Louisiana Transportation Research Center

Final Report 648

Impact of Centerline Rumble Strips and Shoulder Rumble Strips on all Roadway Departure Crashes in Louisiana Two-lane Highways

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TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle
   Impact of Center Line Rumble Strips and Shoulder Rumble Strips on all Roadway Departure Crashes in Louisiana Two-lane Highways
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   Louisiana Department of Transportation and Development
   P.O. Box 94245
   Baton Rouge, LA 70804-9245
5. Report No.
   FHWA/LA.17/648
6. Report Date
   March 2021
7. Performing Organization Code
   LTRC Project Number: 19-4SA
   SIO Number: DOTLT1000295
8. Type of Report and Period Covered
   Final Report
   07/2019–12/2020
9. No. of Pages
   105
10. Supplementary Notes
    Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration
11. Distribution Statement
    Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.
12. Key Words
    Roadway Departure; Rural Two-Lane; Urban Two-Lane; Centerline Rumble Strips; Shoulder Rumble Strips; Empirical Bayes
13. Abstract

To prevent roadway departure crashes, rumble strips have been installed on Louisiana's two-lane highways. This study investigated the impact of rumble strips on 1,593.09 miles of two-lane highways in Louisiana, on which centerline rumble strips (CLRS) and shoulder rumble strips (SRS) were installed between years 2010 and 2016. The comprehensive evaluation consists of observed crash analysis and state-of-the-art crash countermeasure evaluation methods. To capture all departure scenarios and take full advantage of crash data, the observed crash analysis includes not only conventional total crashes and targeted crashes, but also crashes with combined key crash attributes, as well as selected crash report reviews, which helps to the clarify the ambiguous or inconsistent information identified during the initial analysis. The biggest reductions come from fatal and severe injury crashes, which are 34% for rural two-lane and 45% for urban two-lane highways. The safety evaluations from multiple evaluation methods consistently demonstrate the success of rumble strips, particularly the centerline rumble strips installations. The before and after empirical Bayes (EB) analysis, comparison group EB analysis, with-and-without cross-sectional analysis, and ARIMA Intervention Model of trend analysis yield reliable CMF estimations for centerline rumble strips. The expected CMFs from before-after EB method are 0.845, 0.95, and 0.764 for CLRS, SRS, and combination of CLRS and SRS on rural two-lane highways, respectively. They are 0.677, 0.655, and 0.839 on urban two-lane highways, respectively. The huge economic benefits of rumble strips are manifest by the ratio of benefit to cost – 12.98 for combined all rumble strips cases on rural two-lane highways, and 14.64, 1.9, and 7.37 for the CLRS, SRS, and both (CLRS and SRS), respectively. The ratio is 37.2 for all rumble strips on urban two-lane highways, 38.27 for CLRS, and 83.55 for CLRS and SRS combined. This study demonstrates rumble strips as a low cost, effective crash countermeasure on two-lane highways. To reach the state's goal of Destination Zero Deaths, rumble strips should be considered for installation along two-lane highways everywhere, if financially feasible, or if not, by prioritizing the installation projects based on either the crash frequency or crash risk at the network level.

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LTRC Project No. 19-4SA
SIO No. DOTLT1000295

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

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March 2021

Abstract

To prevent roadway departure crashes, rumble strips have been installed on Louisiana's two-lane highways. This study investigated the impact of rumble strips on 1,593.09 miles of two-lane highways in Louisiana, on which centerline rumble strips (CLRS) and shoulder rumble strips (SRS) were installed between years 2010 and 2016. The comprehensive evaluation consists of observed crash analysis and state-of-the-art crash countermeasure evaluation methods. To capture all departure scenarios and take full advantage of crash data, the observed crash analysis includes not only conventional total crashes and targeted crashes, but also crashes with combined key crash attributes, as well as selected crash report reviews, which helps to the clarify the ambiguous or inconsistent information identified during the initial analysis. The biggest reductions come from fatal and severe injury crashes, which are 34% for rural two-lane and 45% for urban two-lane highways. The safety evaluations from multiple evaluation methods consistently demonstrate the success of rumble strips, particularly the centerline rumble strips installations. The before and after empirical Bayes (EB) analysis, comparison group EB analysis, with-and-without cross-sectional analysis, and ARIMA Intervention Model of trend analysis yield reliable CMF estimations for centerline rumble strips. The expected CMFs from before-after EB method are 0.845, 0.95, and 0.764 for CLRS, SRS, and combination of CLRS and SRS on rural two-lane highways, respectively. They are 0.677, 0.655, and 0.839 on urban two-lane highways, respectively. The huge economic benefits of rumble strips are manifest by the ratio of benefit to cost – 12.98 for combined all rumble strips cases on rural two-lane highways, and 14.64, 1.9, and 7.37 for the CLRS, SRS, and both (CLRS and SRS), respectively. The ratio is 37.2 for all rumble strips on urban two-lane highways, 38.27 for CLRS, and 83.55 for CLRS and SRS combined. This study demonstrates rumble strips as a low cost, effective crash countermeasure on two-lane highways. To reach the state's goal of Destination Zero Deaths, rumble strips should be considered for installation along two-lane highways everywhere, if financially feasible, or if not, by prioritizing the installation projects based on either the crash frequency or crash risk at the network level.

Acknowledgments

The research team wants to express their gratitude to the engineers from Louisiana Department of Transportation and Development (DOTD) and particularly the District 03 for providing rumble strip installation data and cost information. The guidance from the project review committee are also gratefully appreciated.

Implementation Statement

The project findings suggest the state steadily implement rumble strips since roadway departure is still a predominant type of crashes on two-lane highways. In addition to reduce total number of roadway departure crashes, CLRS can significantly reduce deadly head-on crashes, a contribution to decrease overall traffic fatalities. Under constant budgetary constraints, the state can prioritize the locations for rumble strip installation either by total departure crashes or risk of such crashes.

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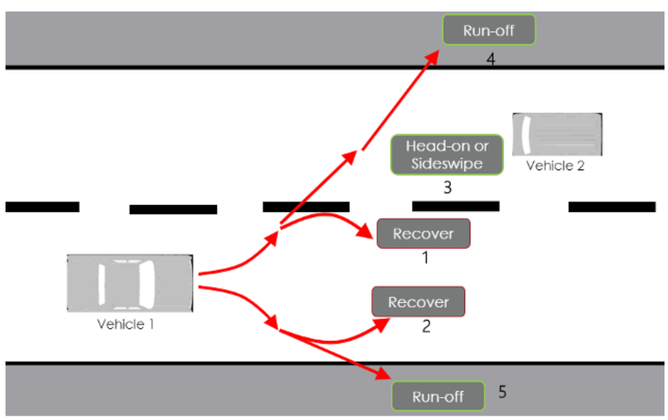
Introduction

A roadway departure crash is a non-intersection crash, which occurs after a vehicle crosses an edgeline or a centerline, or otherwise leaves the travelled roadway *[1]*. Roadway departure crashes are the result of drivers running off the road to the right, crossing the centerline/median into an oncoming lane of traffic (head-on or opposite-direction-sideswipe crashes), or running off the road to the left. Vehicles running off the road may also involve a rollover, an immersion, or hitting a fixed object. The FHWA mentions four key reasons for roadway departure from drivers' perspectives—roadway condition, collision avoidance, vehicle component failure, and driver error *[2]*. Because vehicles involved in roadway departure crashes often end up hitting moving vehicles or fixed rigid structures (bridges, poles, guardrails, etc.), the outcomes of roadway departure crashes tend to be severe. Figure 1 illustrates a simplified roadway departure with presumable crash types including the potential recoveries.

Figure 1. Roadway Departure Crash or Near-Crash Outcomes



Roadway departure crashes are considered to be a major contributor to highway fatalities in the United States. During 2015-2017, more than half of all roadway fatalities occurred due to roadway departure *[1]*. Roadway departure crashes are a serious concern in the state of Louisiana, specifically on two-lane highways. According to the Louisiana crash data between 2005 and 2017, 29.5% of all non-intersection crashes were caused by roadway departure on the state-controlled highways *[3]*. Roadway departure crashes on the rural two-lane (R2L) highways consisted of 72.2% of all R2L non-intersection crashes over the course of 13 years; whereas, 30.4% of non-intersection crashes on U2L highways resulted in roadway departure during the same time period. In the same time period, 79.7% of total fatal non-intersection crashes (4,903 of 6,151) were reported as having been caused by roadway departure, including 37.4% on R2L highways and 15.5% on urban two-lane (U2L) highways. The general descriptive statistics indicate that roadway departure crashes on two-lane highways require serious attention.

National transportation agencies have identified lowering the frequency of roadway departure crashes as a national priority *[4], [5]*. The recently launched FHWA mission of FoRRRwD (Focus on Reducing Rural Roadway Departures) is a call for action to "Reduce the potential for serious injury and fatal roadway departure crashes on all public rural roads by increasing the systemic deployment of proven countermeasures." To prevent roadway departure crashes, the FHWA and AASHTO (American Association of State Highway Transportation Officials) recommended several countermeasures, such as providing adequate pavement friction, alerting drivers with rumble strips (RS), enhancing delineation along horizontal curves, and improving nighttime visibility, etc. *[1], [4]* In line with the nationwide urgency to cut down roadway departure crashes, the Louisiana Department of Transportation and Development (DOTD) also reported preventing roadway departure crashes as one of the top priorities in an effort to obtain the goal of halving the number of traffic fatalities and severe injuries from 2009 to 2030 *[6]*.

Centerline rumble strips (CLRS) and shoulder rumble strips (SRS) are inexpensive countermeasures designed to prevent roadway departure crashes by creating a tactile vibration and audible rumbling by alerting distracted or inattentive drivers to take corrective action before roadway departure. Rumble strips also provide a navigational aid to maintain the intended travel lane during poor visibility at nighttime or in inclement weather.

The Louisiana DOTD continued to implement several countermeasures on a large scale in recent years, notably CLRS and SRS on R2L highways. The Louisiana Transportation Research Center (LTRC) sponsored a study to investigate the safety impact of CLRS along with some other safety countermeasures *[7]*. From the limited verification capability of CLRS presence, that study estimated a 16.9% total crash reduction, using empirical Bayes method and a more than nine benefit-cost ratio from observed crashes. From the crash reduction and economic justification results, the study strongly recommended continuation of implementation of CLRS on the state and non-state two-lane highways, where head-on and sideswipe crash rates are higher than the state average as a very effective safety countermeasure.

There is a need to continue the study on the safety impact of CLRS, SRS, and the combination of both, with a specific look at roadway departure. It is important to investigate crash characteristics analysis of before and after years, as well as benefit-cost ratio for CLRS and SRS implementation on rural and urban two-lane highways.

Literature Review

The literature review is two-fold. First, review from previous studies on factors associated with roadway departures were discussed. Second, results from the selected studies, that used the scientific method including empirical Bayes for safety impact evaluation of CLRS, SRS, or both have been presented.

Factors of Roadway Departure Crashes

A statewide, thorough investigation on the contributing factors related to roadway departure on R2L highways was performed in Texas, with crash, traffic, and geometric data, between 2003 and 2008 *[8]*. Simple descriptive analysis and the negative binomial regression model on roadway departure crashes were used, examining the effect of lane width, shoulder width, traffic volume, curve density, and number of driveways on roadway departure crash frequency.

Typically, the majority of the roadway departure crashes are single-vehicle crashes, or more specifically, single-vehicle run-off-road (SVROR) crashes—as for Louisiana, more than 80% of roadway departure crashes are single-vehicle crashes. Studies are available on the factors related to single-vehicle or SVROR crashes. Using Fatality Analysis Reporting System (FARS) data on fatal crashes involving passenger vehicles during 1991 to 2007, a nationwide study analyzed factors related to SVROR crashes *[9]* by developing a logit model of run-off-road crashes with regards to on-road crashes.

Using the data of 557 randomly selected fatal crashes between 1997-1998 in four southern states in USA, one study applied binary logit models to predict the probability of whether a fatal crash is a SVROR crash or not *[10]*. The study employed roadway design characteristics, roadside environment features, and traffic conditions proximal to the crash site as explanatory variables that could critically influence SVROR crashes. An investigation on run-off road crashes or near-crash events, based on the 100-Car Naturalistic Driving Study, explored the relationship between frequency of run-off-road events per million vehicle miles traveled with different driving condition *[11]*. One study can be found that employed naturalistic driving data to model left-side and right-side departure, separately, using “non-departure” crashes as the “control” *[12]*.

Few studies investigated the dichotomy between roadway departure and non-roadway departure crash characteristics exclusively. A study in Oahu, Hawaii explored roadway geometry, roadway inventory, and environmental characteristics based on 4-year crash data (2008 to 2011) and differentiated roadway departure crashes from non-roadway departure crashes by a non-parametric methodology—classification and regression trees (CART) *[13]*. In a separate study in Hawaii, the spatial distribution of roadway departure crashes at district level was explored by taking into account crash locality, type of collision, roadway design, and human and environmental factors *[14]*. Several of the previous studies cited the issue that simultaneous presence of more than one factor may well be associated *[8]–[10]*. Table 1 summarizes the findings of roadway departure factors.

Table 1. Findings on Roadway Departure Factors

Study	Year	Type of Construction
Lord et al. *[8]*	2003-2008	• Roadway departure crashes occurred more on curves and during nighttime, and driver-related prevalent factors for roadway departure crashes were distracted driving and speeding. • An increase in lane width and shoulder width was associated with a decrease in roadway departure crash frequency; whereas, increased traffic volume and curve density were linked with the increase of roadway departure crashes. • The presence of shoulders was associated with a decrease, and the number of driveways had little effect on roadway departure crash frequency.
Hashemi and Archilla *[13]*	2008-2011	Four key contributing factors with significant roles in distinguishing roadway departure from non-roadway departure crashes are—crashes on curves, on straight segments with two lanes or less, during daylight condition, and on highways with a speed limit greater than 35 mph.
Zhu et al. *[10]*	1997-1998	Lane width, horizontal curve, and lighting conditions are consistently found to critically influence SVROR crashes for all four states.

Study	Year	Type of Construction
Hallmark et al. *[12]*	2011	• The likelihood of 'right side' departure was reduced with an increase in lane width, radius, oncoming vehicle density, amount of time a driver traveling at 10 or more mph over the posted or advisory speed, highly visible markings, absence of shoulder, etc. • 'Left side' departure was more associated with 20-30 year-old drivers, male drivers, moderately visible lane markings, nighttime driving, etc.
Hashemi and Archilla *[14]*	2008-2011	A higher probability of roadway departure crashes was found in urban areas (majority of roads are located in urban areas), two-way undivided roads, curvy roads, hilly roads, dirt and gravel surfaces, oily and wet road surfaces, fatigue and medical medicines consumption by drivers, hazy weather, and dark/no light conditions.

Safety Effectiveness of Rumble Strips

Many studies have been conducted to evaluate the safety effectiveness of rumble strips. As mentioned in the previous report, the empirical Bayes (EB) method has been the popular analysis tool by overcoming the regression-to-the-mean bias and incorporating other crash contributing factors that may change over time and affect crash patterns *[7]*.

One study in Minnesota assessed the safety impact of SRS in reducing SVROR crashes on 183 miles of R2L highways *[15]*. The empirical Bayes (EB) before-after study estimated a 13% reduction in all SVROR crashes and an 18% reduction in injury SVROR crashes.

One study in Virginia, which focused on the safety effectiveness of centerline rumble strips on roadway curvature, showed that the design speed of less than or equal to 55 mph reduced the total crashes by 25%. A crash reduction of 42% was noted for head-on, opposite direction sideswipe, and for fixed object and off-road crashes. In case of tangents, there was a 37% and 46% reduction in total crashes and fatal and injury crashes, respectively. Irrespective of curvature, the total reduction in total crashes is 0.93 and 0.65 for head-on and opposite direction sideswipe for both total and fatal injury severities *[16]*.

A study in Michigan used empirical Bayes method, which predicted that CLRS were effective in reducing cross-centerline crashes by 27.3%, and when used in combination with SRS, it reduced 32.8% of crashes in two-lane highways *[17]*.

An Iowa study indicated that segments with centerline rumble strips reduces the cross centerline crashes by 33.2%, and edgeline/shoulder rumble strips reduced 16.1% of cross edge line crashes *[18]*.

The most notable study on the safety effectiveness of CLRS and SRS implementation on R2L and U2L highways has been conducted by the National Cooperative Highway Research Program (NCHRP) *[19]*. The EB before-after results from combined data from Minnesota, Missouri, and Pennsylvania showed no significant change in “total crashes” and “fatal and injury crashes” after implementation of CLRS and SRS. There was a reduction in SVROR crashes by 15% and SVROR fatal and injury (FI) crashes by 29% following the installation of shoulder rumble strips. On R2L roadways, total crashes reduced by 9%, FI crashes by 12%, total target crashes by 30%, and FI target crashes by 44% after installation of CLRS. The CLRS on U2L roadways had an estimated reduction in total target crashes by 40% and in FI by 64%.

An EB before-after analysis from crash data on 178.63 miles of SRS treatment sites in Idaho showed a 14% reduction in ROR crashes *[20]*. For sites with an annual average daily traffic (AADT) of less than 1,000, a 33% reduction in ROR crashes was estimated. Moreover, SRS implementation was found to be more effective on horizontal tangents and horizontal curves with moderate curvature, and most effective with paved shoulder widths of 3 ft. or more.

Studies have also been found on the safety impact of the combination of countermeasures. The study on R2L segments with both CLRS and SRS in Kentucky, Missouri, and Pennsylvania showed statistically significant crash reduction for all types of crashes. The study revealed all crash type had a crash modification factor (CMF) of 0.8 and for all severity the CMF is 0.771. Run-off-road and sideswipe opposite direction crashes had a CMF of 0.742 and 0.767, respectively. Head-on crashes had a CMF of 0.632. The combination of head-on and opposite-direction sideswipes and combination of run-off-road and head-on and opposite-direction sideswipes had the CMFs of 0.7 and 0.733, respectively *[21]*. Table 2 presents a compilation of selected studies on safety impact evaluation of CLRS and SRS.

The previously mentioned project study in Louisiana showed that the estimated CMF for total crashes for CLRS are 0.83 by empirical Bayes method *[7]*. There is no record of any comprehensive studies on safety impacts of SRS or a combination of CLRS and SRS implementation in Louisiana.

Table 2. A Compilation of Selected Studies on Safety Effectiveness

Study	Place of study	Year of study	No. of sites	Length (miles)	Results	Method used
Torbic et al. *[22]*	Multiple states	2009	962	462.06	SRS are effective in reduction of SVROR crashes by 15% and SVROR FI crashes by 29% on R2L highways. CLRS reduced the crashes on R2L by 9% on total crashes and 12% in FI crashes. Total target crashes were reduced by 30%, and FI target crashes were reduced by 44%. On U2L highways, total target crashes reduction observed was 40%, and target FI crashes reduction was 64%.	Empirical Bayes before-after analysis
Persuad et al. *[23]*	Multiple states	2003	98	210.8	Overall crashes in sites treated with CLRS were reduced by 12% and injury crashes by 14%. Target total and target injury crashes for CLRS (head-on and opposite direction sideswipe) were reduced by and 21% and 25%, respectively. The daytime all crashes were reduced by 8%, and nighttime all crashes were reduced by 15%.	Empirical Bayes before-after analysis
Rhys et al. *[24]*	Kansas	2012	—	—	Total crashes (except animal, intersection, and ice on pavement) following the installation of SRS were reduced by 29.21%. In similar types of crashes, fatalities and injuries were reduced by 34.05%. Crossover crashes were reduced by 67.19% and run-off road crashes were reduced by 19.19%.	Naïve and empirical Bayes analysis
Kay et al. *[17]*	Michigan	2015	—	4,200	CLRS was effective in reducing all crash types by 15.8% and cross-centerline crashes by 27.3%. When CLRS was used in combination with SRS, crashes were reduced by 32.8%.	Empirical Bayes before-after analysis
Olson et al. *[25]*	Washington	2011	69	493.03	For lane departure, CLRS were effective in reducing crashes by 24.9% for all injury levels and 37.7% in fatal and injury crashes. Cross-centerline crashes were reduced by 44.6% for all injury levels and 48.6% in fatal and serious injury collisions.	—
Khan et al. *[20]*	Idaho	2001-2009	38 treatment sites and 53 control sites	178.63	A 14% reduction was observed in ROR crashes after installation of SRS.	Empirical Bayes before-after analysis
Patel et al. *[15]*	Minnesota	2004	23	183	There was a 13% reduction in all SVROR crashes and an 18% reduction in injury-producing SVROR crashes following SRS implementation.	Empirical Bayes before-after analysis

Study	Place of study	Year of study	No. of sites	Length (miles)	Results	Method used
Wu et al. *[26]*	Pennsylvania	2002-2009	310 segments	—	Total number of crashes were reduced following SRS implementation, but had no statistically significant effect on reducing the probability of a severe crash outcome.	Panel fixed effect (FE) and marginal effect (ME) model hybrid
Sayed at al *[27]*	British Columbia, Canada	—	—	—	The installation of rumble strips reduced all injury collisions by a statistically significant 18.0%; SRS reduced off-road right collisions by a statistically significant 22.5%; and CLRS showed a statistically significant reduction of 29.3% in off-road left and head-on collisions.	—
Karkle et al. *[28]*	—	—	29 segments of highways	—	Total crashes judged to be correctable by CLRS were reduced by approximately 29%. Correctable crashes involving fatalities and injuries were reduced by approximately 34%. Cross-over crashes were reduced by approximately 67%.	Naïve and empirical Bayes
Karkle et al. *[29]*	—	—	15.2-mile of US-50, between Newton and Hutchinson. 10.8-mile US 40	—	The Naïve method showed an overall 50.69% reduction in the total number of crashes per mile year and a 92.1% reduction of crossover accidents after installation of CLRS. The EB method indicated an overall 49.4% reduction of total number of crashes and an 89.2% reduction of the crossover crashes.	Naïve and empirical Bayes

Objective

The goal of this project was to evaluate the safety impact of CLRS, SRS, and both CLRS and SRS on rural two-lane and urban two-lane highways under the Louisiana Department of Transportation and Development (DOTD) system. Specifically, the main objectives were to:

1. Investigate the safety effectiveness of CLRS and SRS (in single or combination) on two-lane highways under the DOTD system.
2. Estimate the safety benefit-cost ratio of the countermeasures.

