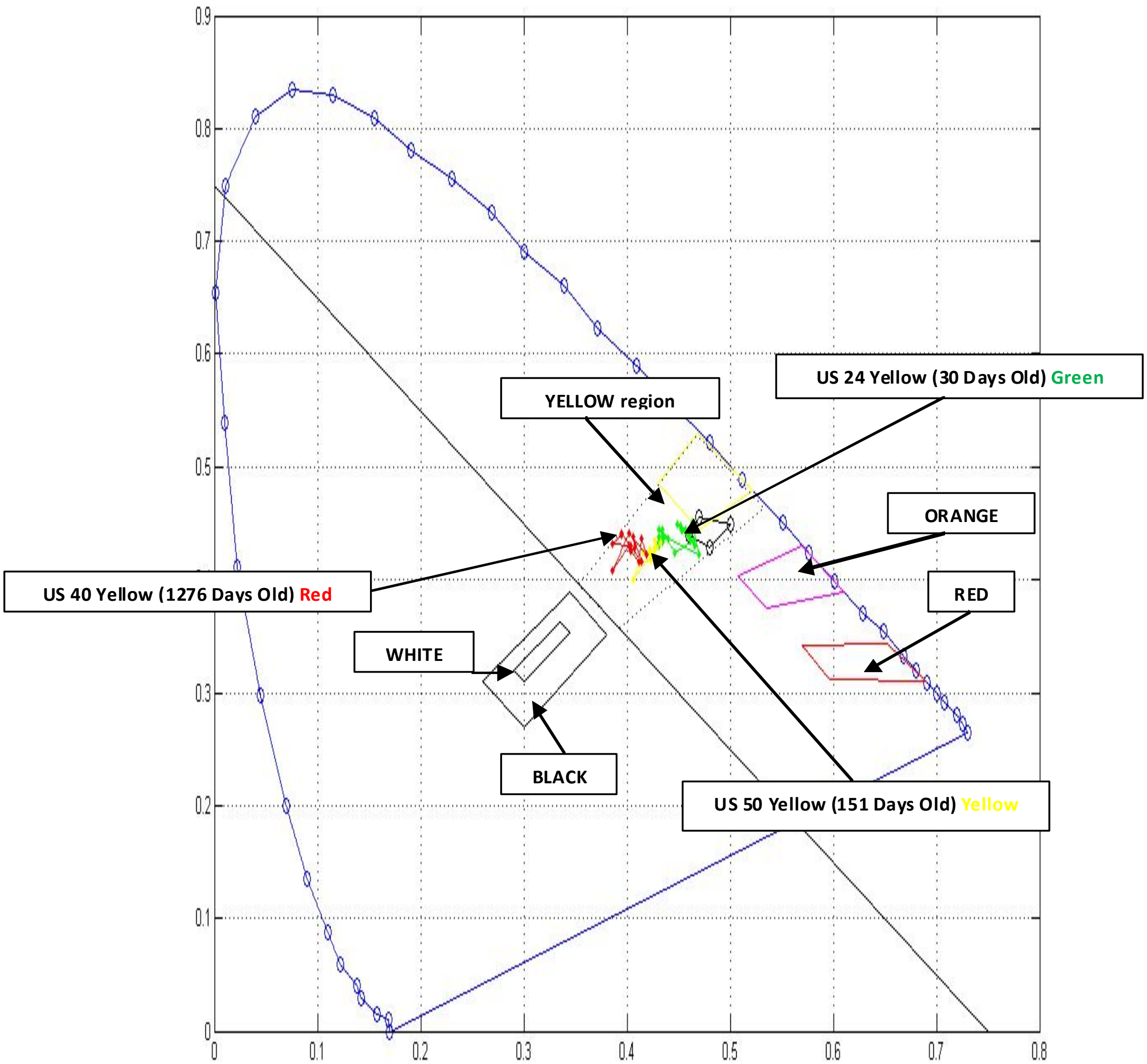


Figure 3.7: D_{65} chromaticity chart obtained from Highway US-24, US-50 and US-40 measurements

3.2.5.2 Retroreflectivity

In order to account for the correlation structure involved in this experiment, data from tables 3.4 to 3.6 were analyzed using a split-plot with repeated measurements design (also commonly referred as split-plot in time design), since the measurements were taken in the same locations at three different times. Therefore, they were correlated, and it is not possible to randomize time.