Scope

This project focused on the rumble strips on the two-lane highways, rural and urban, under the Louisiana Department of Transportation and Development system.

Methodology

This chapter is divided into two subsections. First, the data preparation is presented describing the data source, data verification, and database development. Second, a thorough description is presented on the methodologies used to perform the observational study to investigate the safety impact of CLRS, SRS, and both CLRS and SRS.

Data

The databases used in this research were created from mainly three data sources.

1. Rumble Strips location and installation information obtained from DOTD
2. Crash data from “Crash 1” database
3. Highway section database

DOTD provided the information on location and installation of rumble strips in Microsoft Excel data files that consisted of project description, control section, start and end log mile, segment length of rumble strips installed, and installation dates of rumble strips. Description of project site locations (i.e., highways intersected) was available under “project description,” which was used to identify few sites that had control section and logmile information missing.

The research team utilized the access to the “Crash 1” database—an online portal with restricted access that generates a crash database in several formats based on the specified time and dates, route (including control section and logmile), parish, districts, police troops, and statewide *[3]*. The highway section databases contained roadway geometric information like lane width, shoulder width, pavement type, segment AADT, etc., which were collected from yearly developed Microsoft Access files.

Data Verification and Database Development

The data from the previous projects and the new data of rumble strip installation collected from DOTD were merged for further verification of presence of countermeasures. Visual inspection was carried out using several online tools. The “Google Earth Street View” imagery was used to verify the presence of rumble strips only if the imagery was available in the after period of the known installation year. Based on this imagery, verified presence of the type of rumble strips was coded as “only CLRS,” “only SRS” and “both CLRS and SRS.” Figure 2 presents a section that had both CLRS and SRS.

Figure 2. A Segment with both CLRS and SRS that has been Verified Using Google Street View

Louisiana Lat/Long Converter, an online conversion tool, was used to convert the control section and the logmile to geographic coordinates (i.e., latitude and longitude) that were eventually used in Google Street View to locate the segments *[30]*. Segments for which Google Street View were either unavailable or only available for an earlier year (i.e., before the installation period of rumble strips), an online portal with the video-log image software “ivisionRoadware” provided by DOTD was utilized. The “ivisionRoadware” allowed users to find high quality images of forward (Figure 3) and right-side right of way in both directions of majority of Louisiana roadways captured in 2017 or 2018.

Figure 3. An Illustration of a Two-Lane Section with RS Extracted from "ivisionRoadware"

Table 3 summarizes the verified highway segments presenting the breakdown of length of rumble strip types by highway types. Out of 2,184.9 miles of segments with verified presence of RS, rural two-lane (R2L) segments take the major share, 1,689.01 miles, urban two-lane (U2L) segments have 163.62 miles of RS, rest of the segments were on interstates and other multilane highways. Majority of the segments with verified SRS were on other highways, neither on R2L nor on U2L.

Table 3. Rumble Strips by Length and Highway Type

Rumble Strips	All Highways		R2L		U2L	
	Length (miles)	Percentage	Length (miles)	Percentage	Length (miles)	Percentage
Only CLRS	1,420.15	65.0%	1,303.15	77.2%	109.13	66.7%
Only SRS	457.81	21.0%	113.55	6.7%	33.99	20.8%
Both CLRS and SRS	306.94	14.0%	272.31	16.1%	20.50	12.5%
Total	**2,184.90**	**100%**	**1,689.01**	**100%**	**163.62**	**100%**

Since minimum three years of crash data during both before and after years are required for an observational safety evaluation specifically with EB method, several segments with a construction period of 2017 or later were not included in the final database prepared for analysis. That brings the total mileage rumble strips on R2L to 1,593.1 miles and the total miles of rumble strips on U2L to 97.51 miles, as presented in Table 4 and

Table 5. Two diagrams illustrating the locations of the segments on Louisiana parish maps are presented in Figure 4.

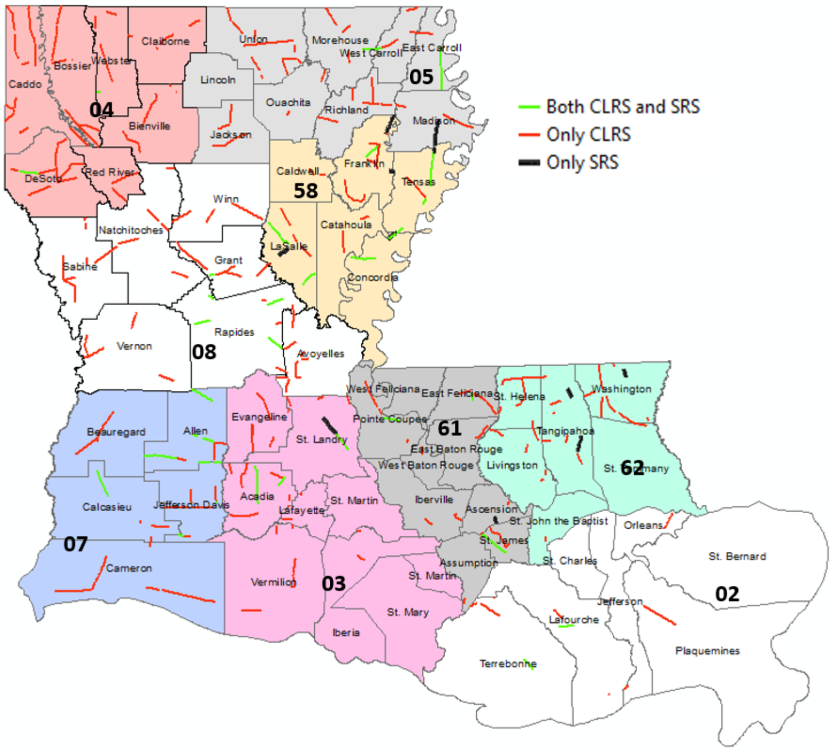
Table 4. Mileage by Four Construction Time Periods (R2L)

Construction Period	Before years	After years	Number of Segments	Total Miles
2010-2011	2007-2008-2009	2012-2013-2014	54	215.12
2010-2012	2007-2008-2009	2013-2014-2015	277	1,128.46
2011-2012	2008-2009-2010	2013-2014-2015	38	205.19
2016	2013-2014-2015	2017-2018-2019	11	44.32
Total	—	—	**380**	**1,593.1**

Table 5. Mileage by Four Construction Time Periods (U2L)

Construction Period	Before years	After years	Number of Segments	Total Miles
2010-2011	2007-2008-2009	2012-2013-2014	4	6.07
2010-2012	2007-2008-2009	2013-2014-2015	30	72.61
2011-2012	2008-2009-2010	2013-2014-2015	4	10.59
2016	2013-2014-2015	2017-2018-2019	3	8.24
Total	—	—	**41**	**97.51**

Figure 4. Location of Rumble Strip Segments on (a) R2L and (b) U2L



(a)

(b)

Only state-controlled R2L and U2L highways were selected for the study as per the scope of the study. Intersection-related crashes were not included in prepared crash database. Crash data from the “Crash 1” database were downloaded from the years 2005 to 2019. Only the crash data identified to have occurred within segment of rumble strips were extracted and geometric information was added to the final complete database on treatment sites.

Observed Crash Analysis

Before applying the scientific methods to estimate the effectiveness of rumble strips, the observed crash analyses were conducted to show changes in observed crashes before and after the rumble strips, which include total crashes by severity at different rumble strip installation locations (centerline, shoulder, or both centerline and shoulder); crash type (manner of collision); targeted crashes; and distribution of crashes by time, driver condition, lighting and pavement surface condition.

To thoroughly investigate changes in targeted crashes, additional crash analyses were performed by using combination of crash attributes. The changes in lane departure and roadway departure crashes that are derived based on the crash characteristics by DOTD were also conducted. Conceptually speaking, there is a difference between lane departure and roadway departure on two-lane highways. Lane departure crash to the right is a roadway departure, but not all lane departures to the left result in roadway departure. In order to conform to the FHWA definition, this report names lane departure and roadway departure derived in “Crash 1” database as “travel lane departure” and “complete roadway departure.” Both scenarios are “roadway departure” according to the FHWA definition.

As shown in Figure 1, single vehicle running off roadway (left and right) recorded as non-collision is a complete roadway departure. The head-on and sideswipe opposite direction collisions are caused by travel lane departure, which may or may not result in a complete roadway departure. The purpose of CLRS is to reduce crashes caused by crossing the centerline. Some complete roadway departures could be caused by multiple-vehicle crashes first such as rear-end collisions that could not be prevented by rumble strips. The intended purpose of SRS is to prevent crashes caused by complete roadway departure (both right and left) and CLRS is for travel lane departure (only to left). Table 6 summarizes the observed crash analysis scheme referencing to Figure 1.

Table 6. Observed Crash Analysis Design

Change in Type of or Defined Crashes	Manner of Collison	Type of Rumble Strips	Run-off roadway case as shown in Figure 1
Total crashes	All	CLRS, SRS, and both CLRS and SRS	Recovered both right and left (1 and 2)
Cross-centerline	Head-on and opposite direction Sideswipe crashes (ODSS)	CLRS	Head-on and Sideswipe crashes (3)
1st harmful event = Ran off road left only (Neither head-on nor ODSS)	Non-collision	SRS	Run off (4)
1st harmful event = Ran off road right	Non-collision	SRS	Run off (5)
Travel lane departure	—	CLRS and possible SRS	—
Complete roadway departure	—	CLRS and SRS	—

In-Depth Crash Analysis

The in-depth crash analysis involves reviewing the original crash reports recorded at each crash site by police officer. The annual crash database is a form of consolidating all individual crash reports. Although the quality of crash record has been improved significantly in the last two decades by the technology, training, and better design, it is still understandably not error free. The objective of crash report reviewing is to clarify the ambiguousness or inconsistency discovered in the crash data analysis. The crash narrative and diagram of individual crash report provide additional information on the nature and sequence of a crash. As it will be discussed in the results, the in-depth analysis reveals exactly what type of crashes can or cannot be prevented by the intended rumble strips.

Assessing Effectiveness of Rumble Strips

Empirical Bayes (EB)

The empirical Bayes method has been used extensively in majority of recent observational before after safety research *[31]*. One of the key reasons this method is widely used is it overcomes the regression-to-the-mean bias. This study used the safety performance functions (SPFs) developed by DOTD for rural two-lane (R2L) highways and urban two-lane (U2L) highways *[32]* to estimate predicted annual crashes as part of the EB procedure. The procedure for EB is discussed below.

Predicted average crash frequency is calculated using applicable SPF during each year of before period ($N_{P,B}$) and after period ($N_{P,A}$). The SPF is taken for "total" crashes and "fatal and severe injury" (FSI) crashes for both R2L and U2L. For example, for R2L highways, the SPF of total crashes is

$$N_{P,B} = 0.0028 * L^{0.9458} * V^{0.7489} \quad (1)$$

For U2L highways, the SPF of total crashes is

$$N_{P,B} = 0.0362 * L^{0.7370} * V^{0.5388} \quad (2)$$

Where, L = segment length, and V = Average annual daily traffic (AADT) in vehicles per day.

The expected average crash frequency $N_{E,B}$ for each site over the before the period is calculated by

$$N_{E,B} = w \times N_{P,B} + (1 - w) \times N_{O,B} \quad (3)$$

$$w = \frac{1}{1+k \times N_{P,B}} \quad (4)$$

For R2L, the overdispersion parameter is

$$\mathrm{k} = \frac{1}{2.64 * \mathrm{L}^{0.9458}} \quad (5)$$

For U2L, the overdispersion parameter is

$$\mathrm{k} = \frac{1}{2.933 * \mathrm{L}^{0.737}} \quad (6)$$

$N_{E,B}$ = Expected average crash frequency at the site for the before period.

N_{SPF}= Predicted crash frequency determined with SPF

$N_{O,B}$ = Observed crash frequency at the site for the before period

k = Overdispersion parameter for applicable SPF

The adjustment factor, r, accounting for differences between predicted crashes in before and after period is calculated as

$$r_i = \frac{N_{P,A}}{N_{P,B}} \quad (7)$$

The expected average crash frequency $N_{E,A}$ and its variance for each site for the after period is calculated as

$$N_{E,A} = r_i \times E_b \quad (8)$$

$$var_{Ea} = r_i^2 \times var_{E,B} = r_i^2 \times (1 - w) \times N_{E,B} \quad (9)$$

Total expected crashes for all sites in the after period

$$\pi = \sum N_{E,A} \quad (10)$$

Total observed crashes for all sites in the after period

$$\lambda = \sum N_{O,A} \quad (11)$$

The safety impact λ/π is potentially biased, therefore the adjustment is needed to obtain an unbiased estimate of countermeasure effectiveness of an adjusted θ

$$\theta = \frac{\frac{\lambda}{\pi}}{1 + \frac{var(\pi)}{\pi^2}} \quad (12)$$

Variance of unbiased estimated safety effectiveness

$$var(\theta) = \frac{\theta^2[\frac{var(\lambda)}{\lambda^2} + \frac{var(\pi)}{\pi^2}]}{[1 + \frac{var(\pi)}{\pi^2}]^2} \quad (13)$$

Comparison of Treatment with Non-Treatment Sites: Cross-sectional Analysis

In order to investigate the safety impact on CLRS, SRS, and both CLRS and SRS, the research team also considered similar non-treatment sites that did not have any rumble strips installed during the after period. Here, the analysis was limited to the treated segments that had a construction year between 2010-2012. The crash data analysis included comparison of crashes between treatment and non-treatment sites during 2013-2015. All other potentially influential variables such as lane width, shoulder width, and AADT were carefully verified and included in this database including non-treatment segments. A comparison of crashes between these two groups were reported in this approach. Additionally, the EB method was utilized in the non-treatment segments aiming to minimize the regression-to-the-mean effect. A description of that approach (i.e., comparison group before-after with EB) is in the following subsection of the report.

Comparison Group Before-After with EB

The before-after comparison group with EB also takes into account a comparison group (i.e., non-treatment sites) to estimate how safety would have changed at the treatment sites had no treatment been implemented *[33]*. This procedure using the comparison group evaluation study method to determine the safety effectiveness of the rumble strips being evaluated, expressed as a percentage change in crashes, and to assess its precision and statistical significance, is presented below step by step. For further details, the Highway Safety Manual (HSM) can be referred *[33]*.

Step 1: Using SPF and AADT, the sum of predicted average crash frequencies at treatment and comparison sites in the before and after period is calculated.

Step 2: For each treatment and comparison sites, adjustment factor to account for differences in traffic volumes and number of years between treatment sites i and comparison sites j during the before and after period from equation (14) and (15) respectively is calculated.

$$Adj_{i,j,B} = \frac{N_{predicted,T,B}}{N_{predicted,C,B}} \times \frac{Y_{BT}}{Y_{BC}} \text{ where,} \tag{14}$$

$N_{predicted,T,B}$ = Sum of predicted average crash frequencies at treatment site i in before period.

$N_{predicted,C,B}$ = Sum of predicted average crash frequencies at comparison site j in before period using the same SPFs (equation 1 and equation 2).

Y_{BT} = Number of years in before period for treatment site i

Y_{BC} = Number of years in before period for comparison site j

$$Adj_{i,j,A} = \frac{N_{predicted,T,A}}{N_{predicted,C,A}} \times \frac{Y_{AT}}{Y_{AC}} \text{ where,} \tag{15}$$

$N_{predicted,T,A}$= Sum of predicted average crash frequencies at treatment site i in after period.

$N_{predicted,C,A}$ = Sum of predicted average crash frequencies at comparison site j in after period using the same SPFs (equation 1 and equation 2).

Y_{AT} = Number of years in after period for treatment site i

Y_{AC} = Number of years in after period for comparison site j

Step 3: Using adjustment factor, the expected average crash frequencies in the before and after period for each comparison site j and treatment site i can be calculated from the following equations (16) and (17), respectively.

$$N_{expected,C,B} = \sum\nolimits_{\text{All sites}} N_{observed,C,B} \times Adj_{i,j,B} \tag{16}$$

where,

$\sum N_{observed,C,B}$ = Sum of observed crash frequencies at comparison site j in before period.

$$N_{expected,C,A} = \sum\nolimits_{\text{All sites}} N_{observed,C,\text{A}} \times Adj_{i,j,\text{A}} \tag{17}$$

where,

$\sum N_{observed,C,A}$ = Sum of observed crash frequencies at comparison site j in after period

Step 4: For each treatment site, total comparison group expected average crash frequencies in before and after period are calculated from equation (18) and (19).

$$N_{expected,C,B,total} = \sum\nolimits_{All\ comparision\ sites} N_{expected,C,B} \quad (18)$$

$$N_{expected,C,\mathrm{A,total}} = \sum\nolimits_{All\ comparison\ sites} N_{\mathrm{expected},C,\mathrm{A}} \quad (19)$$

Step 5: The comparison ratio $r_{i,C}$ is calculated as

$$r_{i,C} = \frac{N_{expected,C,A,total}}{N_{expected,C,B,total}} \quad (20)$$

Step 6: The expected average crash frequency for treatment site i in after period had no treatment been implemented is calculated as

$$N_{expected,T,A} = \sum_{All\ sites} N_{observed,T,B} \times r_{iC} \quad (21)$$

Step 8: Odds ratio and log odds ratio are

$$OR_i = \sum_{All\ sites} \frac{N_{observed,T,A}}{N_{expected,T,A}} \quad (22)$$

$$R_i = ln(OR_i) \quad (23)$$

Step 9: The weight for each treatment site is calculated as

$$w_i = \frac{1}{R^2_{i(se)}} \text{ where,} \quad (24)$$

$$R^2_{i(se)} = \frac{1}{N_{observed,T,B,total}} + \frac{1}{N_{observed,T,A,total}} + \frac{1}{N_{expected,C,B,total}} + \frac{1}{N_{expected,C,A,total}} \quad (25)$$

Step 10: The weighted average log odds ratio across all treatment sites is calculated as

$$R = \frac{\sum_n wiRi}{\sum_n wi} \quad (26)$$

Step 11: The overall effectiveness of the treatment, expressed as an odds ratio, is calculated as

$$OR = e^{R} \tag{27}$$

Step 12: Finally, the safety effectiveness as % change in crash frequency is calculated as

$$\theta = 100 \times (1 - R) \tag{28}$$

Step 13: The standard error and statistical significance are expressed as

$$\sigma(\theta) = 100 \frac{OR}{\sqrt{\sum_{n} w_i}} \tag{29}$$

Step 14: A conclusion can be drawn based on the following criteria.

If $Abs[\theta/\sigma(\theta)] < 1.7$, treatment is not significant at the (approximate) 90% confidence interval (CI).

If $Abs[\theta/\sigma(\theta)] \geq 1.7$, treatment is significant at the (approximate) 90% CI.