The whole-plot part of the experiment had a randomized complete block design structure, with the Road term as the random blocking factor, since each studied highway had specific characteristics. The treatment structure was a 3-way factorial. Water and CLRS were the whole-plot treatments, and Visit was the slit-plot treatment. The error term to test the whole-plot treatment was the interaction between the blocking factor and the whole-plot treatments. The Visit effect was tested using the residual mean square as the error term.

There were many levels of the treatments with missing values in the data collection, so the degrees of freedom for the tests were approximated using the Kenward-Roger method of approximation. The Mixed procedure in the Statistical Analysis Software (SAS) was used to analyze this experiment. The results from the analysis are summarized in Tables 3.7 to 3.10.From table 3.7, it can be seen that the variance components are greater than zero, since the Satterthwaite's type of confidence intervals do not contain zero.

Table 3.7: Covariance Parameter Estimates

Cov Parm	Estimate	Standard Error	Z Value	Pr > Z	Alpha	Lower	Upper
Road	2412.29	2703.25	0.89	0.1861	0.05	592.09	215045
Road*Water*CLRS	473.49	705.84	0.67	0.2512	0.05	89.8271	1013462
Residual	2107.31	563.78	3.74	<.0001	0.05	1326.56	3857.30

Table 3.8: Type 3 test for Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Water	1	10.4	0.41	0.5336
CLRS	1	8.98	14.47	0.0042
Water*CLRS	1	8.98	19.30	0.0017
Visit	2	27.9	8.62	0.0012

From Table 3.8, it can be seen that there is a significant interaction between *Water* and *CLRS*.

The *Water* main effect is not significant, but it was kept in the model due to the significant interaction. The *CLRS* main effect and the *Visit* main effect were also significant at the 0.05 confidence level. By analyzing this table is possible to conclude that:

- Retroreflectivity varies over time, since the *Visit* main effect is significant. From Table 3.9, it can be noticed that as the paint gets older, the retroreflectivity decreases. Overall, the relationship between the estimated difference in retroreflectivity and the difference in days of measurements could be approximated to a linear trend, since the correlation between these variables is 0.98.
- The *CLRS* main effect is significant, which means that there is a statistically significant difference between the retroreflectivity measured at asphalt pavements with and without CLRS. This difference might be due in part to a supposed incapability of the equipment in correcting the

readings from concave shape of the rumble strips, as proposed by (Hallmark et. al, 2009) or, in fact due to the actual difference between the surfaces, assuming that the reflectometer is able to mimic the vision of human beings, even when taking readings from concave surfaces. The LTL-2000 retroreflectometer used in this study has a height tolerance or ability to measure retroreflected luminance at depths up to four millimeters (0.157 inches). The depth of the studied CLRS was 0.5 inches. Therefore, the instrument used was not able to get readings from the bottom of the strips. However, since the depressions were filled with water up to approximately 80 percent of their depth, the retroreflectometer may or may not have worked properly at the water level of 0.1 inches deep, which could explain the differences in the results.

- Since the interaction of *CLRS* with the *Water* effect is significant, at each level of the *Water* effect, one type of surface presented a better result, as shown in Table 3.9.
- For the dry condition, the retroreflectivity of the pavement markings over CLRS is greater than pavement without CLRS. On the other hand, for the wet condition, the retroreflectivity value of asphalt pavement without CLRS is greater than the retroreflectivity measured over CLRS.
- The significant interaction also implies that the presence of water enhances the retroreflectivity on asphalt pavement without CLRS, and decreases the retroreflectivity over CLRS, as shown by the comparisons made in Table 3.10. The cause of such results could be the small sample

size evaluated with missing observations for the wet condition measurements over pavements without CLRS. Another potential reason is that the layer of water applied over CLRS was much greater (the CLRS grooves were filled with water up to 80 percent of the depth – see Figure 3.3) than the one applied over pavement without CLRS, that had actually no water film "thickness."

Table 3.9: Least Square Means

Effect	Water	CLRS	Visit	Estimate	Standard Error	DF	t Value	Pr > |t|
Visit			1	222.78	34.1859	3.35	6.52	0.0052
Visit			2	154.17	32.2474	2.66	4.78	0.0228
Visit			3	139.36	31.1392	2.31	4.48	0.0353
Water	Dry			164.75	31.1579	2.29	5.29	0.0251
Water	Wet			179.46	34.0457	3.27	5.27	0.0107
CLRS		No		213.89	33.8301	3.19	6.32	0.0066
CLRS		Yes		130.32	31.0795	2.27	4.19	0.0419
Water*CLRS	Dry	No		158.28	34.5843	3.34	4.58	0.0154
Water*CLRS	Dry	Yes		171.22	32.8481	2.71	5.21	0.0176
Water*CLRS	Wet	No		269.50	42.1145	7.2	6.40	0.0003
Water*CLRS	Wet	Yes		89.4213	34.3010	3.23	2.61	0.0740

Table 3.10: Differences of Least Squares Means

Effect	Water	CLRS	Visit	_Water	_CLRS	_Visit	Estimate	Standard Error	DF	t Value	Pr > |t|
Visit			1			2	68.6056	20.5295	27.9	3.34	0.0024
Visit			1			3	83.4222	20.5295	27.9	4.06	0.0004
Visit			2			3	14.8167	16.7623	27.9	0.88	0.3843
Water	Dry			Wet			-14.7088	22.8414	10.4	-0.64	0.5336
CLRS		No			Yes		83.5653	21.9706	8.98	3.80	0.0042
Water* CLRS	Dry	No		Dry	Yes		-12.9444	25.8240	4.31	-0.50	0.6407
Water* CLRS	Dry	No		Wet	No		-111.22	36.8986	16.2	-3.01	0.0081
Water* CLRS	Dry	Yes		Wet	Yes		81.8009	25.4434	4.05	3.22	0.0318
Water* CLRS	Wet	No		Wet	Yes		180.08	35.5520	14.4	5.07	0.0002

3.3 KEY FINDINGS

- From the results of the analyses above, it can be seen that there is a significant correlation between the RRPM's paint coverage and the retroreflectivity values at the sites on US-40, but no such correlation exists on US-24 or US-50. The possible explanation for this result is that the RRPMs on US-24 and US-50 were only 30 and 151 days old (since installation), whereas RRPMs on US-40 were 1279 days old. The RRPMs paint coverage on US-24 and US-50 was nearly 100 percent and coverage on US-40 was between 46 to 69 percent. The paint coverage range on US-24 and US-50 was almost constant, probably due to being relatively new, and that could be the reason for showing no significant correlation with retroreflectivity at these two test locations. Overall, based only on the results from this study, the method of measuring paint coverage should not be used as a substitute for the retroreflectomer readings for an analysis of retroreflectivity.
- The spectrometry measurements showed that the color of the pavement markings did not vary from yellow over time. The spectrometry method should be used as a complementary analysis, and not to substitute the retroreflectomer readings for an analysis of retroreflectivity.
- Estimated retroreflectivity decreases over time in a straight line, since the correlation with time was 0.98.
- On locations without CLRS, the wet retroreflectivity of pavement markings was 41 percent higher than the dry retroreflectivity. This difference was

statistically significant. Overall, at locations without CLRS, the estimated wet retroreflectivity was above the acceptable retroreflectivity limit for yellow retroreflective paint material, but the estimated dry retroreflectivity was below the limit.