If $Abs[\theta/\sigma(\theta)] \geq 2.0$, treatment is significant at the (approximate) 95% CI.

Crash Trend Analysis

Three separate methods were applied as part of an aggregate level crash trend analyses reflecting the change in crashes and considering the varying timeline of rumble strips installation. First, the Mann-Kendall trend test is a nonparametric trend test used to identify monotonic trends in crashes present in time series data. Second, the innovative trend analysis (ITA) is a graphical method that can detect overall trend of crashes whether it increased or decreased over time. Third, the ARIMA (autoregressive integrated moving average) intervention model is used to identify the change in mean level of the crashes considering installation of rumble strips as an intervention event. All the time series analyses were performed on R2L crash data.

M-K Test: The purpose of the Mann-Kendall (M-K) test is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time. A monotonic upward (or downward) trend means that the variable consistently increases (or decreases) through time, but the trend may or may not be linear. The M-K test can be used in place of a parametric linear regression analysis to test if the slope of the estimated linear regression line is different from zero. The regression analysis requires that the residuals from the fitted regression line be normally distributed; an assumption not required by the M-K test, since the M-K test is a non-parametric (i.e., no distributional assumptions) test.

If monthly crash frequencies $x_1, x_2, \dots., x_n$ denote the measurements of trends at times $1, 2, \dots., n$ respectively, and the sign of all possible differences $x_j - x_k$, where $j > k$, then,

$$S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} sgn(x_j - x_k) \tag{30}$$

which is the number of positive differences minus the number of negative differences. If S is a positive number, observations obtained later in time tend to be larger than observations made earlier. If S is a negative number, then observations made later in time tend to be smaller than observations made earlier. Two other measures based on M-K test that indicate the direction of trend are Kendal's tau and Sen's slope. Kendall's tau is a measure of correlation (i.e. the strength of the relationship) between the two variables. Kendall's tau, is carried out on the ranks of into two equal halves of the data. Sen's slope is another measure that can be calculated by

$$\beta = median\left(\frac{x_j - x_i}{j - i}\right), j > i \tag{31}$$

where β is Sen's slope estimate. $\beta > 0$ indicates upward trend in a time series. Otherwise the data series presents downward trend during the time period.

ITA: The basic methodology of ITA method is to divide the time series data into two equal halves and plotting each time series into a cartesian coordinate system after ranking each series in ascending order. The ITA method provides advantage of graphical clarification of database in addition of the M-K test. The basic methodology of ITA is that when the first half of the series is plotted against its second half time series, this enables researchers to compare "low," "medium," and "high" values first half with "low," "medium," and "high" values of second half. If the data points lay on 1:1 line, there is no trend in the data, above the line indicate a positive (increasing) trend, and in the bottom triangle reveal a negative (decreasing) trend of the data.

ARIMA intervention model is a process that is divided into two important steps. The first step is to identify the appropriate order of the ARIMA (p, d, q) model, using Box-

Jenkins methodology *[34]*. Here p stands for order of autoregressive (AR) term, d stands for order of differences required to make the time series stationary, and q stands for order of moving average (MA) term. Box-Jenkins methodology consists of a three step iterative process: 1) model identification; 2) parameter estimation; and 3) diagnostic checking. Following all these steps, appropriate order of the ARIMA model is estimated for the preintervention period (2005-2012). The second step is to fit an intervention model, considering the whole period (2013-2017), using Box-Tiao methodology *[35]* and can be expressed as:

$$Y_t = f(I_t) + N_t \tag{32}$$

Here, $f(I_t)$ is the intervention component of the model, and N_t represents noise component of the model, which is modeled by the ARIMA (p, d, q) technique. Intervention I_t can be modeled as a step or pulse function depending on the type of intervention encountered. Installation of rumble strips to reduce the number of total crashes can be assumed to step function. Therefore, parameter I_t is coded as a dichotomous variable, which takes the value 0 during the preintervention period and 1 during postintervention period. The *general format of the intervention model* can be expressed in the following form:

$$Y_t = \frac{(\omega_0 - \omega_1 B - \omega_2 B^2 - \cdots - \omega_s B^s)}{(1 - \delta_1 B - \delta_2 B^2 - \cdots - \delta_r B^r)} I_t + N_t \tag{33}$$

Where, $\omega =$ intervention magnitude; $\delta =$ decay term; $B =$ backshift operator, $s =$ order of numerator operator, and $r =$ order of denominator operator. The notation N_t stands for ARIMA noise model and can be expressed in the following form:

$$N_t = \frac{(1 - \theta_1 B - \theta_2 B^2 - \cdots - \theta_q B^q)}{(1 - \varphi_1 B - \varphi_2 B^2 - \cdots - \varphi_p B^p)} e_t \tag{34}$$

Where, φ stands for autoregressive coefficient, θ for moving average coefficient, and e_t for errors terms. Including the effect of seasonality on time series data, the ARIMA noise model can take the following format.

$$N_t = \frac{\theta(B)\, \Theta(B^s)}{\varphi(B)\, \Phi(B^s)(1 - B)^d (1 - B^s)^D} e_t \tag{35}$$

Benefit-Cost Analysis

Benefit-cost analysis is an integral part of safety impact evaluation. The anticipated benefits include a reduction in crash frequency and a reduction in the level of crash injury severity. Crash benefits were estimated as savings of crash costs from reduction of crashes in the after period. The benefit estimation is based on the latest information from the FHWA and from the state regarding average cost of crashes per KABCO severity level—fatal, severe injury, moderate injury, complaint injury, and no injury. The unit costs for centerline rumble strips and shoulder rumble strips were estimated with the data from DOTD and the project contractor. The total cost typically includes other costs associated with material, labor, and mobilization.

Results

Observed Crash Analysis

Before conducting the crash analysis, AADT changes between the before and after years were examined first since the annual crash occurrences are closely related to the facility's exposure factor. Table 7 lists the average AADT before and after implementation for R2L highways. Figure 5 displays the cumulative distribution of the AADT. Overall, the differences are small between the before and after years.

Table 7. AADT of Rural Two-Lane Highway Segments with RS

AADT	Before	After
Minimum average AADT	108	55
Maximum average AADT	18,633	18,167
Three years average AADT	3,719	3,679

Figure 5. Cumulative AADT Distribution of R2L

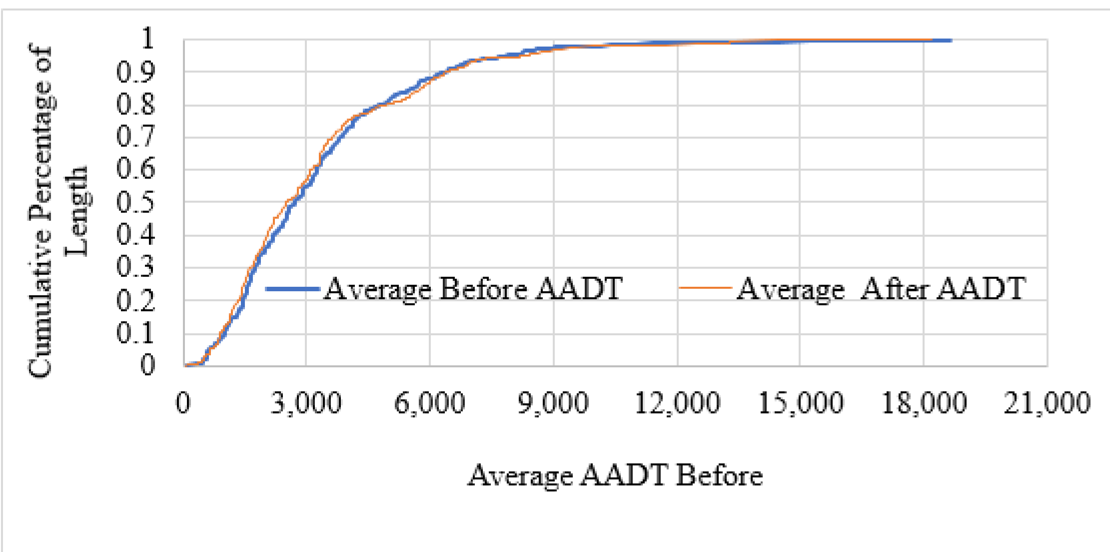
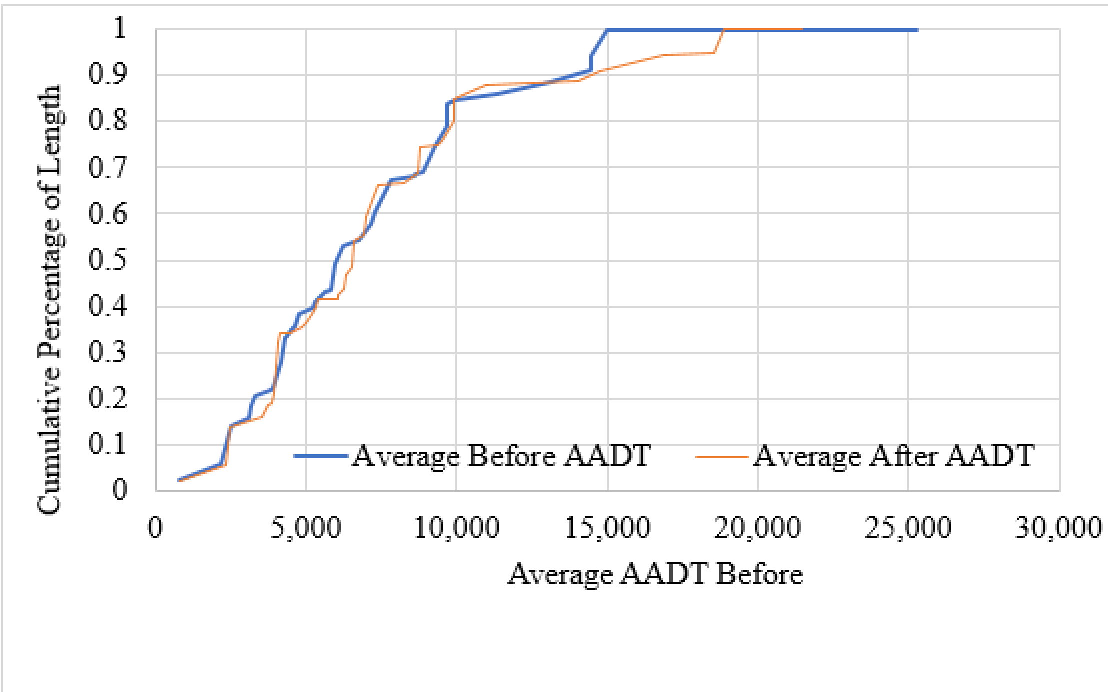


Table 8 lists the average AADT in the before and after period for U2L highways. Figure 6 shows the cumulative distribution of the AADT of U2L. The AADT on urban two-lane highway is much higher than that on rural two-lane highways.

Table 8. AADT of Urban Two-Lane Highway Segments with RS

AADT	Before	After
Minimum average AADT	767	790
Maximum average AADT	25,267	21,500
Three years average AADT	7,851	7,842

Figure 6. AADT Distribution of U2L



The changes in total crashes and average crash rate for both rural and urban two-lane highways are listed in Table 9. Table 9 shows the total number of crashes and the average crash rates in the before and after period of the rumble strips installation, which reveals a 17.1% and 23.4% crash reduction for R2L and U2L highways, respectively. The reduction in average crash rate is 12.2% and 32.7% for the R2L and U2L roadway segments, respectively.

Table 9. Changes in Total Crashes and Average Crash Rate

Crash Frequency and Rate for All RS Locations	R2L	U2L
Number of crashes Before	5,245	1,085

Crash Frequency and Rate for All RS Locations	R2L	U2L
Number of crashes After	4,346	831
Reduction	**899 (17.1%)**	**254 (23.4%)**
Average crash rate Before	1.15	1.59
Average crash rate After	1.01	1.07
Reduction	**0.14 (12.2%)**	**0.52 (32.7%)**

Analysis by Total Crashes and Crash Severity

Figure 7 shows the total number of observed crashes between 2005 and 2019 for the R2L segments with rumble strips. It appears that crashes are decreasing over the years, possibly reflecting the effect of gradual application of rumble strips.

Figure 7. Total Observed Crashes (R2L)

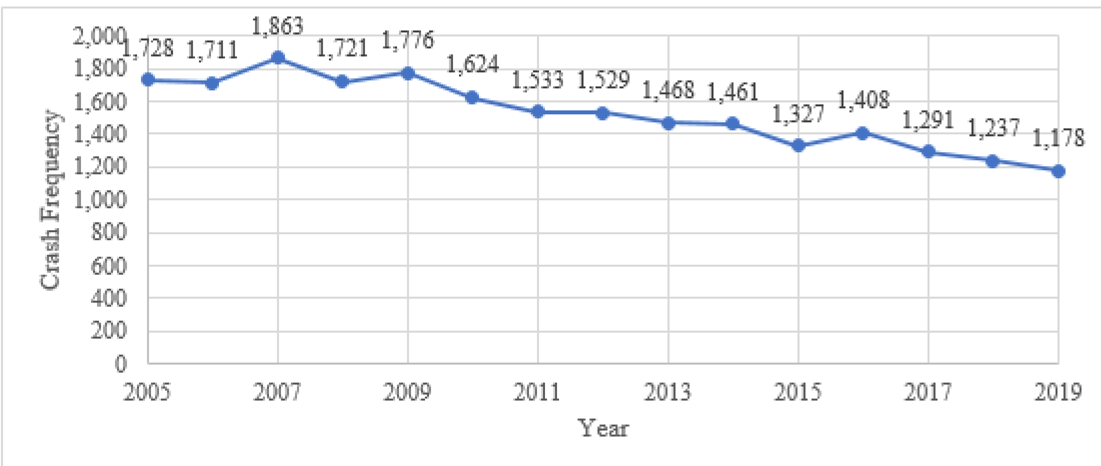


Figure 8 indicates the crashes by severity on R2L treatment sites. It is clear that crashes of all severity types—fatal, injury, PDO—are generally decreasing over the years.

Figure 8. Crashes by Severity (R2L)

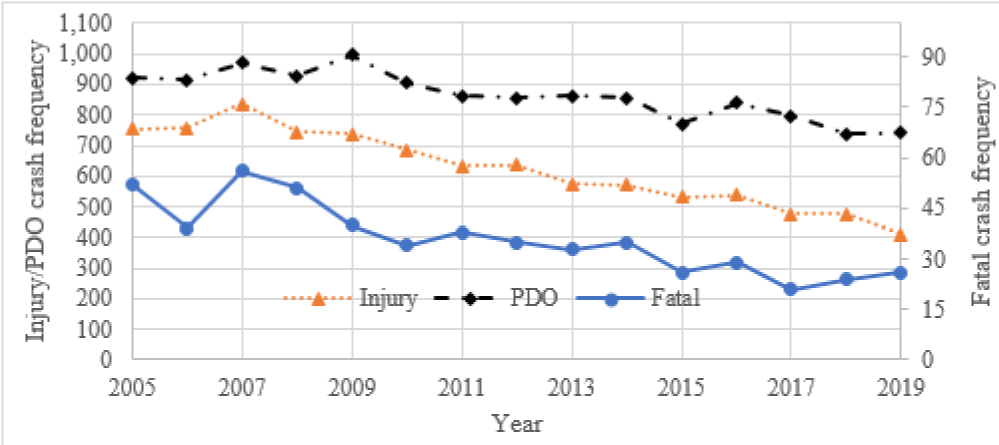


Figure 9 presents the annual frequency of total crashes on the U2L segments treated by rumble strips during 2010-2016. Annual crash frequency from 2007 to 2019 shows a general decreasing, but steady, trend in last five years.

Figure 9. Total Observed Crashes (U2L)

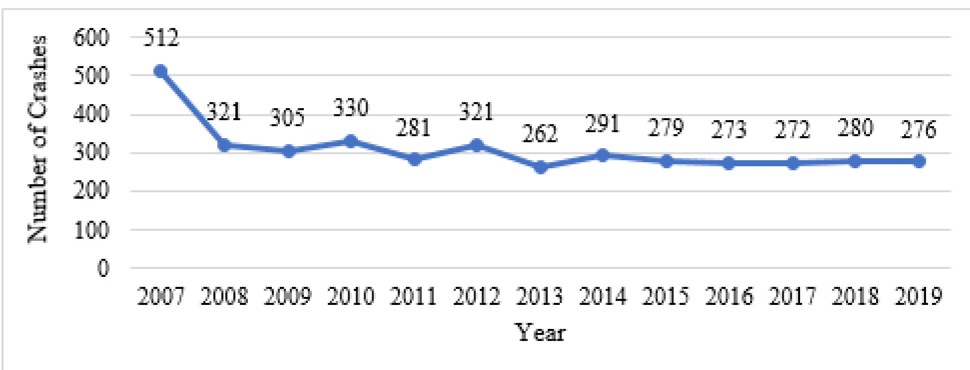
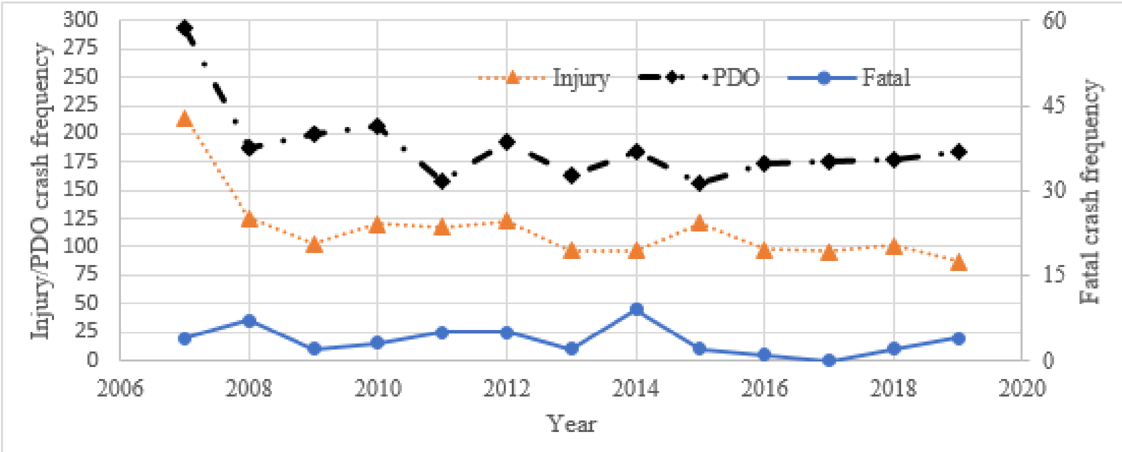


Figure 10 shows 2007-2019 crashes by severity on U2L segments with rumble strips. Injury and PDO crashes showed a decline from 2007.

Figure 10. Crashes by Severity (U2L)



The observed total crash and severities for each type of rumble strips are presented in Table 10. Injury severity types from the KABCO scale are K (fatal injury), A (severe/incapacitating), B (moderate/non-incapacitating), C (possible/complaint), and O (no injury/property damage only). From the table, it can be observed that, except for SRS, application of CLRS, or a combination CLRS and SRS, resulted in a reduction in crashes of all types of severity. There is an increase in fatal and severe crashes and in PDO crashes on segments with SRS. The fatal and severe crashes in SRS are constant in both the before and after periods.

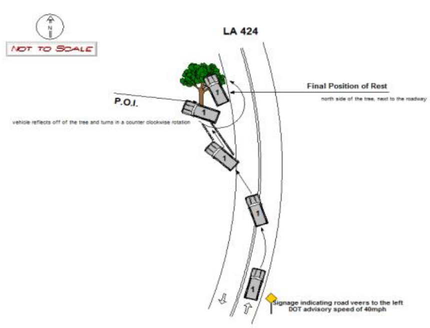
Table 10. Changes in Crash Severity on R2L Segments with RS

Rumble Strips	Total by RS Location			Fatal and Severe Injury			Moderate and Complaint Injury			PDO		
	Before	After	Crash Reduction	Before	After	Crash Reduction	Before	After	Crash Reduction	Before	After	Crash Reduction
CLRS	4,435	3,614	18.5%	162	104	35.8%	1,919	1,369	28.7%	2,354	2,141	9.1%
SRS	97	109	-12.4%	2	2	0%	41	35	14.6%	54	72	-33.3%
Both CLRS and SRS	713	623	12.6%	27	21	22.2%	275	250	9.1%	411	352	14.4%
Total	**5,245**	**4,346**	**17.1%**	**191**	**127**	**33.5%**	**2,235**	**1,654**	**26%**	**2,819**	**2,565**	**9%**

Since fatal and severe crashes on R2L segments following rumble strip installation were not changed, four crash reports were reviewed. Crash diagrams/locations in the before (two crashes) and after periods (two crashes) are presented in Figure 11 and Figure 12, respectively. From the diagram of the severe injury crash in the before period presented in Figure 11 (a), it was apparent that the first harmful event of the severe crashes in the before period was cross-centerline. Furthermore, according to the crash report, the driver was inattentive, and crash narratives mentioned the driver was not using the seat belt. This crash may have been prevented by SRS.