- On locations with CLRS, the dry retroreflectivity value was 47 percent higher than the wet retroreflectivity. It was also noted that over CLRS, the estimated retroreflectivity value for the dry condition was higher than the acceptable limit for yellow, retroreflective paint material, but the wet retroreflectivity value was below the limit.
- For dry conditions, CLRS produced better, but not statistically significant, retroreflectivity values than pavement without CLRS.
- For wet conditions, the retroreflectivity of pavement without CLRS was statistically, significantly better than the one measured over CLRS. However, the wet retroreflectivity measurements were different for CLRS and without CLRS conditions. The grooves of CLRS were filled up to 80 percent of the depth, which could not be reproducible on smooth pavement surfaces. This may explain the significant interaction found between the CLRS and the Water effects. The small layer of water found on smooth pavement enhanced the retroreflectivity as compared with the dry condition. The retroreflectivity value decreased as the grooves of CLRS were filled with water up to 80 percent of their depth. This tendency agrees with the literature.

3.4 CONCLUSIONS

This study applied three methods of evaluating the visibility of pavements markings. Based only on the limited data collected, it can be concluded that the coverage check method should not substitute the retroreflectometer readings for studies of retroreflectivity, since the correlation of the two methods was not reliable. In addition, the spectrometry method should only be used as a complementary analysis. The spectrometry method revealed that the yellow pavement markings remained within the yellow spectrum over the study period at all three locations.

Based on the retroreflectivity analysis, it can be concluded that the overall estimated retroreflectivity value decreases over time in a linear manner. At dry conditions, CLRS presented better retroreflectivity than pavement without rumble strips, but the difference was not statistically significant. For wet conditions, the retroreflectivity values of pavement without CLRS were statistically, significantly better than the CLRS values, but the measurements were taken for different conditions (grooves were filled up to 80 percent of their depth, which was not reproducible over smooth pavement conditions that had essentially no water film “thickness”). A small or insignificant layer of water over the pavement may enhance the retroreflectivity, but as the water accumulates in the groves, the luminance intensity of the pavement marking decreases, which agrees with the literature. The authors believe that even if CLRS would reduce wet luminance of pavement markings, there are other aspects in their utilization that may contribute to safety. The value of CLRS goes beyond visibility, especially in heavy rain situations when overall visibility is affected, the vibration caused by the strips would help in letting the driver know he/she is too far toward the center of the roadway.

The difference in the results between measurements taken over CLRS and over asphalt pavement without CLRS found in this study may be due to the incapacity of the retroreflectometer used in this study in taking readings at points on the CLRS grooves deeper than 0.157 inch Therefore, further measurements should be conducted in order to better explain such results, using retroreflectometers that have height tolerance greater than 0.5 inch (12.7 mm), which is the required depth of CLRS in Kansas.

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APPENDIX A - MOTORCYCLE RIDERS' SAFETY SURVEY

Kansas State University research team conducted a questionnaire survey on motorcycle riders travelling on undivided highways with CLRS. The 44 participants consisted of a diversified group of motorcyclists riding both sports and cruise motorcycles. Out of the total of 44, six participants were in the age group of 18-24, thirty in the age group of 25-45, seven in the 45 – 65 age group and one rider was above 65 years old. Eighty-six percent of participants were males and 14 percent females. Two percent of the participants had less than 1 year of riding experience, 34 percent had 1-5 years and 64 percent had above 5 years of motorcycle riding experience. Majority of the participants were employees of Harley-Davidson's Vehicle and Power train operations plant in Kansas City, Missouri.
A paper based questionnaire survey was developed by Kansas State University research team. The questions were designed to determine the key safety factors impacting motorcycle riders when traversing over CLRS. This study focused on the following factors: CLRS effect on motorcyclist in reducing heads on collisions on undivided two-lane and four-lane highways, effects of sound and vibratory warnings in correcting the lane position, rider's initial reaction when encountering CLRS, erratic maneuvers encountered while traversing CLRS, intensity of difficulty encountered in motorcycle handling, motorcycle rider's opinion on rumble effect, and difficulty and safety concerns while making legal passing maneuvers. The period of study was between April and June, 2008.