Figure 11 (b) shows the location of the fatal crash in the before period. The crash report was not available, and crash data showed the first harmful event in this crash involved a distracted pedestrian. This crash could not have been prevented by SRS, had SRS been installed, as the distracted pedestrian was walking “inside the roadway.”

Figure 11. Severe and Fatal Crash on Segment with SRS in the Before Period



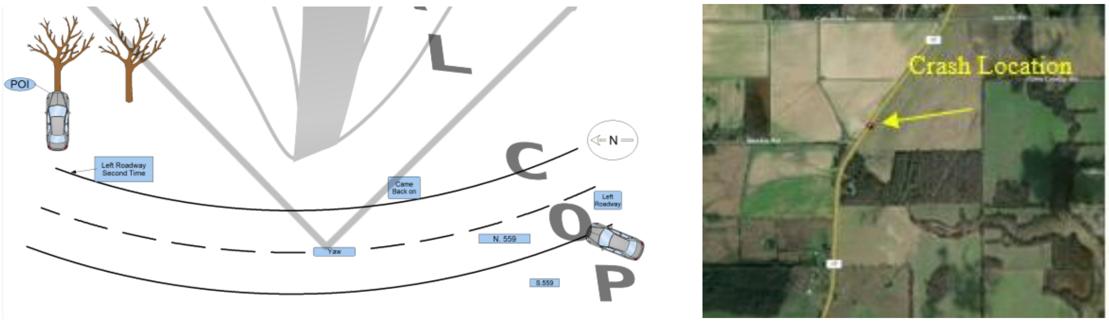
(a) Severe crash

(b) Fatal crash (crash report not available)

The after-period crash diagram of the severe crash is presented in Figure 12 (a). According to the crash report, the first harmful event was “ran off road left”; however, the narrative explains that the vehicle left the roadway to the right side, onto the shoulder, and came back to the roadway. According the police officer’s narrative, “the ledge of the roadway caused the vehicle out of control,” and the vehicle left the roadway and ended up striking a tree. This crash in the after period could have been prevented by SRS.

Figure 12 (b) shows the location of a fatal crash in the after period. Since there was no crash report available, crash data showed that the driver was inattentive and intoxicated with alcohol during the crash. This was a head-on crash, which could not have been prevented by SRS.

Figure 12. Severe and Fatal Crash on Segment with SRS in After Period



(a) Severe crash (b) Fatal crash (crash report not available)

Table 11 represents the before-after observation of total crashes and crashes by severity on U2L highway segments. In aggregate level, all the rumble strips showed a reduction in total as well as injury crashes. The segments with only CLRS had a reduction in total crashes by 24.6% and a reduction in fatal and severe crashes by 47.8%. There is a reduction (36.5%) in the total crashes following SRS installation, but an increase in the fatal and severe injury crashes. Fatal and severe crashes increased from zero crashes to three crashes after the installation of SRS. No crash reports were available for these crashes.

Table 11. Observed Total Crashes and Crashes by Severity on U2L

Rumble Strips	Total by RS Location			Fatal and Severe Injury			Moderate and Complaint Injury			PDO		
	Before	After	Crash Reduction	Before	After	Crash Reduction	Before	After	Crash Reduction	Before	After	Crash Reduction
CLRS	893	673	24.6%	23	12	47.8%	325	239	26.5%	545	422	22.6%
SRS	74	47	36.5%	0	3	-100%	30	18	40.0%	44	26	40.9%
Both CLRS and SRS	118	111	5.9%	8	2	75.0%	48	39	18.8%	62	70	-12.9%
Total	1,085	831	23.4%	31	17	45.2%	403	296	26.6%	651	518	20.4%

Table 12 shows the information sorted from reports on fatal crashes that occurred during post-installation period of SRS. Driver condition attributes more to these crashes. The crash data indicated drivers' alcohol involvement, which led either to impaired or asleep driver conditions.

Table 12. Information on Fatal Crashes during Post-Installation Period of SRS

Analysis Criteria	Fatality-1	Fatality-2	Fatality-3
First Harmful Event	Crossed centerline	Ran off road right	Crossed centerline
Most Harmful Event	MV in transportation	Overturned	MV in transportation
Manner of Collision	Head on	Non-Collision	Head on
Alcohol	Yes	Yes	Yes
Lighting	Dark	Dark	Daylight
Driver Condition	Unknown	Alcohol-Impaired	Asleep
Roadway Departure	No	Yes	No
Lane Departure	Yes	Yes	Yes

Analysis by Manner of Collision and Target Crashes

Table 13 shows the change in before and after crash percentages by manner of collision. The result shows a reduction in crashes with all manners of collisions, except the right turn. Right-turn crashes are not considered as the target crashes for rumble strips.

Table 13. Crash Type by Manner of Collision on All RS Locations (R2L)

Manner of Collision for All RS Locations	Before	After	Crash Reduction
Non-Collision (Single vehicle)	3,012	2,462	18.3%
Rear end	846	842	0.5%
Head on	128	86	32.8%
Right angle	218	188	13.8%
Left turn	242	228	5.8%
Right turn	19	20	-5.3%
Sideswipe same direction	193	130	32.6%
Sideswipe opposite direction	223	153	31.4%
Other and unknown	364	237	34.9%
Total	**5,245**	**4,346**	**17.1%**

From Table 14, it is observed that the installation of CLRS resulted in reducing head-on crashes by 41.8% and opposite sideswipe crashes by 28.7% on R2L segments. Following the installation of SRS on 59.58 miles of R2L, an increase in total crashes by 19.6% was observed. However, the segments where both CLRS and SRS were implemented showed a 6.7% reduction in single-vehicle crashes and a 47.9% reduction in sideswipe opposite direction crashes. However, there was an increase in head-on crashes by 20%.

Table 14. Before After Targeted Crash (R2L)

RS Location	Targeted Crashes	Change in crashes		
		Before	After	Crash Reduction
CLRS	Head on	103	60	41.8%
	Sideswipe opposite direction	174	124	28.7%
SRS	Non-Collision (Single vehicle)	51	61	-19.6%
CLRS and SRS	Non-Collision (Single vehicle)	313	292	6.7%
	Head on	20	24	-20%
	Sideswipe opposite direction	46	24	47.8%

There is a reduction of crashes by travel lane departure and complete roadway departure except for SRS, as shown in Table 15. It needs to be reiterated that information on travel lane departure and complete roadway departure are derived from police crash reports.

Table 15. Crashes by Travel Lane Departure and Complete Roadway Departure (R2L)

Crashes	Travel Lane Departure			Complete Roadway Departure		
	Before	After	Crash Reduction	Before	After	Crash Reduction
Total	3,803	3,071	19.2%	3,324	2,696	18.9%
CLRS	3,294	2,615	20.6%	2,913	2,319	20.4%
SRS	54	68	-25.9%	50	61	-22%
Both CLRS and SRS	357	309	13.4%	313	287	8.3%

Table 16 shows changes in known target crashes by type of rumble strips on U2L segments. Segments with CLRS had a 50% reduction in head-on and a 62.2% reduction in opposite direction sideswipe crashes. Single-vehicle crashes on segments with SRS had a 40% reduction. For segments with a combination of CLRS and SRS, there was a reduction of 28.3% in single-vehicle crashes, a 20% reduction in head-on crashes, but there was a 50% increase in opposite direction sideswipe crashes.

Table 16. Before After Targeted Crashes (U2L)

RS Location	Targeted Crashes	Crashes		
		Before	After	Crash Reduction
CLRS	Head on	22	11	50.0%
	Sideswipe opposite direction	37	14	62.2%
SRS	Non-Collision (Single vehicle)	15	9	40.0%
CLRS + SRS	Non-Collision (Single vehicle)	46	33	28.3%
	Head on	5	4	20.0%
	Sideswipe opposite direction	4	6	-50.0%

Table 17 provides the summary for manner of collision before-after analysis for U2L highways. There is a reduction in crashes, except for left turn and same direction sideswipe crashes. An increase in these two crash types may not be directly associated with the installation of rumble strips.

Table 17. Crash Type by Manner of Collisions for RS Locations (U2L)

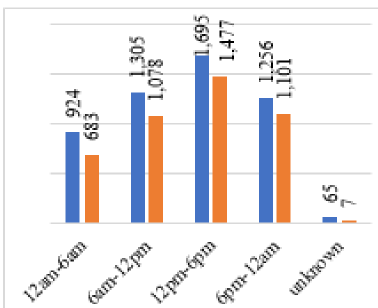
Manner of Collision for All RS Locations	Before	After	Crash Reduction
Non-Collision (Single vehicle)	362	263	27.3%
Rear end	428	341	20.3%
Head on	29	18	37.9%
Right angle	71	50	29.6%
Left turn	47	55	-17.0%
Right Turn	10	8	20.0%
Sideswipe same direction	27	31	-14.8%
Sideswipe opposite direction	43	20	53.5%
Other and unknown	68	45	33.8%
Total	**1,085**	**831**	**23.4%**

A before-after analysis in travel lane departure and complete roadway departure crashes, presented in Table 18, shows a reduction. For segments with SRS, there is a 5.3% increase in travel lane departure crashes.

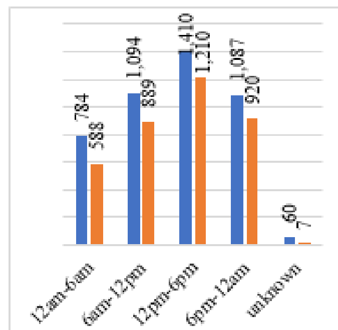
Table 18. Crashes by Travel Lane Departure and Complete Roadway Departure (U2L)

Crashes	Travel Lane Departure			Complete Roadway Departure		
	Before	After	Crash Reduction	Before	After	Crash Reduction
CLRS	401	279	30.4%	342	238	30.4%
SRS	19	20	-5.3%	16	12	25.0%
Both CLRS and SRS	58	54	6.9%	51	39	23.5%
Total	478	353	26.2%	409	289	29.3%

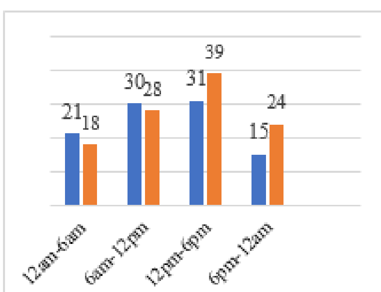
Figure 13. Crashes by Time on R2L Segments



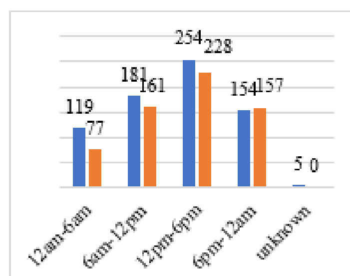
(a) Crashes on all RS



(b) Crashes on CLRS



(c) Crashes on SRS



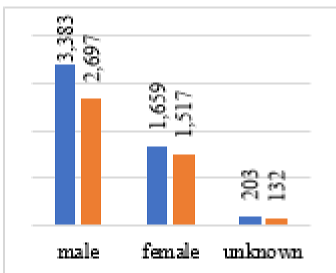
(d) Crashes on SRS and CLRS

Analysis by Crash Characteristics

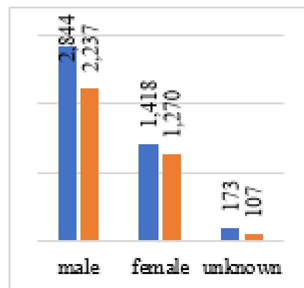
Figure 13 shows the before-after (in consecutive blue and orange colored bars) crashes by time (four quarters of the day) on R2L segments with rumble strips, where an overall reduction in crashes during any time period can be seen. Segments with CLRS also had reduction in all four-time intervals. However, the segments with SRS showed increases in crashes in both intervals from 12 pm to 12 am. There were also increases in crashes between 6 pm to 12 am on segments with both CLRS and SRS.

Figure 14 shows there is a reduction in crashes with both male and female drivers at fault when all segments with RS are considered. Segments with SRS had an increase in crashes with both male and female drivers. Segments with both CLRS and SRS had an increase in crashes with female drivers at fault.

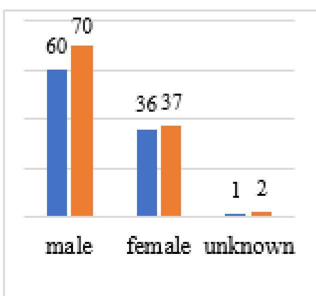
Figure 14. Crashes by Gender on R2L segments



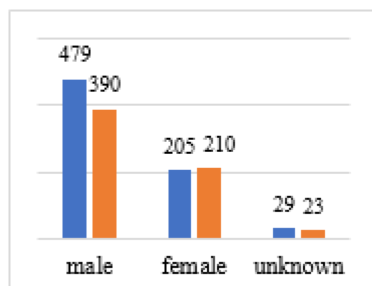
(a) Crashes on all RS



(b) Crashes on CLRS



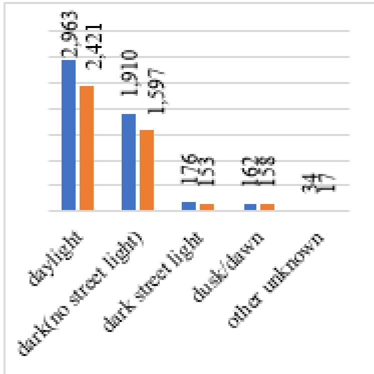
(c) Crashes on SRS



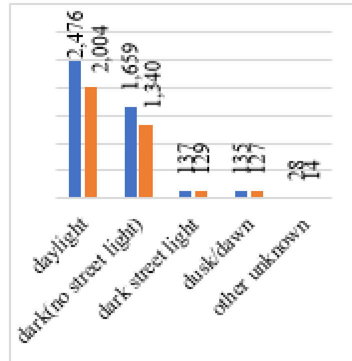
(d) Crashes on SRS and CLRS

Figure 15 shows reductions in crashes under all lighting conditions on R2L segments with RS and CLRS. An increase in crashes during daylight, darkness with no streetlight, and dusk/dawn can be found on the segments with SRS. There is a small increase in crashes at dusk/dawn on segments with both CLRS and SRS.

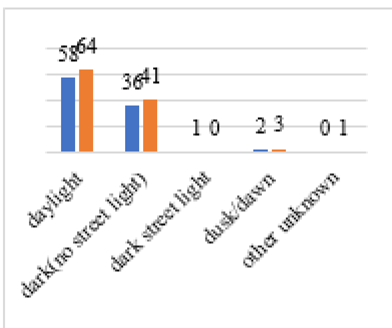
Figure 15. Crashes by Lighting Condition on R2L Segments



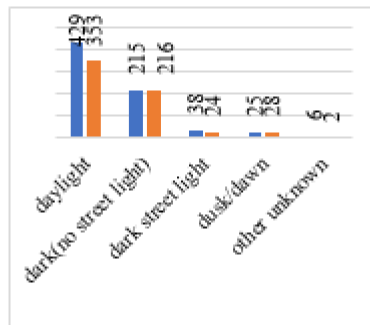
(a) Crashes on all RS



(b) Crashes on CLRS



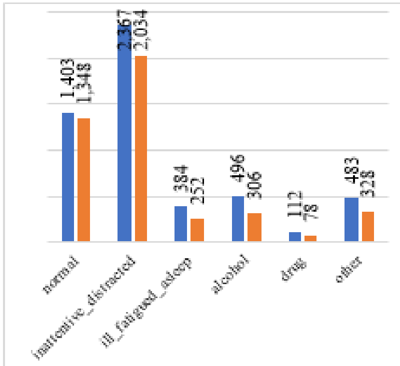
(c) Crashes on SRS



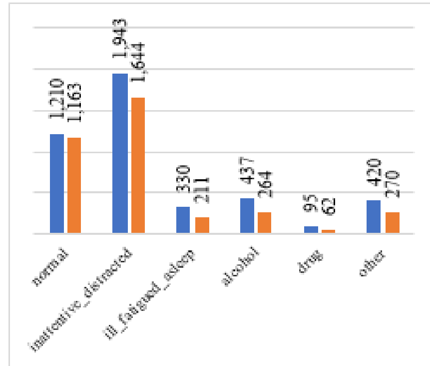
(d) Crashes on CLRS and SRS

Since one of the features of the installation of rumble strips is to alert drivers, driver condition was considered as an important part of the analysis. As Figure 16 presents, there was a 14% reduction of crashes with inattentive and distracted drivers on R2L segments. Crashes due to ill/fatigue and asleep drivers were reduced by 34%. Alcohol-related crashes were reduced by 38% on segments with RS. On segments with CLRS, there was a reduction by around 15%, 36%, and 40% in inattentive/distracted, ill/fatigued or asleep, and alcohol-related crashes, respectively. However, on segments with SRS, there was an increase in normal and ill/fatigue and asleep drivers. Segments with both CLRS and SRS also showed reduction in all driver conditions.

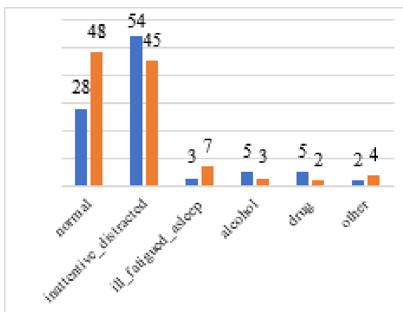
Figure 16. Crashes by Driver Condition on R2L Segments



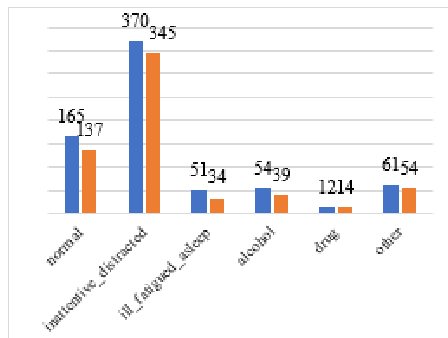
(a) Crashes on all RS



(b) Crashes on CLRS



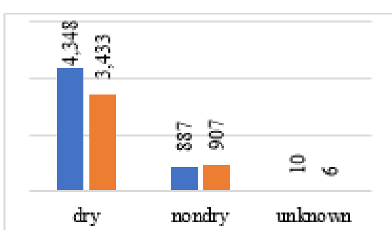
(c) Crashes on SRS



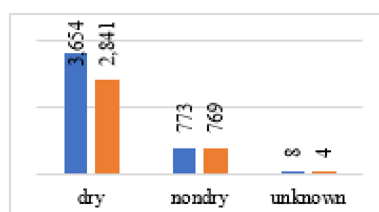
(d) Crashes on CLRS and SRS

Figure 17 shows reduction in surface condition in all cases except non-dry condition in all RS segments, dry and non-dry conditions in segments with SRS, and non-dry condition in segments with both CLRS and SRS.

Figure 17. Crashes by Surface Condition on R2L Segments

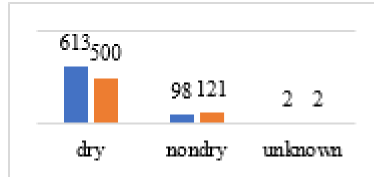


(a) Crashes on all RS



(b) Crashes on CLRS

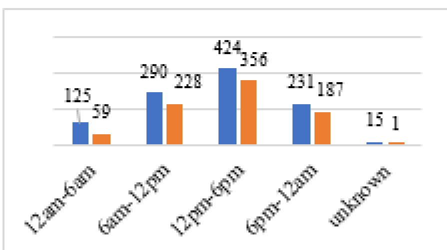
(c) Crashes on SRS



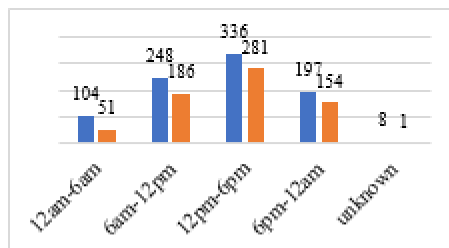
(d) Crashes on CLRS and SRS

The following results are on crash conditions on U2L highways. Figure 18 shows there is a reduction in crashes during all four intervals of the day in all cases except for during 6 pm to 12 am on segments with SRS and 6 am to 12 pm on segments with both CLRS and SRS.

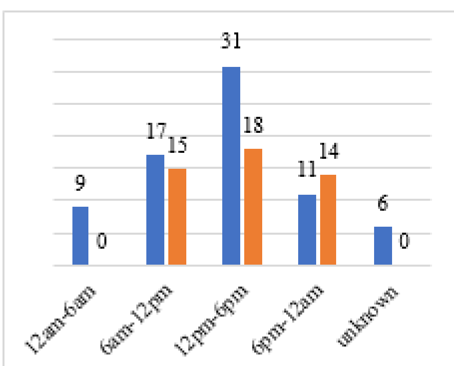
Figure 18. Crashes by Time on U2L Segments



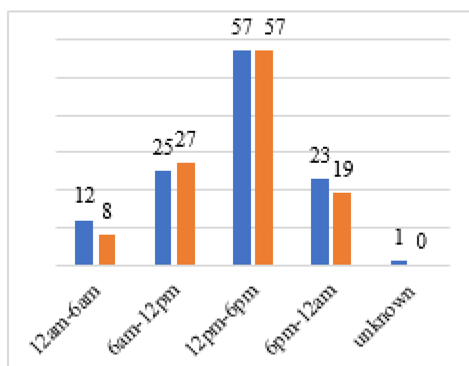
(a) Crashes on all RS



(b) Crashes on CLRS



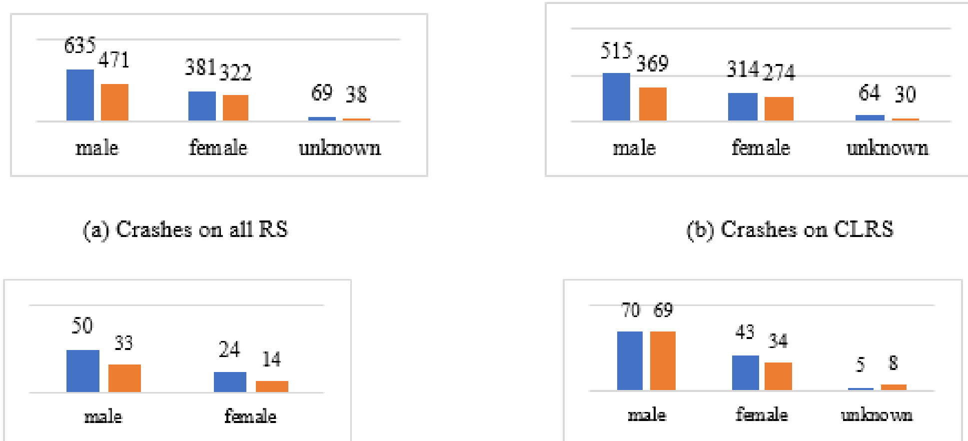
(c) Crashes on SRS



(d) Crashes on CLRS and SRS

Figure 19 shows there is a reduction in male and female crashes after installation of all types of rumble strips on U2L segments.

Figure 19. Crashes by Gender on U2L Segments



(a) Crashes on all RS

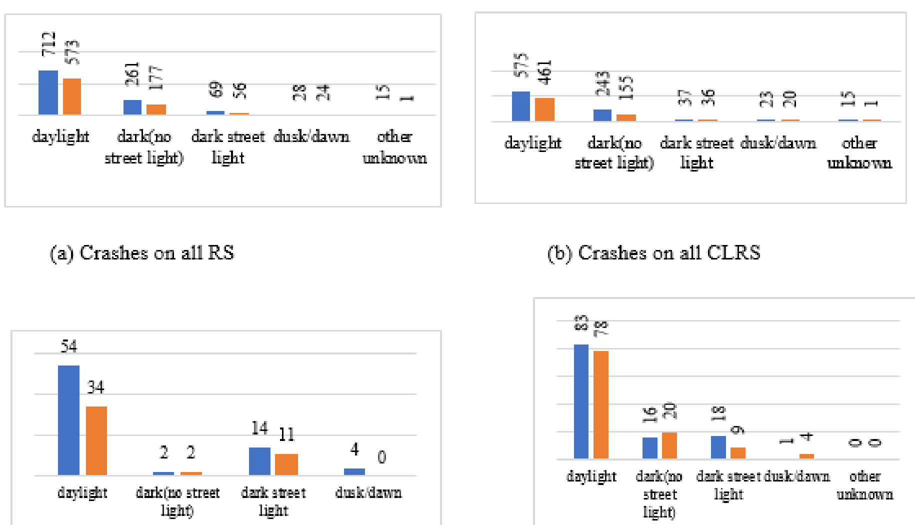
(b) Crashes on CLRS

(c) Crashes on SRS

(d) Crashes on CLRS and SRS

Figure 20 showed a decrease in crashes in terms of all lighting conditions except for during darkness with no streetlight and dusk/dawn for segments with both CLRS and SRS.

Figure 20. Crashes by Lighting Condition on U2L Segments



(a) Crashes on all RS

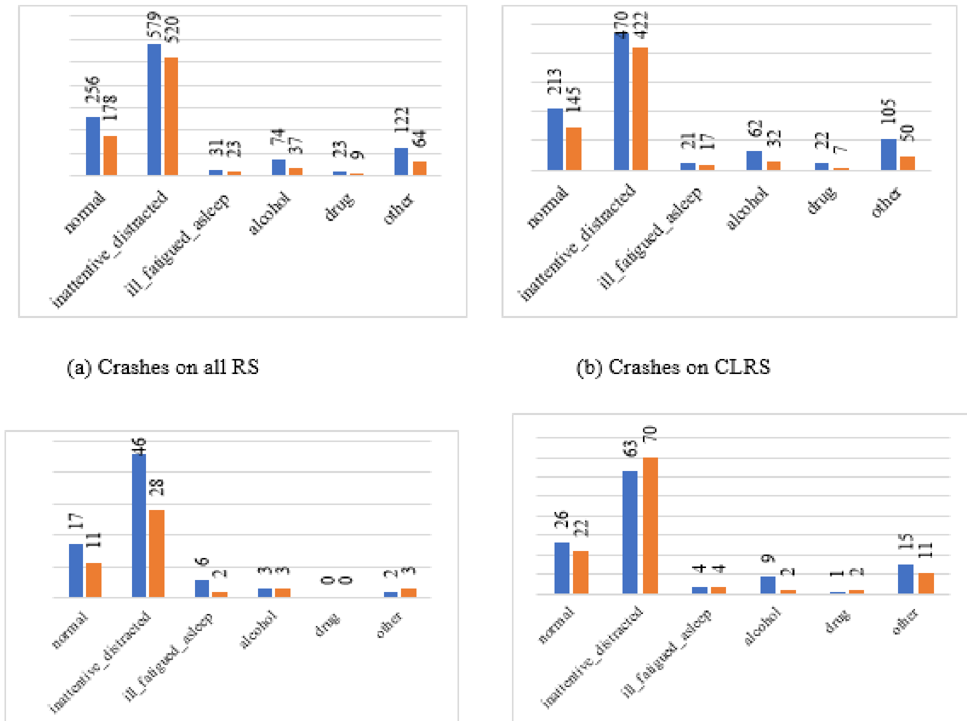
(b) Crashes on all CLRS

(c) Crashes on all SRS

(d) Crashes on CLRS and SRS

Figure 21 shows that there was a reduction in all driver conditions except for other conditions in segments with SRS and inattentive and distracted drivers for U2L segments with both CLRS and SRS.

Figure 21. Crashes by Driver Condition on U2L Segments



(a) Crashes on all RS

(b) Crashes on CLRS

(c) Crashes on SRS

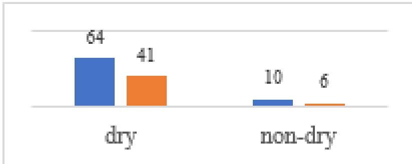
(d) Crashes on CLRS and SRS

Figure 22 shows there was a reduction in crashes in all surface conditions in all patterns of rumble strips on U2L segments.

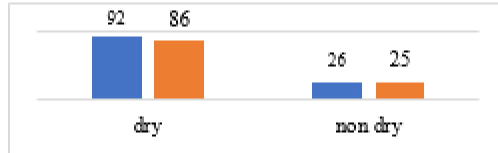
Figure 22. Crashes by Surface Condition on U2L Segments

(a) Crashes on all RS

(b) Crashes on CLRS



(c) Crashes on all SRS



(d) Crashes on CLRS and SRS

Findings from the In-Depth Crash Analysis

This subsection describes the analysis of crash record narratives and safety analysis related to roadway departure associated with sites containing RS. Based on the crash records listed in the "Crash 1" database, the research team explored the availability of electronic versions of crash reports for each of the *Top 30* sites with highest number of crashes, as presented in Appendix C. In addition to the codes provided in the database, these reports contained the officers' narratives and diagrams as Figure 11 and Figure 12 presented. Using the information obtained from these reports, the research team then analyzed the data to look for information that would suggest causes for roadway departure crashes on R2L highways in Louisiana.

As presented in Appendix C, there was a clear lack of availability of crash reports, often the number of reports available was less than 10% of the number of crashes. The research team decided to perform the in-depth analysis on one segment, which over 90% of crash reports were available.

The segment (site 29 in Appendix C) was 11.01 miles on a R2L highway with CLRS present. The implementation year was 2016, which means the before period of 2013-2015 and after period of 2017-2019 were considered for analysis. There were 34 crashes in the before period and 29 crashes in the after period. Interestingly, this segment did not have any head-on or opposite direction sideswipe crashes (i.e., known target crashes for CLRS) in the before or after period.

To pinpoint on investigating the preventable target crashes due to the presence of CLRS, the first harmful events were cross-checked with crash narratives and diagrams in crash reports. According to the document of State of Louisiana Uniform Motor Vehicle Traffic Crash Report, the "first harmful event" is "the first event in the crash sequence that produces damage or injury and it is used to define crash type and location. For example, if vehicle one sideswipes vehicle two which causes a loss of control and vehicle one subsequently strikes a tree resulting in the death of an occupant, the crash would be classified vehicle striking vehicle, not vehicle striking fixed object, since the "first harmful event" involved the collision of two motor vehicles." *[36]* Appendix D presents the summary description of crashes on the selected site.

From the cross-check between and narratives and coding, the "first harmful event" variable were found miscoded in several crash reports. Collision with fixed objects should not be a first harmful event as there must be a prior event for a vehicle to collide with fixed objects. The examples are shown in Figure 23 and Figure 24. In case of Figure 23, the first harmful event is "ditch" but for a similar pattern of the crash in case 2 the first harmful event is "ran to the left." Because of this error, the target crash for CLRS could not be found accurately**.**

Figure 23. Crash diagram and Sequence of Harmful Events (case 1)

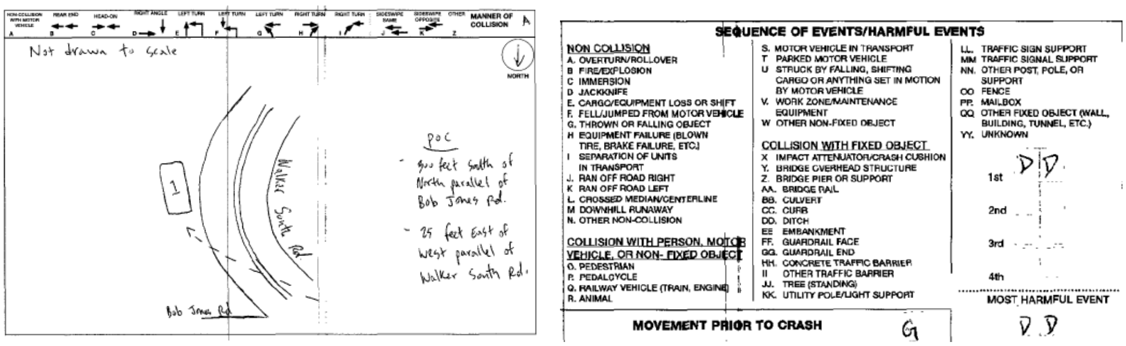
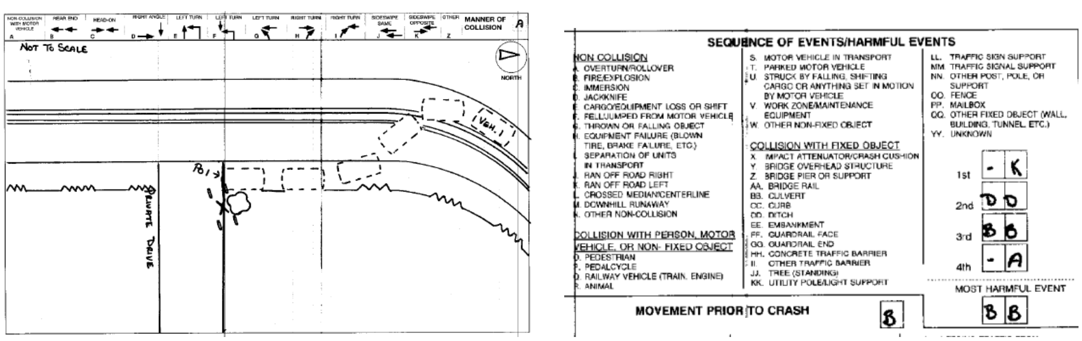


Figure 24. Crash diagram and Sequence of Harmful Events (case 2)



In this analysis, the research team explored whether the first harmful event scenarios "crossed the centerline" and "ran to the left" were in the narratives and diagrams. Based on the criteria, it was clear that during the before period, there were 5 out of 34 crashes that could have been the target crashes for CLRS, and in the after period, there were 2 out of 29 similar crashes. Crash narratives explained that 2 of these 5 crashes have occurred due to hydroplaning on the roadway and due to patch of ice on the roadway. Table 19 shows the target crashes in before period and Table 20 shows target crashes in the after period.

Table 19. Key Narratives of Selected Target Crashes in Before Period

Harmful Event				Condition of Driver	Manner of Collision	Key narratives
1st	2nd	3rd	4th			
Ran off road left	Tree			Inattentive	Other	Driver didn't realize vehicle was drifting off the roadway, and when she realized, her vehicle was already going down the ditch.
Crossed Centerline	Ran off left	Ditch	Tree	Normal	Non-Collision	Hydroplaned roadway surface made vehicle swerved into a ditch.
Ran off road left				Normal	Non-Collision	Driver hit a patch of ice on road and lost control to left of road. Vehicle struck several trees after leaving roadway.
Ran off road left	Ditch	Utility Pole		Asleep	Non-Collision	Driver fell asleep at the wheel and ran off road to the left.
Crossed Centerline	Ran off left	Culvert		Impaired by alcohol	Non-Collision	Driver said deer ran out into the roadway, and he swerved to miss the deer but lost control of the vehicle. Officer stated that vehicle 1 crossed centerline and into the opposing lane then drove off the roadway and left. The vehicle crashed into a culvert.

Table 20. Key Narratives of Selected Target Crashes in After Period

Harmful Event				Condition of Driver	Manner of Collision	Key narratives
1st	2nd	3rd	4th			
Crossed Centerline	Ran off left	Overturn	Utility pole	Asleep	Non-collision	Driver fell asleep while driving; when he woke up, vehicle was against a pole.
Ran off the road left	Utility pole			Unknown	Non-collision	Vehicle slid sideways and came to stop 30 ft. west of roadway.

From the understanding of crash narratives and associated sequence of harmful events, the team found out that rumble strips have very little to do in the event of a crash associated with first harmful event such as “animal.” Table 21 shows that the crashes with first harmful event “animal” in cases of both travel lane departure and complete roadway departure crashes were on the rise on R2L segments with RS in the after period.

Table 21. Animal Crashes on Travel Lane Departure and Complete Roadway Departure (R2L)

	Number of crashes (Before)	Number of crashes (After)	Crash Reduction
Travel Lane Departure = Yes, and First Harmful Event = Animal	426	488	+14.55%
Complete Roadway Departure = Yes, and First Harmful Event = Animal	424	487	+14.85%

Moreover, it was estimated that when CLRS target crashes such as head-on crashes were considered alongside travel lane departure and complete roadway departure, the number of crashes was reduced. Table 22 shows the before-after comparison of total head-on crashes and head-on crashes with travel lane departure and complete roadway departure.

Table 22. Head-On Crashes on Travel Lane Departure and Complete Roadway Departure (R2L)

	Number of crashes (Before)	Number of crashes (After)	Crash Reduction
Head on crashes	128	86	32.81%
Head on crashes on Travel Lane Departure	104	72	30.77%

	Number of crashes (Before)	Number of crashes (After)	Crash Reduction
Head on crashes on Complete Roadway Departure	23	11	52.17%

When before-after target crashes for CLRS, SRS, or both were compared based on first harmful event, the number of crashes were reduced as presented in Table 23.

Table 23. Analysis on First Harmful Event (R2L)

	First Harmful Event	Before Crashes	After Crashes	Crash Reduction	Observed Targeted Change
CLRS	Ran off road (left) or cross-centerline	918	719	21.7%	Head-on: 41.8% ODSS: 28.7%
SRS	Ran off road (right and left)	22	20	9.1%	Non-Collision: +19.6%
Both CLRS and SRS	Ran off road (right and left) or collision with fixed object	175	146	16.6%	Head-on: +20% ODSS: 47.8% Non-Collision: 6.7%

The research team also investigated the coding error issue as presented in Figure 23 and Figure 24 on a large scale. A thorough look at single-vehicle crashes that had a first harmful event of “collision with a fixed object” showed large number of errors. On R2L segments with RS, 220 single-vehicle crashes in the before period had “first harmful event” miscoded, and in the after period, 157 similar crashes were miscoded. Due to these coding error issues, the most reliable measurement for CLRS target crashes remains to be “head-on” and “opposite direction sideswipe,” and “non-collision” crashes can be considered as target crashes for SRS.

Findings from Cross-Sectional Analysis

For this analysis, the non-treatment sites were selected from the DOTD highway section database. All the selected segments were verified from “Google Earth Street View” to ensure that there were no rumble strips present during the analysis year. The distributions of AADT for the segments with rumble strips (treatment sites) and segments without rumble strips (non-treatment sites) are shown in Table 24. The cumulative percentage of both of the sites as shown in Figure 25 also shows the closely similar distribution of AADT.

Table 24. AADT with and without Rumble Strips (R2L)

AADT	With Rumble Strip	Without Rumble Strip
Minimum AADT	103	390
Maximum AADT	19,867	19,100
Average AADT	3,737	3,320

Figure 25. Cumulative Percentage of Length with AADT

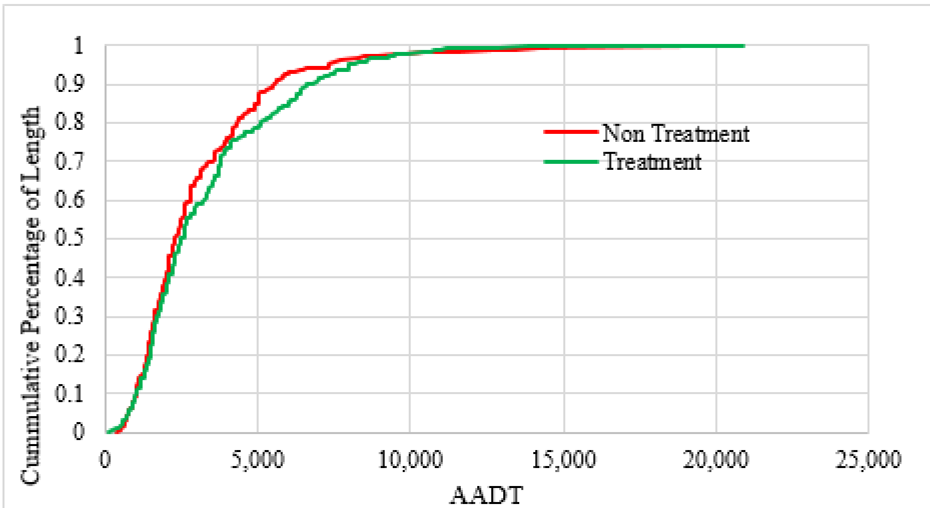


Table 25 to Table 30 show the comparisons of number of segments, length of segments, and lane width and shoulder width comparison between treatment and non-treatment segments. The crash data used for 2013-2015 for both treatment or non-treatment.

The results showed the fair distribution of data in non-treatment sections in terms of segments length. The distribution of data in non-treatment sites may not be the exact of treatment section, but it should be similar to the treatment section. The highest percentage of length lies between "1-5 miles" in both the treatment and non-treatment RS database. A similar trend is for lane width where 12 ft. of lane width has most of the segments in both of the sites. In the case of shoulder width, the majority of treatment and non-treatment sites lie in the "no shoulder" and "shoulder greater than 6 ft." group.