Question 1: Have you driven over (come in contact with) the Centerline Rumble Strips (CLRS)?
Respondents were asked to answer "yes" or "no" to the first question. If they answered "yes", they were asked to continue to question two. If they answered" no" they were asked to continue to question thirteen.
<u>Result:</u> 57% (n = 25) of the respondents answered yes that they have encountered CLRS. Forty three % (n = 19) respondents answered that they have not encountered CLRS. All respondents, including the participants who have not encountered CLRS answered questions 14 through 18.

Question 2: Do you remember the location where you encountered Centerline Rumble Strips? If so please write down the location.
Locations where riders came across CLRS are shown below:

Response Distribution for Question 2, Motorcycle Survey

	Location
1	US-40 Topeka, Kansas.
2	Highway 169 North of Smithville, Missouri
3	South Missouri & Arkansas
4	210 from North Kansas City to Orrick, Missouri.
5	Highway 13 south of Warrensburg to Clinton, Missouri.
6	Highway 59 between ST-Joseph, Missouri & Atchison, Kansas.
7	Warsaw, Missouri.
8	Highway 92 between Kearney & Springs, Missouri.

It can be seen that the locations where CLRS were encountered by riders in the survey were all in Kansas and Missouri.

Question 3: Type of rumble strip encountered (Mark all that applies)?
In this question respondents were asked the types of CLRS encountered. For this question three answering options were given, a. Rectangular CLRS, b. Football CLRS and c. Both.
Result: 64% (n = 16) have encountered rectangular rumble strips, 28% (n = 7) football shaped and 8% (n = 2) have encountered both. Hence, most of the respondents have encountered rectangular shaped CLRS.

Question 4: Did you encounter a motorcycle handling problem?
In this question respondents were asked about the difficulty encountered in motorcycle handling when they traversed CLRS. Here the respondents were asked to answer either "yes" or "no".
Result: 52% (n = 13) answered yes that they have encountered motorcycle handling trouble and 48% (n = 12) answered no. Hence we can see that only about half of the respondents feel that they have encountered problems in motorcycle handling when they encountered CLRS.

Question 5: If your answer is 'Yes' to Question # 4, please rate the level of difficulty encountered on a scale of 1-5 (1 for Low and 5 for High). If your answer is 'No' to Question # 4, please continue to Question # 6.
This question was only for respondents who answered "yes" to Question # 4. In this question respondents were asked to rate their difficulty encountered in motorcycle handling on a scale of 1-5 (1 for Low and 5 for High). For those who answered "no" to Question # 4 were asked to continue to Question # 6.

Result: 8.33% (n = 1) of respondents faced level 5, 4 & 1 difficulty, 41.67% (n = 5) faced level 3 difficulties and 33.33% (n = 4) faced level 2 difficulties. From this response rating it can be concluded that little difficulty in motorcycle handling is faced when riders ride over CLRS.

Question 6: When you drove over centerline rumble strips what was your initial reaction, did you correct to the left, to the right or overcorrect?
This question was meant to determine riders' initials reaction when they rode over CLRS. Response to this question determined what erratic maneuvers riders encountered when they rode over CLRS. There were three answering options for the question. If the answer was anything other than those three answering options they were asked to write that down that in the form of a comment.
Result: 71% (n = 12) of rider's initial reaction was to turn right for correcting their lane position, 18% (n = 3) turned left and 12% (n = 2) overcorrected their lane position. Also some of the respondents gave interesting comments which are quoted at the end of this chapter. From this distribution it can be seen that the majority of respondents reacted properly to the corrective stimuli given by CLRS.

Question 7: Did you ride on them unknowingly?
In this question respondents were asked to answer either "yes" or "no".
Result: response distribution shows that 56% (n = 14) of riders rode over CLRS unknowingly.

Question 8: What is your initial impression on Centerline Rumble Strips?

☐ Like, please rate your opinion on a scale of 1-5 (1 for Low and 5 for High) on how strongly you like _____

Or

☐ Dislike, please rate your opinion on a scale of 1-5 (1 for Low and 5 for High) on how strongly you dislike _____

Result: 68% (n = 17) of respondents say that they like CLRS and 32% (n = 8) of them dislike CLRS.

From the likeness distribution, 5.88 % (n = 1) of respondents gave a likeness rating of 1 and 5, 17.65 % (n = 3) gave a rating of 3, 41.18% (n = 7) and 29.41% (n = 5) gave a rating of 4.

From the "Dislike" distribution, 25 % (n = 2) of respondents gave a dislike rating of 1 and 3. 37.5% (n = 3) gave a rating of 4 and 12.5% (n = 1) gave a rating of 5.

Question 9: Do you think they are a nuisance while making legal passing maneuvers?

This question asks respondents whether they think CLRS are a nuisance while they make legal passing maneuvers. Here respondents were asked to answer either "yes" or "no".

Result: 76 % (n = 19) believe that CLRS are a nuisance while making legal passing maneuvers. Considering Question 8, it can be seen that 68% of respondents like CLRS, from Question 6, it can be seen that 71% corrected properly and Question 5, it can be seen that only little difficulty was encountered by most. Also from Question 10, respondents rated CLRS effectiveness as high and Question 11shows that CLRS provide safety improvement in reducing heads on collision. Hence, only 24% of the respondents consider CLRS as nuisance.

Question 10: What is your impression of the effectiveness of the rumble effect? Giving consideration to vibratory alertness provided by Centerline Rumble Strips please rate your answer on a scale of 1-5 (1 for Low and 5 for High).

Result: 16% (n = 4) of respondents have rated effectiveness level-5, 40% (n = 10) have rated effectiveness level-4, 32% (n = 8) have rated effectiveness level-3 and 12% (n = 3) have rated effectiveness level-2. Therefore from the distribution it can be seen that most of the respondents rate the overall effectiveness of CLRS as high.

Question 11: Do you think Centerline Rumble Strips provide a suitable safety improvement for reducing head-on collisions?

This question asks respondents whether they think CLRS provide a suitable safety improvement for reducing head-on collision. Here respondents were asked to answer either "yes" or "no".

Result: 72 % (n = 18) believe that CLRS provide a suitable safety improvement for reducing head-on collision.

Question 12: If CLRS are proven to reduce head-on collisions and improve safety, would your impression of them change?

This question was designed under the assumption that majority of responders would not have a good initial impression on CLRS, but results were contradictory and it was seen from Question 8 that majority (68%) liked CLRS and Question 10 rating shows CLRS is highly effective. Here respondents were asked to answer either "yes" or "no".

Result: 72% (n = 18) of respondents say that their initial impression on CLRS would change if CLRS is proven to reduce head-on collision and improve safety. Due to the misassumption while designing the study this response has low validity.

Question 13: Do you think Kansas Department of Transportation should implement Centerline Rumble Strips in more locations across the state?

This question asks respondents whether they think KDOT should install CLRS in more locations. Here also respondents were asked to answer either “yes” or “no”.

Result: 70% (n = 31) of respondents suggest that KDOT should install CLRS on more locations across the state.

Many respondents requested that their response to this question should be also shared with Missouri DOT.

Question 14: Do you prefer wearing a helmet while riding motorcycle?

This question asked respondents about their preference in wearing a helmet while riding motorcycle. Here also respondents were asked to answer either “yes” or “no”.

Result: 70% (n = 31) of respondents prefer wearing a helmet while riding.

Comments

Respondents were requested to provide additional comments concerning centerline rumble strips. They are as follows,

“Rumble strips are very effective on the outside of lane, so they probably would be in the middle also. I have ridden on shoulder rumble strips with no loss of control.”

“Potentially widening the rumble strips and gradually taper from their depth would provide a subtle warning before being on centerline.”

“Centerline Rumble Strips is a good idea. I have never encountered one but based on my experience with other types of road conditions, a motorcycle rider could safely negotiate a lane change over centerline rumble strips without incident impacting safety.”