Table 25. Distribution of Number of Segments and Length (With RS)

Segment Length (miles)	Number of Segments	Total Length	Percentage
Less than 1 mile	35	21.53	1.35%
1-5 miles	228	691.45	43.40%
5-10 miles	100	666.27	41.82%
10-15 miles	14	164.18	10.31%
Greater than 15 miles	3	49.66	3.12%
Total	**380**	**1,593.09**	**100%**

Table 26. Distribution of Number of Segments and Length (Without RS)

Segment Length (miles)	Number of Segments	Total Length (miles)	Percentage
Less than 1 mile	56	30.1	4.10%
1-5 miles	155	407.48	55.53%
5-10 miles	43	275.77	37.58%
10-15 miles	2	20.39	2.78%
Greater than 15 miles	0	0	0
Total	**256**	**733.74**	**100%**

Table 27. Distribution of Lane Width by Length

Lane width (LW) (ft)	With Rumble Strips		Without Rumble Strips	
	Miles	Percentage	Miles	Percentage
Less than 10	0	0%	3.88	0.53%
$10 \le LW < 11$	66.89	4.2%	54.66	7.45%
$11 \le LW < 12$	407.73	25.59%	157.03	21.40%
Equal to 12	1,094.79	68.72%	518.17	70.62%
Greater than 12	23.68	1.49%	0	0%
Total	**1,593.09**	**100%**	**733.74**	**100%**

Table 28. Distribution of Lane Width by Segments

Lane width (LW) (ft)	With Rumble Strips		Without Rumble Strips	
	Number of Segments	Percentage	Number of Segments	Percentage
Less than 10	0	0%	2	0.78%
10 ≤ LW < 11	17	4.47%	19	7.42%
11 ≤ LW < 12	94	24.74%	57	22.27%
Equal to 12	264	69.47%	178	69.53%
Greater than 12	5	1.32%	0	0%
Total	**380**	**100%**	**256.00**	**100%**

Table 29. Distribution of Shoulder Width by Length

Shoulder width (SW) (ft)	With Rumble strips		Without Rumble Strips	
	miles	Percentage	miles	Percentage
0	346.76	21.77%	395.99	53.97%
SW ≤ 2	130.34	8.18%	84.88	11.57%
2 < SW ≤ 4	362.84	22.78%	54.31	7.40%
4 < SW ≤ 6	133.02	8.35%	33.85	4.61%
SW > 6	620.14	38.93%	164.71	22.45%
Total	**1,593.1**	**100%**	**733.74**	**100%**

Table 30. Distribution of Shoulder Width by Segments

Shoulder width (SW) (ft)	With Rumble Strips		Without Rumble Strips	
	Number of Segments	Percentage	Number of Segments	Percentage
0	76	20.00%	143	55.86%
SW ≤ 2	35	9.21%	25	9.77%
2 < SW ≤ 4	86	22.63%	18	7.03%
4 < SW ≤ 6	39	10.26%	13	5.08%
SW > 6	144	37.89%	57	22.27%
Total	380	100%	256	100%

The results reveal that the crash rate of segments with rumble strips have a lower crash rate in after periods than non-treatment sections, as shown in Table 31. This indicated that the installation of rumble strips has lowered the crash rate in treatment sites. The difference of average crash rates between treatment and non-treatment is 33%, 29%, 72%, and 55% for All RS, CLRS, SRS, and both CLRS and SRS, respectively.

Table 31. Cross-Sectional Analysis Results

	Number of Sites	Average Crash Rate in After Period (crashes per million vehicle miles)			
		All RS	CLRS	SRS	Both CLRS and SRS
With RS	370	0.87	0.92	0.36	0.57
Without RS	256	1.29			
Difference in average crash rate		32.6%	28.7%	72.1%	55.8%

Comparing the treatment sections with non-treatment by shoulder width also shows that the average crash rate for treatment sites is lower than non-treatment sites. In Table 32, for treatment sections with shoulder width of 6 ft. or less, the average crash rate was 1.03; whereas, the non-treatment section had an average crash rate of 1.43. Similarly, with shoulder width greater than 6 ft., the treatment section had average crash rate of 0.60; whereas, the non-treatment section had an average crash rate of 0.77 in the after period.

Table 32. Cross-Sectional Analysis by Shoulder Width

	Shoulder Width	Average AADT	Total Crashes	Average Crash Rate (crashes per million vehicle miles)
With Rumble Strips	≤ 6 ft.	3,010	2,603	1.03
	> 6 ft.	4,901	1,541	0.60
Without Rumble Strips	≤ 6 ft.	3,140	2,023	1.43
	> 6 ft.	3,274	622	0.77

Table 33 represents the cross-sectional analysis by lane width in treatment and non-treatment segments. Separating the segments into the group of lane width of “less than 12 ft.” and “12 ft. or greater” shows that crash rates were in the treatment sections for all lane widths compared to non-treatment sections. The average crash rate in lane width narrower than 12 ft. with rumble strips is 0.97, which is lower than the average crash rate of 1.57 in non-treatment sections. The table also shows lower crash rates of treatment sites with lane width 12 ft. or greater.

Table 33. Cross-Sectional Analysis by Lane Width

	Lane Width	2013-2014-2015		
		Average ADT	Total Crashes	Average Crash Rate
With Rumble Strips	Less than 10	N/A	N/A	N/A
	10 ≤ LW < 11	1,728	105	1.25
	11 ≤ LW < 12	3,227	949	0.93
	≥ 12 ft.	4,006	3,090	0.83
Without Rumble Strips	Less than 10	1,398	11	1.99
	10 ≤ LW < 11	2,215	131	1.46
	11 ≤ LW < 12	2,412	623	1.59
	≥ 12 ft.	3,565	1,880	1.16

Cross-sectional analysis was also carried out for target crashes. Table 34 shows the rates for target crashes—head-on and opposite direction sideswipe. The crash rate for opposite direction sideswipe for the treatment section is lower than non-treatment sections. But the result is not similar for head on crashes. The treatment section doesn't show improvement as compared to non-treatment sections.

Table 34. Cross-Sectional Analysis for Target Crashes on CLRS

		Average ADT	Total Crashes	Average Crash Rate
Head On	With Rumble Strips	3,608	63	0.018
	Without Rumble Strips	3,180	48	0.016
Opposite Direction Sideswipe	With Rumble Strips	3,608	116	0.02
	Without Rumble Strips	3,180	109	0.055

Table 35 indicates the single vehicle crashes which are target crashes for SRS. The after period average crash rate shows much lower crashes in treatment sections when comparing with non-treatment sections. The average crash rate for treatment sections is 0.31, and the average crash rate for non-treatment sections is 0.80.

Table 35. Cross-Sectional Analysis for Target Crashes on SRS

	Avg. AADT	Total Crash	Average Crash Rate
With Rumble Strips	2,130	24	0.31
Without Rumble Strips	3,180	1, 549	0.80

For segments with CLRS and SRS, the target crashes will be single-vehicle crashes, head-on crashes, and opposite direction sideswipe crashes. Table 36 indicates installation of rumble strips in combination has been effective as the average crash rate is much lower than non-treatment sections, 0.32 vs. 0.87.

Table 36. Cross-Sectional Analysis for Target Crashes on Both CLRS and SRS

Single Vehicle Crashes + Head-On Crashes + Opposite Direction Sideswipe	Average AADT	Total Crash	Average Crash Rate
With Rumble Strips	4,776	325	0.32
Without Rumble Strips	3,180	1,706	0.87

Table 37 presents average crash rate differences between treatment and non-treatment sections within lane departure and roadway departure. In both of the case treatment sites, each had lower crash rates than non-treatment sites.

Table 37. Cross-Sectional Analysis for Travel Lane Departure and Complete Roadway Departure on both CLRS and SRS

		Average ADT	Total Crashes	Average Crash Rate
Travel Lane Departure	With Rumble Strips	4,776	360	0.36
	Without Rumble Strips	3,191	1,883	0.91
Complete Roadway Departure	With Rumble Strips	4,776	296	0.296
	Without Rumble Strips	3,191	1,676	0.83

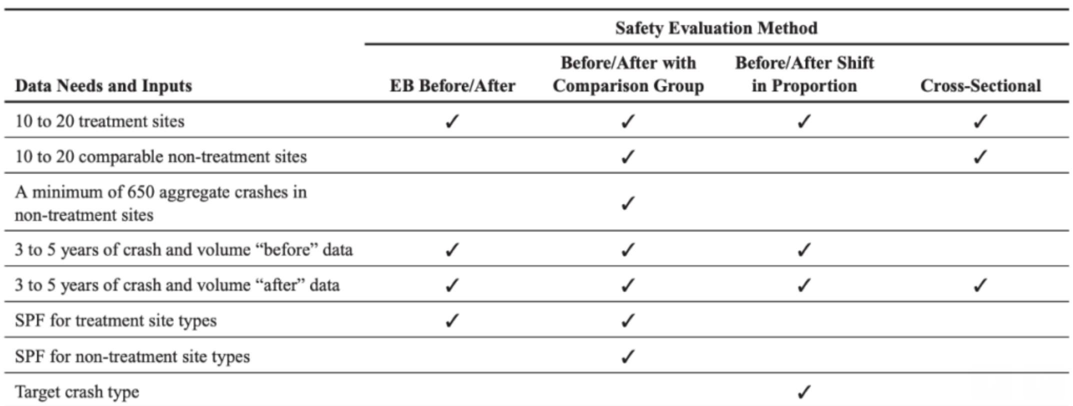
Safety Evaluation was carried out by three methods:

- Before-After Analysis (EB)
- Before-After Comparison Group with EB
- Crash Trend Analysis

Before-After Analysis with EB Results

For EB analysis and EB with comparison group analysis, SPF developed by the DOTD was used. The analysis was conducted for total crashes and FSI crashes. Before conducting safety evaluation, sample size segments were checked with reference to HSM safety evaluation criteria as shown in Figure 26.

Figure 26. Criteria for safety Evaluation by HSM



Data Needs and Inputs	Safety Evaluation Method: EB Before/After	Before/After with Comparison Group	Before/After Shift in Proportion	Cross-Sectional
10 to 20 treatment sites	✓	✓	✓	✓
10 to 20 comparable non-treatment sites		✓		✓
A minimum of 650 aggregate crashes in non-treatment sites		✓		
3 to 5 years of crash and volume "before" data	✓	✓	✓	
3 to 5 years of crash and volume "after" data	✓	✓	✓	✓
SPF for treatment site types	✓	✓		
SPF for non-treatment site types		✓		
Target crash type			✓	

Criteria for safety evaluation by HSM in Figure 26 shows the basic data and sample size requirement for carrying out the EB analysis. It mentions for the before after analysis, researchers need 10-20 treatment sites along with 3-5 years of before and after data and AADT along with SPF for treatment sites. R2L has all the requirement fulfilled, but SRS and both CLRS and SRS in U2L don't have enough sites for before/after analysis, as presented in Table 38 and Table 39.

Table 38. Comparison of R2L sites with HSM for EB Analysis

R2L		CLRS	SRS*	Both CLRS and SRS	Total
Total Crashes	Number of Sites	315	12	53	380
	Crashes	4,435/3,614	97/109	713/623	5,245/4,346
FSI	Number of Sites	315	12	53	380
	Crashes	162/104	2/2	27/21	191/127

* not meeting the HSM required criteria on sample size and or the minimum number of crashes

Table 39. Comparison of U2L sites with HSM Criteria for EB Analysis

U2L		CLRS	SRS*	Both CLRS and SRS*	Total
Total Crashes	Number of Sites	35	1	5	41
	Crashes	893/673	74/47	118/111	1,085/831
FSI	Number of Sites	35	1	5	41
	Crashes	23/12	0/3	8/2	31/17

* not meeting the HSM required criteria on sample size and or the minimum number of crashes

Table 40 and Table 41 present the estimated safety effectiveness (θ) in total crashes and FSI crashes on R2L; whereas, Table 42 and Table 43 present the estimated safety effectiveness (θ) in total crashes and FSI crashes on U2L. The results of SRS and both SRS and CLRS on U2L may not be accurate as the number of samples is below the HSM requirement.

Table 40. EB Results of Total Crashes on R2L Segments

Rumble Strips	CMF, θ	Standard deviation, σ	95% CI for θ	Expected percentage reduction	95% confidence interval for percentage reduction
ALL	0.835	0.016	(0.804, 0.866)	16.5%	(13.4%, 19.6%)
CLRS	0.845	0.017	(0.812, 0.878)	15.5%	(12.2%, 18.8%)
SRS	0.95	0.113	(0.729, 1.171)	5%	(-17.1%, 27.1%)
Both CLRS and SRS	0.764	0.037	(0.691, 0.837)	23.6%	(16.3%, 30.9%)

Table 41. EB Results of FSI Crashes on R2L Segments

Rumble Strips	CMF, θ	Standard deviation, σ	95% CI for θ	Expected percentage reduction	95% confidence interval for percentage reduction
ALL	0.590	0.058	(0.476, 0.704)	41%	(29.6%, 52.4%)
CLRS	0.604	0.066	(0.475, 0.733)	39.6%	(26.7%, 52.5%)
SRS	0.328	0.232	(0, 0.783)	67.2%	(21.7%, 0)
Both CLRS and SRS	0.556	0.134	(0.293, 0.819)	44.4%	(18.1%, 70.7%)

Table 42. EB Results of Total Crashes on U2L Segments

Rumble Strips	CMF, θ	Standard deviation, σ	95% CI for θ	Expected percentage reduction	95% confidence interval for percentage reduction
ALL	0.695	0.031	(0.634, 0.756)	30.5%	(24.4%, 36.6%)
CLRS	0.677	0.034	(0.61, 0.744)	32.3%	(25.6%, 39%)
SRS	0.655	0.117	(0.426, 0.884)	34.5%	(11.6%, 57.4%)
Both CLRS and SRS	0.839	0.105	(0.633, 1.045)	16.1%	(-4.5%, 36.7%)

Table 43. EB Results of FSI Crashes on U2L Segments

Rumble Strips	CMF, θ	Standard deviation, σ	95% CI for θ	Expected percentage reduction	95% confidence interval for percentage reduction
ALL	0.463	0.122	(0.224, 0.702)	53.7%	(29.8%, 77.6%)
CLRS	0.400	0.123	(0.159, 0.641)	60%	(35.9%, 84.1%)
SRS	0.711	0.426	(0, 1.546)	28.9%	(-54.6%, 0)
Both CLRS and SRS	0.622	0.437	(0, 1.479)	37.8%	(-47.9%, 0)

Before-After Analysis of Comparison Group with EB Results

Again, as in EB method, the sample size of comparison group was compared with the basic requirement with HSM. SRS segments did not have enough sample size for analysis, and hence not included in this analysis. Table 44 shows the sample size of number of sites by rumble strip type for comparison group evaluation. As mentioned in the methodology, Louisiana SPF for total crashes was used for analysis.

Table 44. Comparison of R2L Sites with HSM Criteria for EB with Comparison Group Analysis

R2L		CLRS	SRS	Both CLRS and SRS	Total
Total Crashes	Number of Sites	312	7	50	369
	Crashes	4,435/3,614	97/109	713/623	5,245/4,346
FSI	Number of Sites	312	7	50	369
	Crashes	162/104	2/2	27/21	191/127

Table 45 indicates the comparison group with EB results for all RS, CLRS, and both CLRS and SRS on R2L. All rumble strips and CLRS results are statistically significant at 95% CI, whereas, both CLRS and SRS are not statically significant at 90% CI according to HSM criteria. Analysis was not carried out for U2L because of the low number of segments.

Table 45. EB with Comparison Group Results of R2L Segments

Rumble Strips	Statistical Significance	θ	σ	CI for θ	Expected percentage reduction
ALL	7.90 (>2, significant at 95% CI)	0.854	0.018	(0.819, 0.889)	14.6%
CLRS	8.13 (>2, significant at 95% CI)	0.840	0.020	(0.801, 0.879)	16%
Both CLRS and SRS	1.35 (<2, not significant at 90% CI)	0.927	0.054	(0.838, 1.016)	7.3%

Crash Trend Analysis Results

Results of Mann Kendall (MK) Test

Table 46 presents the M-K test, which detects the negative slope of trend indicating a reduction in crashes. Negative value of test statistic S, Kendall's tau, and Sen's slope confirms decreasing trend of crashes for all segments with RS, segments with both CLRS and SRS, and segments having only CLRS for the period 2005-2017. The monthly crash frequency of segments with SRS contains a lot of "zero" values may have led to inconclusive results (p-value > 0.05).

Table 46. Mann Kendall Test for Total Crashes on R2L

Parameter	All Segments	Only CLRS	Only SRS	Both CLRS and SRS
S	-5,722	-5,610	579	-2,272
Var(S)	425,574	425,444.7	382,228.3	423,351.3
Z-Value	-8.76	-8.59	0.93	-3.49

Parameter	All Segments	Only CLRS	Only SRS	Both CLRS and SRS
P-Value	1.79E-18	8.02E-18	0.349	0.000482
Kendall's Tau	-0.47	-0.46	0.04	-0.18
Sen's Slope	-0.28	-0.25	0	-0.02

Result of Innovative Trend Analysis

Figure 27 presents the trend of crashes on all R2L segments with RS. The data points, plotted between first and second half of time series from two equal halves of monthly crash frequencies, lie in the bottom of 1:1 line. This indicates monotonic decreasing trend of crashes on all segments with RS.

Figure 27. ITA Plot of Monthly Crash Frequencies on All R2L Segments with RS

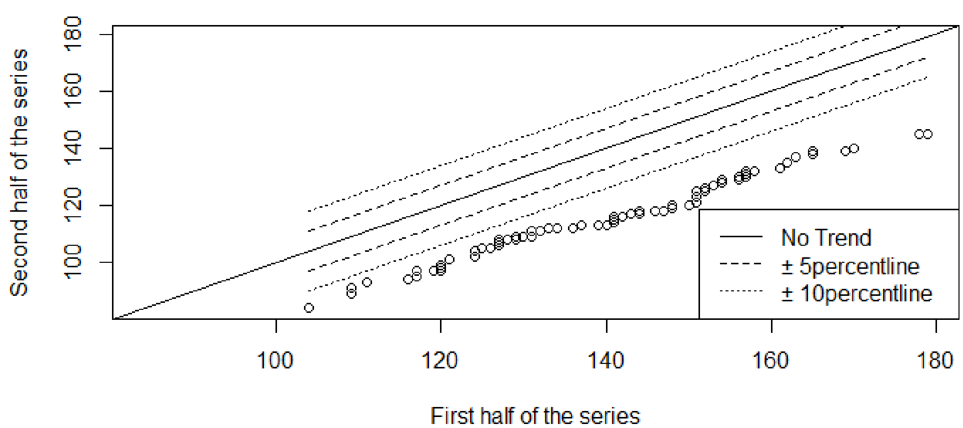
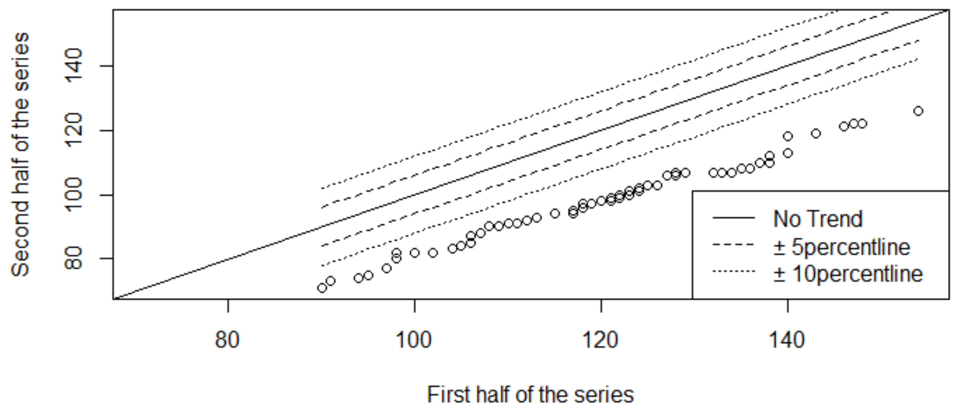


Figure 28, presenting the trend of crashes on R2L segments with CLRS, also shows all the data points are in the bottom of 1:1 line indicating a monotonic decreasing trend.

Figure 28. ITA Plot of Monthly Crash Frequencies on All R2L Segments with CLRS



Similarly, Figure 29, presenting monthly crash data points on segments with both CLRS and SRS, indicates a monotonic decreasing trend.

Figure 29. ITA Plot of Monthly Crash Frequencies on All R2L Segments with both CLRS and SRS

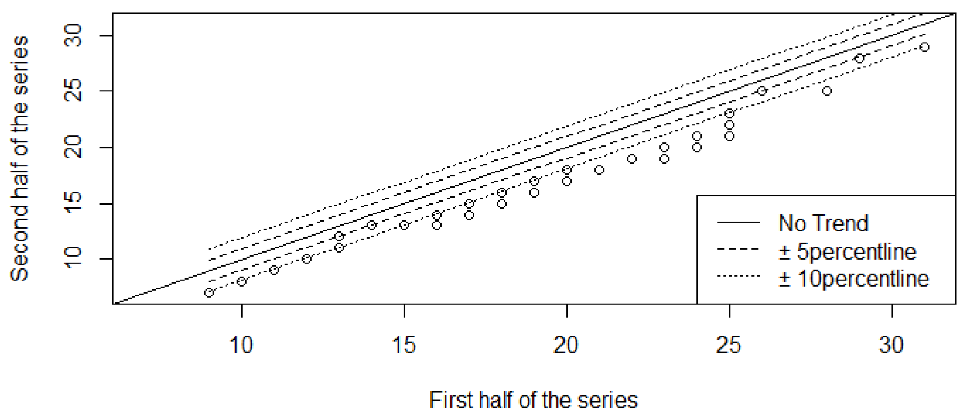
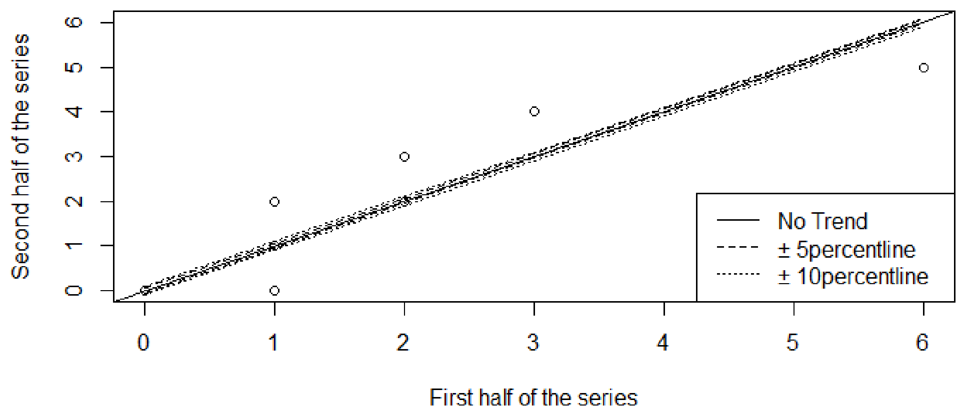


Figure 30, presenting the trend of crashes on R2L segments with SRS, shows few available data points are scattered as majority of the monthly crash frequencies are zero.

Figure 30. ITA Plot of Monthly Crash Frequencies on All R2L Segments with SRS



ARIMA Intervention Model

The ARIMA intervention model results in Table 47 shows 16.3%, 17.4%, and 11% crash reduction on segments with RS, CLRS, and both CLRS and SRS, respectively, at 95% confidence level. Because of small number of sites for SRS, it was not included in analysis.

Table 47. ARIMA Intervention Model

Features	Observed crash (2013-2017)	Impact parameter ω_0	Total Impact	Percentage Crash Reduction	P-value
All Segments	6,758	-22.08	1,320	16.3%	<.0001
CLRS	5,715	-20.45	1,200	17.4%	<.0001
CLRS and SRS	975	-2.47	120	11.0%	0.0031

Benefit-Cost Analysis Results

According to DOTD's information, the installation costs of centerline ground-in rumble strips and shoulder/edgeline rumble strips are $891.65 and $813.33 per mile, respectively. In the total estimation, pavement stripping, the costs for temporary signs and barricades, and mobilization during construction were also included. Table 48 and Table 49 present the breakdown of rumble strip installation costs on R2L and U2L highways, respectively.

For the estimation of benefits, latest unit crash costs by injury severity were collected from DOTD's website *[37]*. Benefits were calculated by multiplying the number of crashes reduced for each injury severity with unit costs. Table 50 and Table 51 present the breakdown of benefits due to installation of rumble strips in terms of reduction in crashes by severity on R2L and U2L highways, respectively. Installation costs were analyzed in two approaches. In option 1, associated installation costs (mobilization, temporary signs and barricades, pavement strips) were included. In option 2, only rumble strips installation cost was considered.

Table 48. Cost Estimation of Rumble Strip Installation on R2L Segments

Description	Unit	Unit Cost	CLRS		SRS		Both CLRS and SRS	
			Quantity	Cost	Quantity	Cost	Quantity	Cost
Miles of roadway			1,291.22		59.58		242.29	
Temporary Signs and Barricades	LS	5%		$430,406		$19,627		$90,616
Mobilization	LS	5%		$430,406		$19,627		$90,616
Plastic Pavement Strip (Solid Line)	Mile	$1,800.00	3,873.66	$6,972,588	178.74	$321,732	726.87	$1,308,366
Plastic Pavement Strip (Broken Line)	Mile	$750.00	645.61	$484,208	29.79	$22,343	121.145	$90,859
Rumble Strips (Centerline Ground-In)	Mile	$ 891.65	1,291.22	$1,151,316			242.29	$216,038
Rumble Strips (Edgeline Ground-In)	Mile	$813.33			59.58	$48,458	242.29	$197,062
Total (Option 1)				**$9,468,923**		**$431,786**		**$1,993,557**
Total (Option 2)				**$1,151,316**		**$ 48,458**		**$413,100**

Table 49. Cost Estimation of Rumble Strip Installation on U2L Segments

Description	Unit	Unit Cost	CLRS		SRS		Both CLRS and SRS	
			Quantity	Cost	Quantity	Cost	Quantity	Cost
Miles of roadway			77.95		6.87		12.69	
Temporary Signs and Barricades	LS	5%		$25,983		$2,263		$4,746
Mobilization	LS	5%		$25,983		$2,263		$4,746
Plastic Pavement Strip (Solid Line)	Mile	$1,800.00	233.85	$420,930	20.61	$37,098	38.07	$68,526
Plastic Pavement Strip (Broken Line)	Mile	$750.00	38.975	$29,231	3.435	$2,576	6.345	$4,759

Description	Unit	Unit Cost	CLRS		SRS		Both CLRS and SRS	
Rumble Strips (Centerline Ground-In)	Mile	$ 891.65	77.95	$69,504			12.69	$11,315
Rumble Strips (Edgeline Ground-In)	Mile	$813.33			6.87	$5,588	12.69	$10,321
Total (Option 1)				**$571,632**		**$49,788**		**$104,413**
Total (Option 2)				**$69,504**		**$5,588**		**$21,636**

Table 50. Estimation of Safety Benefits on R2L

	Unit Cost	All RS				CLRS				SRS				Both CLRS and SRS			
		B	A	B-A	Benefit	B	A	B-A	Benefit	B	A	B-A	Benefit	B	A	B-A	Benefit
Fatal	$1,710,561	134	87	47	$80,396,367	112	71	41	$70,133,001	1	1	0	$0	21	15	6	$10,263,366
Severe	$489,446	57	40	17	$8,320,582	50	33	17	$8,320,582	1	1	0	$0	6	6	0	$0
Moderate	$173,578	627	409	218	$37,840,004	550	353	197	$34,194,866	12	4	8	$1,388,624	65	52	13	$2,256,514
Complaint	$58,636	1608	1245	363	$21,284,868	1369	1016	353	$20,698,508	29	31	-2	-$117,272	210	198	12	$703,632
No injury	$24,982	2819	2565	254	$6,345,428	2354	2141	213	$5,321,166	54	72	-18	-$449,676	411	352	59	$1,473,938
Total					**$154,187,249**				**$138,668,123**				**$821,676**				**$14,697,450**

Table 51. Estimation of Safety Benefits on U2L

	Unit Cost	All RS				CLRS				SRS				Both CLRS and SRS			
		B	A	B-A	Benefit	B	A	B-A	Benefit	B	A	B-A	Benefit	B	A	B-A	Benefit
Fatal	$1,710,561	14	10	4	$6,842,244	9	6	3	$5,131,683	0	3	-3	-$5,131,683	5	1	4	$6,842,244
Severe	$489,446	17	7	10	$4,894,460	14	6	8	$3,915,568	0	0	0	$0	3	1	2	$978,892

	Unit Cost	All RS				CLRS				SRS				Both CLRS and SRS			
Moderate	$173,578	104	55	49	$8,505,322	87	46	41	$7,116,698	5	2	3	$520,734	12	7	5	$867,890
Complaint	$58,636	299	241	58	$3,400,888	238	193	45	$2,638,620	25	16	9	$527,724	36	32	4	$234,544
No injury	$24,982	651	518	133	$3,322,606	545	422	123	$3,072,786	44	26	18	$449,676	62	70	-8	-$199,856
Total					**$26,965,520**				**$21,875,355**				**-$3,633,549**				**$8,723,714**

Final results of benefit-cost ratios are presented in Table 52.

Table 52. Benefit-Cost Analysis Results

		Only CLRS	Only SRS	Both CLRS and SRS	All RS
Option 1	Rural two-lane	14.64	1.9	7.37	12.98
	Urban two-lane	38.27	Negative	83.55	37.2
Option 2	Rural two-lane	120.44	16.96	35.58	95.6
	Urban two-lane	314.73	Negative	403.20	278.78

Results of all observed crashes are presented Table 53. Results of all CMFs estimated from all methods are presented in Table 54.

Table 53. Percentage Change in Observed Crashes

	Reduction in Total Crashes	Reduction in Crash Rates	Reduction in FSI	Reduction in Total Crashes	Reduction in Crash Rates	Reduction in FSI
Rural two-lane (R2L)				Urban two-lane (U2L)		
Total	17.1%	12.2%	33.5%	23.4%	32.7%	45.2%
CLRS	18.5%	16.6%	35.8%	24.6%	35.6%	47.8%

	Reduction in Total Crashes	Reduction in Crash Rates	Reduction in FSI	Reduction in Total Crashes	Reduction in Crash Rates	Reduction in FSI
SRS	-12.4%	-78.8%	0%	36.5%	32.8%	-100%
Both CLRS and SRS	12.6%	13.7%	22.2%	5.9%	11.3%	75%

Table 54. Summary of CMF/Percentage Change Estimated from All Methods

	Expected CMF with EB				**Group comparison with EB**		**Cross-Sectional Analysis**	**Trend Analysis**
	θ (Total)	**95% CI**	**θ (FSI)**	**95% CI**	**θ**	**95% CI**	**Reduction in Crashes**	**Reduction in Crashes**
Rural two-lane (R2L)								
Total	0.835	(0.804, 0.866)	0.590	(0.476, 0.704)	0.854	(0.819, 0.889)	32.6%	16.3%
CLRS	0.845	(0.812, 0.878)	0.604	(0.475, 0.733)	0.840	(0.801, 0.879)	28.7%	17.4%
SRS	0.95	(0.729, 1.171)	0.328	(0, 0.783)	N/A	N/A	72.1%	N/A
Both CLRS and SRS	0.764	(0.691, 0.837)	0.556	(0.293, 0.819)	0.927	*(0.838, 1.016)	55.8%	11.0%
Urban two-lane (U2L)								
Total	0.695	(0.634, 0.756)	0.463	(0.224, 0.702)	N/A	N/A	N/A	N/A
CLRS	0.677	(0.61, 0.744)	0.400	(0.159, 0.641)	N/A	N/A	N/A	N/A
SRS	0.655	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Both CLRS and SRS	0.839	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: *not significant at 90% CI

Discussion of Results

The comprehensive observed crash analysis and safety effectiveness evaluation results lead to the following discussions.

Discussion on Observed Crashes

Rumble strips reduce crash severity and targeted crashes significantly, particularly with centerline installation on two-lane highways. The reduction in the targeted head-on crashes—one of the deadliest types of crashes—is 41.8% on rural and 50% on urban two-lane highways, and in sideswipe opposite direction crashes, 28.7% for rural and 62.2% for urban, respectively. The shoulder rumble strips' performance is not impressive nor consistent among the sites. While on the urban sites with only SRS installed, the single vehicle running off roadway—the targeted crash—drops 40%; whereas, the rural segments experience a 19.6% increase. The much smaller sample size (12 segments in rural and only one in urban) with shoulder rumble strip installation is probably the reason for the crash increase, since the smaller the sample size, the less reliable the results.

The crash reductions associated with different running-off-roadway maneuvers, illustrated in Figure 1, are listed in Table 55. By using different combinations of crash attributes, it is possible to capture the safety improvement associated with all five running-off-roadway maneuvers that are targeted by rumble strips at different locations. Since an exact number of recovered running-off-roadway maneuvers is hard to know, non-collision (i.e., single vehicle) crash reduction is the best indicator to reflect the benefit of rumble strips. Combining the *first harmful event* with *manner of collision* enables the crash analysis on the other four maneuvers. The crash reduction in all cases are consistent and impressive. Due to the identified errors in the first harmful event coding discussed previously, the results in Table 55 only serves as a complementary analysis.

Table 55. Change in Crashes Associated with Possible Roadway Departure Maneuvers (R2L)

First Harmful Event	Manner of Collision	Maneuvers indicated in Figure 1	Could be Preventable by	Before Crashes	After Crashes	Crash Reduction
Not considered	Non-Collision	1 and 2	All RS	3,012	2,462	18.26%

First Harmful Event	Manner of Collision	Maneuvers indicated in Figure 1	Could be Preventable by	Before Crashes	After Crashes	Crash Reduction
Crossed centerline	Head-on and ODSS	3	CLRS	122	103	15.57%
Ran off Road all the way to the left (neither head-on nor ODSS)	Non-Collision	4	Centerline and SRS on left	928	746	19.61%
Ran off road to the right	Non-Collision	5	SRS on right	18	14	22.22%
Ran off road all the way to left or right	Non-Collision	4+5	All RS	1,637	1,201	26.63%

As presented in Table 56, the crash reductions associated with different running-off-roadway maneuvers on urban two-lane (U2L) highways are consistent except for the scenario "ran off to the right."

Table 56. Change in Crashes Associated with Possible Roadway Departure Maneuvers (U2L)

First Harmful Event	Manner of Collision	Maneuvers indicated in Figure 1	Could be Preventable by	Before Crashes	After Crashes	Crash Reduction
Not considered	Non-Collision	1 and 2	All RS	1,085 (total crashes)	831 (total crashes)	23.41%
Crossed centerline	Head-on and ODSS	3	CLRS	19	10	47.37%
Ran off Road all the way to the left (neither head-on nor ODSS)	Non-Collision	4	Centerline and SRS on left	101	42	58.42%
Ran off road to the right	Non-Collision	5	SRS on right	4	5	- 25%
Ran off road all the way to left or right	Non-Collision	4+5	All RS	42	20	52.38%

The in-depth crash investigation was conducted on one CLRS segment that has the highest percentage of original crash report available (91% and 100% for before and after periods). Although there is no the targeted crashes (head-on and sideswipe opposite direction) in the before and after time periods, it does have a crash reduction illustrated in Figure 1 as the maneuver type 4, which could be due to the presence of CLRS and SRS.

To investigate whether the CLRS induces single-vehicle ran-off-to-right crashes after vehicle switching quickly to the right from the left, additional analysis was performed by examining number of crashes defined by two crash attributes, i.e., non-collision as in *manner of collision* and ran-to-right as in *first harmful event*. As shown in Table 57, there is a 22.4% crash reduction on all CLRS sites. Thus, it is most likely that the CLRS does not result in single-vehicles ran-off-to-right crash.

Table 57. The Specifically defined Crashes Reduction on CLRS sites

Only CLRS sites	Before	After	Crash Reduction
Non-Collision and Run off Right crashes on CLRS segments.	1,131	878	22.4%

Assessing Effectiveness of Rumble Strips

The analyses from all four methods yield similar results on the effectiveness of rumble strips. On rural two-lane (R2L) highways, the estimated CMF for total crashes is 0.835 with before-after EB analysis and 0.854 with EB Comparison Group analysis. The with-and-without (cross-sectional) analysis and trend analysis shows 32.6% and 16.3% reductions in total crashes, respectively. The CMF for fatal and severe injury crashes is 0.59 by the before-after EB method. Because of the huge sample size, the CMF for centerline rumble strips has the most reliable results, judging by its very small variance. The SRS have the largest estimated variance, which causes the CMF to vary between 0.729 and 1.171 with possibility of 17% crash increase. Again, as discussed before the small sample size ($n = 12$) makes the estimation less reliable.

The huge economic benefits of rumble strips are manifested by the ratio of benefit to cost from conservative estimate—12.98 for combined all rumble strips cases on rural two-lane highways and 14.64, 1.9, and 7.37 for the CLRS, SRS, and combined (CLRS and SRS), respectively. The ratio is 37.2 for all rumble strips on urban two-lane highways, 38.27 for CLRS and 83.55 for CLRS and SRS. When other associated costs are not considered, rumble strip installation could yield benefit cost ratio as high as 95.6 and 278.78 for rural two-lane and urban two-lane highways.

Conclusions

This report documents a comprehensive analysis of the rumble strips' safety effects on the two-lane highways in Louisiana. The study consists of close to 1,700 miles of two-lane highways with rumble strips, including 1,369 miles with CLRS, 68 miles with SRS and 255 miles with both CLRS and SRS from the rural and urban two-lane highways. The results of the observed crash analysis, before-and-after EB analysis, comparison group before-and-after EB analysis, cross-sectional (with and without) analysis, and the time-series analysis method lead to the following conclusions:

- CLRS on two-lane highways is a very effective crash countermeasure, particularly for fatal and severe injury crashes. The fatal and severe crash reduction is as high as 35.8% on rural and 47.8% on urban, much better than the results from the majority of the studies. CLRS also significantly reduces the targeted head-on collisions—one of the deadliest crashes—41.8% and 50% for the rural and urban two-lane highways, respectively. The estimated CMF for total crashes with the before-and-after EB method is 0.835 for rural and 0.695 urban two-lane highways. The estimated CMFs for fatal and severe injury crashes are more impressive at 0.590 for rural and 0.463 for urban. The big ratio of benefit to cost makes CLRS the most cost-effective countermeasure for two-lane highways. Because of the large sample size on R2L (315 sites totaling 1,291 miles), the estimated CMF could vary between 0.804 and 0.866 for total crashes, 0.476 and 0.704 for fatal and severe injury crashes with 95% confidence level. With 35 sites on U2L, the estimated CMF could vary between 0.634 and 0.756 for total crashes and between 0.224 and 0.702 for fatal and injury crashes.
- Even though the number of sites with both CLRS and SRS are smaller (53 on R2L and five with U2L), the crash reduction is still impressive with the highest percentage reduction in fatal and severe injury crashes (22.2% for R2L and 75% for U2L). The estimated CMF with before-and-after EB method for R2L is 0.764 for total crashes and 0.556 for fatal and severe injury crashes.
- The smallest sample size (12 in R2L and one in U2L) for SRS makes the evaluation results inconsistent and not reliable. This project only evaluates the RS installation made between 2007 and 2015. Even though this project does not yield reliable results of SRS, many previous key studies have proven the effectiveness of shoulder rumble strips on two-lane highways *[15], [17]–[20]*.

- In addition to focusing on total and targeted crashes, utilizing additional crash attributes, such as the first harmful event in combination with manner of collision (type of crash), helps to effectively evaluate the five possible roadway departure maneuvers and demonstrates how rumble strips at different locations could reduce such maneuvers.
- In short, the project findings show the success of the DOTD rumble strips program. Rumble strips should be continuously used as a key crash countermeasure in maintaining a sustainable fatal and severe injury crash reduction in the future for the state.