“I’ll be in favor of implementing centerline rumble strips. I would also be very selective of the locations where they are added. i.e. very high head-on collision only areas.”

“Judging from my experience I don’t feel that these strips would affect handling of motorcycle. They would definitely reduce the number of head on collisions on two-lane roads.”

“Make drivers aware that centerline rumble strips are installed ahead. Then they won’t come across any erratic maneuver which affects safety.”

“This is a good way to deal with the already uneducated driving public.”

“It’s better to have them to reduce head on collision and suggest having more of them on undivided highways.”

“I was aware of centerline rumble strips - No surprise. My response might have been different if I was unaware of the situation.”

Conclusions

From the results of this survey it can be seen that 57% of motorcycle riders have traversed over CLRS and about half of them encountered motorcycle handling problems while traversing CLRS. However, it can be seen from the difficulty response distribution that the level of difficulty encountered is not high. Also 68% of respondents liked the rumble effect and 72% believed in their effectiveness in reducing head-on-collisions. In addition, 70% of respondents strongly recommended that Kansas Department of Transportation should implement CLRS in more locations across the state. Therefore, it can be concluded that the majority of the motorcycle riders believe in the effectiveness of CLRS. Motorcycle riders noted that when they were aware of the situation (installation of CLRS) they didn’t encounter much difficulty in motorcycle handling. Warning signs like “Centerline Rumble Strips Ahead” (see example below) would warn the motorcycle riders of the upcoming situation. This should reduce any unexpected reactions when they encounter CLRS.

Possible Warning Signs

APPENDIX B - NOISE SURVEY

In October 2009, surveys were sent out to the residents along the section of the US-40 highway where the football CLRS were installed in May 2005. The main idea behind the survey was to compare the results of a similar survey given out to the residents along the same section in January 2006. The survey consisted of eight questions which gives the residents' likes, dislikes or concerns related to the noise produced from vehicles traveling over CLRS. The surveys were mailed back to the K-State rumble research team at the Department of Industrial and Manufacturing Systems Engineering and the data was analyzed to determine the residents' response to the external noise generated by vehicles traveling over CLRS, after 53 months since installation.
A total of 22 surveys were sent out through the mail to the residents along the stretch of the US-40 Highway where football CLRS were installed in May 2005. The results of each question in the survey are discussed below along with any comments from the residents. A total of 12 surveys were received back from the residents which constitutes a 55% return rate.

Question 1: How many years have you been at the current address?
The residents were asked to notify the number of years they have been living at the current address. The results were allotted into three categories: less than 3 years, 3-10 years and more than 10 years.
<u>Result:</u> 75% (n=9) of the residents were living at the current address for more than 10 years. Also, 17% (n=2) of the residents were living between 3-10 years and 8% (n=1) of the residents were living for less than 3 years at the current address. This is a positive response as the residents were living at the current address well before the installation of CLRS and can compare the change in the noise levels for before and after installation.

Question 2: Can you hear any noise of Traffic on US 40 from your residence?
The residents were asked to answer yes or no for the question 2.
<u>Result:</u> 100% of the residents (n = 12) hear noise from the traffic on US-40 highway.

Question 3: Can you hear from your residence when a driver crosses over (comes in contact with) the centerline rumble strips?
The residents were asked to answer yes or no to the question 3. If the answer was yes, they must proceed to question 4 or else proceed to question 6.
<u>Result:</u> 92 % of the residents (n = 11) hear noise from the vehicles when they cross over CLRS and 8 % (n = 1) said they do not hear noise when vehicles cross over CLRS.

Question 4: The residents were asked to choose one from the four following options: the noise is unnoticeable and not a concern, noise is noticeable and not a concern, the noise is only inconvenient and annoying and the noise is produced is loud enough to cause a concern or a distraction.
<u>Result:</u> 90% (n=9) of the residents agree that the noise is noticeable and it is not a concern. This is a positive response as it indicates that these residents most likely have gotten used to the noise generated from the vehicles traveling over CLRS.
The results to the survey conducted in January 2006 indicated that 16 % of residents said the noise was loud enough to cause a problem or a distraction and 32 % of residents said the noise is inconvenient or annoying. Even though the number responding to the follow-up survey is less, it is speculated that those not responding have no major concerns with the noise generated; otherwise, it is likely they would have taken this opportunity to express concerns regarding noise.

Question 5: If you answered yes to question3, how often can you hear the noise produced from a driver crossing the centerline rumble strips?

The residents on US-40 highway were asked to mention the number of times they hear the noise produced by vehicles traveling over CLRS in a day, for which they had to pick from the available four options: Less than once a day, 1-5 times a day, 5-10 times a day and more than 10 times a day.

Result: From the response distribution graph, it can be noticed that 90 % of the residents hear the noise from vehicles crossing from CLRS is not more than 5 time a day. It can be also seen that none of the residents responding hear the noise more than 10 times a day whereas the results from the survey in January 2006 said that 36 % of the residents said they hear the noise from the US-40 traffic when crossing centerline rumble strips.

Question 6: What is the approximate distance from your house to US-40?

The residents were asked to give the approximate distance from their house to US-40, so that the intensity of noise reaching their house from the US-40 traffic can be roughly assessed based on the results from field studies.

Result: Nine residents answered "more than 250 feet". Two residents answered "100-250 feet" and one respondent answered "50-100 feet".

Question 7: Do you believe Centerline rumble strips on US 40 contribute to your driving safety?

Residents were asked to answer Yes, No or No Opinion for question 7 of the survey.

Result: 92% (n=11) of residents think that the centerline rumble strips contribute to their driving safety and 8% (n=1) of the residents say they have no opinion. This is a positive response as all of the residents believe that CLRS will contribute to their driving safety. From the results of the survey sent out in January 2006 to the residents of US 40 highway, 16 % of the residents responded said that centerline rumble strips do not contribute to drivers safety.

Question 8: Do you believe the potential safety effect is worth some level of annoying noise?

The residents were asked to answer yes, no or no opinion for the question 8 of the survey.

Result: 100% (n=12) of the residents believed that potential safety is worth some level of annoying noise. This is a positive response as it helps in future research regarding the CLRS on undivided highways.

Comments

Respondents were also asked to write any additional comments about the centerline rumble strips and the noise produced from driving over them. The following are the additional comments.

"I believe that rumble strips are a helpful safety factor. I would like to see them on many 2 lane highways."

"I think the rumble strips are a good thing to have."

"One of the best things that ever happened. It is a safety factor, it helps."

"We appreciate the rumble strips. It definitely makes you aware you are driving a little carelessly when you venture onto it."

"Those strips have already saved my life more than once and I have only lived here two months."

"Rumble strips really help staying in the same lane on two way highways."

Conclusions

According to the resident survey results, 90 % (n = 11) of the respondents think that the noise generated from the vehicles crossing over centerline rumble strips was noticeable but not a concern to them. Also, it was evident that none of the respondents to the resident survey responded that they heard the noise from vehicles crossing CLRS more than 10 times a day. Also, 100% of the respondents (n = 12) said that CLRS contribute to drivers safety and also that they believe the potential safety effect is worth some level of annoying noise. Therefore, it can be concluded that majority of the residents on US 40 highway believed that installation of centerline rumble strips was a positive step taken to ensure the drivers' safety. When compared to a similar survey results conducted by a Kansas State University CLRS research team during January 2006, the %age of residents who believed that installation is a good safety measure increased substantially over the past three and a half years and that the residents are getting used to CLRS, and the number of residents paying attention to or concerned over noise produced by the CLRS has decreased over the past three and a half years.

K - TRAN

KANSAS TRANSPORTATION RESEARCH
AND
NEW - DEVELOPMENTS PROGRAM

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION

THE UNIVERSITY OF KANSAS

KANSAS STATE UNIVERSITY