Recommendations

While the expensive crash countermeasures, such as flattening horizontal curves and roadside slopes (4:1 or flatter), extending lane width or shoulder width, and making roadside in higher degree of forgiving, are almost infeasible under the financial constraints, rumble strips at centerline, shoulder, or both locations are the best low-cost engineering solutions in reducing roadway departure crashes, particularly the fatal and severe injury crashes. Based on the findings of this project, the following recommendations are made to the state DOTD Safety Improvement Program:

- Continue the current systematic safety analysis program for rumble strips installation at locations with high roadway departure crashes and or high targeted crashes such as head-on collisions.
- Consider utilizing systemic safety analysis method to select sites with low AADT but high risk of roadway departure crashes. The risk analysis considers not only crash frequency and severity but also the design (for example horizontal curve with small radius) and traffic operation features (speed differential between adjacent segments and different type of vehicles).
- Support parish and local government in rumble strips installation on non-state highways since these roadways may have high roadway departure risk. The risk analysis considers not only crash frequency but also design features.
- Work with the state crash record committee for correcting few crash recording errors (first harmful event and head-on collision) discovered in this project to improve the crash data accuracy.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway Transportation Officials
ARIMA	Autoregressive Integrated Moving Average
CI	Confidence Interval
CLRS	Centerline Rumble Strips
CMF	Crash Modification Factor
DOTD	Department of Transportation and Development
EB	Empirical Bayes
FHWA	Federal Highway Administration
FoRRWD	Focus on Reducing Rural Roadway Departures
FSI	Fatal and Severe Injury
ft.	foot (feet)
HSM	Highway Safety Manual
LTRC	Louisiana Transportation Research Center
ODSS	Opposite Direction Sideswipe
R2L	Rural Two-Lane
ROR	Run-off Roadway
RS	Rumble Strips
SRS	Shoulder Rumble Strips
SPF	Safety Performance Function
SVROR	Single Vehicle Run Off Road
U2L	Urban Two-Lane

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Appendices

Appendix A: Difference from 15-3SA Project

Limitations from 15-3SA Projects

"Google Street View" for verification of CLRS presence was limited as approximately 40% of rural-two lane segments did not have street view after 2008. The project team relied on the data provided by the DOTD for the accuracy of the presence of rumble strips on the locations. Furthermore, roadway departure was not investigated as PRC members requested.

Changes in 19-4SA

The current project scope has been expanded to R2L and U2L. The "ivisionRoadware" tool provides a new alternative to verify the presence of rumble strips at given sites. Safety analysis has been conducted on different types of rumble strips such as CLRS, SRS and combination of CLRS and SRS. Other than safety analysis, this project also focuses on looking at crash narratives and diagrams from crash reports to find out target crash for rumble strips. The major difference between previous research and current research is compared in tabular form in Table A1.

Table A1. Difference between 15-3SA and 19-4SA (current report)

15-3SA Project	19-4SA Project (Current report)
Analysis of safety effectiveness of CLRS was based on: • Total crashes • Head-on and opposite sideswipe crashes	Analysis of safety effectiveness of CLRS, SRS and combination of CLRS and SRS was based on: • Total crashes • Target crashes • Lane departure and roadway departure crashes

15-3SA Project	**19-4SA Project (Current report)**
The methodology used to determine safety effectiveness: • Empirical Bayes for Total Crashes	The methodology used to determine safety effectiveness: • Empirical Bayes for total crashes and Fatal and severe crashes • EB by comparison group • Cross-sectional analysis (based on crash rate) • Crash trend analysis
Variable investigated: • Manner of Collision	Variable investigated: • Manner of collision • Lane departure • Roadway departure • Sequence of events
Tools used for investigation: • Google street view (verification of countermeasure presence)	Tools used for investigation: • Google street view (verification of countermeasure presence) • "ivisionRoadware" (verification of countermeasure presence) • Crash reports (narratives and diagrams)

Appendix B: Details on Data Verification

The first critical task of this project was to identify where and when each countermeasure was installed on the vast state two-lane highway network. Location information from the previous project (15-3SA) and the latest data were mixed for database development. The rumble strips identified from these locations were classified into four types as shown in the table below.

Table B1. Possible cases for countermeasure implemented on two lane highways

Location	CLRS	SRS	Remarks
Segment 1	Yes	No	Only CLRS
Segment 2	No	Yes	Only SRS
Segment 3	Yes	Yes	Combination of CLRS and SRS
Segment 4	No	No	No Rumble Strips

Figure B1. LADOTD Latitude/Longitude Converter

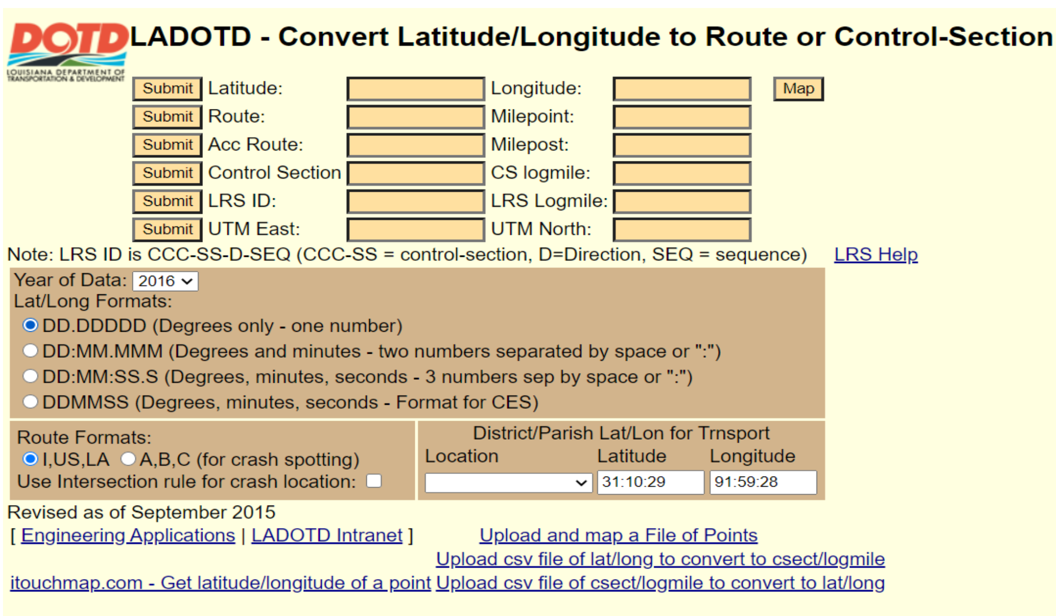

Figure B2. Location Verified as Combination of CLRS and SRS

Figure B3. "ivisionRoadware" for Verification

Figure B4. Segments with no Rumble Strips

Figure B5. Change in Rumble Strips over the Years in Same Segment (Clockwise) – No Rumble Strips (May 2008), CLRS (June 2014), Construction (May 2018), SRS (November 2018)

Figure B6. Segments with SRS on Interstate (I-49)

Appendix C: Top 30 Sites

Table C1. Top 30 RS Sites with Highest Frequency of Crashes

S/N	District	Control Section	Log mile From	Log mile To	Length (miles)	Total Crash (before)	Total Crash (after)	Report Available (before)	Report Available (after)	% Available (before)	% Available (after)
1	62	268-01	0	6.32	6.32	160	105	8	27	5%	26%
2	8	074-02	0	6.71	6.71	98	94	1	1	1%	1%
3	8	033-01	2.31	9.93	7.62	70	79	0	1	0%	1%
4	62	852-03	3.08	6.19	3.11	45	58	1	2	2%	3%
5	61	265-01	0.9	3.47	2.57	45	56	9	17	20%	30%
6	2	005-04	1	11.2	10.2	58	52	2	4	3%	8%
7	62	277-01	0	4.71	4.71	46	48	6	1	13%	2%
8	62	278-02	0.319	7.458	7.139	46	46	0	2	0%	4%
9	61	266-02	5.42	7.72	2.3	44	45	7	13	16%	29%
10	7	031-06	3.8	12.3	8.5	37	44	2	0	5%	0%
11	62	278-01	3.14	4.99	1.85	42	43	0	0	0%	0%
12	2	064-05	8.52	13.13	4.61	30	40	0	5	0%	13%
13	8	033-01	11.95	15.14	3.19	46	39	0	5	0%	13%
14	5	067-09	0	2.02	2.02	31	36	0	1	0%	3%

S/N	District	Control Section	Log mile From	Log mile To	Length (miles)	Total Crash (before)	Total Crash (after)	Report Available (before)	Report Available (after)	% Available (before)	% Available (after)
15	61	861-03	0	3.7	3.7	51	34	0	16	0%	47%
16	8	009-03	0	13.92	13.92	26	33	1	8	4%	24%
17	4	021-02	7.63	17.74	10.11	38	32	7	12	18%	38%
18	8	052-07	4.14	9.43	5.29	53	32	1	0	2%	0%
19	2	065-01	1.09	6.02	4.93	25	32	2	2	8%	6%
20	61	254-03	1.78	7.8	6.02	45	32	5	4	11%	13%
21	8	417-02	1.6	8.15	6.55	27	32	0	4	0%	13%
22	4	048-01	0	4.97	4.97	25	31	13	27	52%	87%
23	3	057-05	0	5.75	5.75	43	31	0	1	0%	3%
24	5	038-01	6.29	11.48	5.19	38	30	1	1	3%	3%
25	4	082-30	0	6.16	6.16	41	30	19	18	46%	60%
26	62	260-07	1.04	4.94	3.9	27	30	2	6	7%	20%
27	4	011-04	5.3	12.84	7.54	50	29	29	25	58%	86%
28	62	013-12	4.65	8.39	3.74	50	29	4	29	8%	100%
29	*4*	*045-03*	*0*	*11.01*	*11.01*	*34*	*29*	*31*	*29*	*91%*	*100%*
30	62	260-07	4.94	10.08	5.14	21	28	0	0	0%	0%
				Total	**174.77**	**1,392**	**1,279**	**151**	**261**		

Appendix D: A Compilation of Crash Narratives for In-Depth Analysis

Table D1. In-Depth Exploration of Crashes on Selected Segment (Control Section 045-03, Logmile 0 to 11.01)

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
Only CLRS (before year crashes), Before year 2013/2014/2015, Number of crashes = 34											
5.97	Ditch	Tree	Traffic sign support		Ditch	Normal	Non-collision	Driver entered the curve and his load shifted. Driver ran off the road to the right and he over corrected the truck. The truck flipped on its side and stopped in the ditch.	yes	yes	no
6.32	Thrown or fallen object				Thrown or fallen object	Normal	Other	Driver was suddenly hit by something and caused driver to lost control of his motorcycle. A limb fell from the tree and hit the motorcycle.	yes	yes	no
2.24	Unknown-vehicle 1 Ran off road right-vehicle 2	Other fixed object: Vehicle 1	Tree-vehicle 1			Unknown-vehicle 1 normal-vehicle 2	Other	Driver of vehicle 2 swerved to avoid the oncoming vehicle in her lane and ran off the road.	yes	yes	no
4.66	Ran off the road to right	Tree			Tree	Normal	Non collision	A deer ran out in front of the driver, when driver tried to miss the deer, he ran off the road and hit a tree.	yes	yes	no
9.83	Animal				Animal	Normal	Other	While driving driver noticed a donkey standing in the southbound lane. Driver swerved on the north bound lane but still hit the donkey.	yes	yes	no
3.32	S*				S	Normal	Rear-end	Vehicle 2 had to make a sudden stop due to a tree in the roadway. Vehicle 1 behind was unable to stop to avoid striking the rear end of vehicle.	no	no	no
51	Ran off the road to right	Tree			Tree	Unknown	Non collision	The vehicle was travelling north. The tire mark indicated that vehicle travelled through the grass on a slope leaving off the roadway, then striking a tree and rotating counterclockwise and coming to a rest.	yes	yes	no

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
3.97	S	Ran off road right	Tree		Tree	Distracted	Rear end	Driver turned back to look at children and did not see vehicle in front of her making a left turn, driver steered to right, but hit the back of vehicle 2. Vehicle then spun clockwise off the road and hit a tree.	no	no	no
4.94	Tree				Tree	Normal	Non collision	Driver ran off the roadway to left and hit several trees while avoiding hitting a deer.	yes	yes	no
10.84	Ran off the road to right	Other pole/post	Overturn	utility pole	Overturn	Normal	Non collision	While exiting from the curve driver felt trailer started sliding towards the edge of roadway. Driver was unable to keep vehicle on the roadway then it stroked board, continued down on the shoulder before turned over the ditch.	yes	yes	no
5.87	S				S	Inattentive	Rear end	Vehicle 2 was behind a funeral procession and when the procession stopped unexpectedly due to a procession making right turn, vehicle 2 stopped but vehicle 1 hit vehicle 2 from behind.	no	no	no
3.26	Ran off the road to right	Ditch	Tree		Tree	Normal	Non-collision	Truck slid off the roadway in the curve hit the tree after running into the ditch.	yes	yes	no
4.61	S				S	Normal	Rear-end	Vehicle 1 hit vehicle 2 in which was slowing down to turn left due to sun glare.	no	no	no
1.71	S				S	Normal	Right angle	Driver of vehicle 1 was travelling at 40 mph and when he presses his brakes they locked up and he slid through the stop sign into the driver 2. He said his vehicle struck driver 2 in the driver side rear making driver 2 spin into the shoulder of the road.	no	no	no
5.12	Ditch	Tree			Tree	Fatigued	Non-collision	Driver said he fell asleep and ran off the roadway. Police reports he ran off the road on the east side of road, overcorrected and slid sideways across the highway into the west side of ditch. Vehicle started to flip several times and hit a tree. The vehicle came to rest on passenger side of vehicle.	yes	yes	no

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
0.47	S				S	Normal	Rear end	Vehicle 1 was slowing down to let another vehicle turn in driveway. Vehicle2 hit vehicle 1 in the rear end.	no	no	no
8.22	Ran off the road to left	Tree			Tree	Inattentive	Other	Driver did not realize vehicle was drifting off the roadway and when she realized her vehicle was already going down the ditch.	yes	yes	yes
9.52	Ran off the road to right	Ditch			Ditch	Normal	Non-collision	Vehicle struck the ditch. The front end of the vehicle 1 was partially in the ditch and bed of the truck was on the shoulder of the road.	yes	yes	no
8.12	Crossed centerline	Ran off left	Ditch	Tree	Tree	Normal	Non-collision	Vehicle hydroplaned and drove vehicle into a ditch. After hitting the ditch, vehicle struck a standing tree with the passenger side door and window.	yes	yes	yes
0.65	Animal				Animal	Normal	Non-collision	Driver stated that he got a call and glanced at his computer to make sure he cleared from the call. He said at that time his windshield exploded. And he drifted to the side of the road to a stop. He saw a dead animal lying dead on the west side of roadway.	yes	yes	no
2.56	S				S	Normal	Non-collision	When driver came near TEE intersection he blanked out and struck tree on the side.	yes	yes	no
8.88	Utility pole	Overturn			Utility pole	Normal	Non-collision	Driver lost control of vehicle in curve.	yes	yes	no
2.96	Ran off the road to right	Overturn			Overturn	Impaired-alcohol	Non-collision	Driver looked down to open a pack of cigarettes and ran off to the right. He then over corrected and truck rolled over. Driver was not wearing his seatbelt and was totally ejected from the vehicle.	yes	yes	no
2.24	Ran off the road to right	Ditch			Ditch	Normal	Non-collision	Vehicle entered the curve and started to slide on ice. Driver stated she tried to turn the wheel, but the vehicle continued to slide of the roadway to the right and into the mud.	yes	yes	no
2.93	Ran off the road to left				Ditch	Normal	Non-collision	Driver hit a patch of ice on road and lost control to left of road. Vehicle struck several trees after leaving roadway.	yes	yes	yes*

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
3.33	Ran off the road to right	Ditch			Ditch	Impaired-alcohol	Non-collision	Drivers used mobile to text back and ran off the road. Driver was intoxicated.	yes	yes	no
1.7	Ran off the road to left	Ditch	Utility pole		Utility pole	Asleep	Non-collision	Driver fell asleep at the wheel and ran off the road to left.	yes	yes	yes
2.28	Crossed centerline	Ran off left	Culvert		Culvert	Impaired-alcohol	Non-collision	Driver said deer ran out into the roadway and he swerved to miss the deer but lost control of the vehicle. Officer stated that vehicle 1 crossed centerline and into the opposing lane then drove off the roadway left and impacted a culvert.	yes	yes	yes
5.18	Ran off the road to right	Tree	Tree	Tree	Tree	Impaired-alcohol	Non-collision	Vehicle drove off the roadway to right, while not making a turn in a curve. Vehicle hit two separate trees on the left side of the vehicle.	yes	yes	no
4.11	Ran off the road to right	Tree			Tree	Unknown	Non-collision	Vehicle went off road in intersection. Driver arrested, accident possibly due to impaired driving.	yes	yes	no
3.2	Animal				Animal	Normal	Non-collision	Deer ran in front of vehicle.	yes	yes	no
8.72					Animal	Normal	Other	NO CRASH REPORT AVAILABLE	yes	yes	
2.88					S	Normal	Rear end	NO CRASH REPORT AVAILABLE	No	No	
0.68					Fence	Physical impairment	Non collision	NO CRASH REPORT AVAILABLE	yes	yes	
Only CLRS (after year crashes), After year 2017/2018/2019, Number of crashes = 29											
5.02	Ran off the road to right	Ditch	Tree	Tree	Tree	Unknown	Non-collision	Driver ran off road, continued in the ditch and struck a large tree pulling it loose from the ground and got wedged between two small trees, and pinned between two small trees.	yes	yes	no
3.4	Ran off the road to right	Ran to left	Overturn	Tree	Tree	Alcohol-impaired	Other	Vehicle ran to right; driver tried to correct the vehicle and ran to the left rolling over. Driver had alcoholic beverage.	yes	yes	no

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
6.51	Ran off the road to right	Utility pole			Utility pole	Alcohol-impaired	Non-collision	Driver had high level of impairment not able to give statement. Officer stated vehicle was vehicle appeared turned too sharp and struck utility pole head on.	yes	yes	no
5.51	Other post				Other post	Normal	Non-collision	Driver did not see the power line hanging on the road. He drove through the hanging power line.	yes	yes	no
5.15	Ran off the road to right	Ditch	Tree	Utility pole	Tree	Normal	Non-collision	Vehicle ran off the road while avoiding the car that was coming on her lane. The car which came to another lane did not stop.	yes	yes	no
10.9 7	Ditch	Overturn			Overturn	Alcohol-impaired	Other	Driver was drunk and stated she lost her control while driving.	yes	yes	no
9.86	Crossed centerline	Ran to left	Overturn	Utility pole	Utility pole	Asleep	Non-collision	Driver fell asleep while driving when he woke up vehicle was on its side against a pole.	yes	yes	yes
2.35	Ran off the road to right	Ditch	Culvert	Utility pole	Culvert	Unknown	Non-collision	Fatal: Driver did not wear seatbelt, no indication of careless operation at scene. The vehicle ran off the roadway to the right then traveled through a ditch.	yes	yes	no
3.87	Struck by falling object				Struck by falling object	Normal	Other	Bicycle fell from vehicle 1 ahead and strike the vehicle 2 at back.	no	no	no
3.35	Equipment failure	Ran to left	Ditch	Tree	Tree	Normal	Non-collision	Vehicle began to pull to left, driver lost the control. Then driver accidently pressed gas instead of brake and hit the tree.	yes	yes	no
4.13	S				S	Normal	Right angle	Vehicle 2 was going to turn left with sidelight on. Vehicle 1 entered intersection and hit vehicle 1 struck driver side of vehicle 2.	no	no	no
3.83	Ran off the road to right	Traffic sign support			Traffic sign support	Normal	Non-collision	Driver tried to avoid a deer and struck sign and then went to ditch.	yes	yes	no
5.22	Ran off the road to right	Tree			Tree	Normal	Non-collision	Driver swerved to right to avoid the deer, left the roadway to right and into the ditch.	yes	yes	no

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
9.01	Animal				Animal	Normal	Non-collision	Driver hit a hog on the road.	yes	yes	no
5.18	Ran off the road to right	Crossed median	Tree		Tree	Distracted	Non-collision	The evidence showed that the driver was heading north on the highway when she lost the control and ran off the road. The driver over corrected and the car turned around backward and into the tree.	yes	yes	no
3.36	Ran off the road to right	Tree	Other post		Tree	Fatigued	Non-collision	Driver fell asleep while driving and ran to the right, struck root of tree, and collided with the pole.	yes	yes	no
10.26	Animal				Animal	Normal	Other	Deer came in front of car and collided.	yes	yes	no
6.45	S				S	Physical impairment	Left turn	Driver didn't have her glasses and couldn't see very well. Driver stopped to turn to parking lot and hit driver side of another vehicle.	no	no	no
6.16	Ran off the road to left	Utility pole			Ran to left	Unknown	Non-collision	Vehicle slid sideways and came to stop 30 ft. west of roadway. Driver was not at the scene.	yes	yes	yes
3.37	Ran off the road to right	Culvert			Culvert	Alcohol-impaired	Other	Driver was driving above the speed limit. Strong smell of alcohol from driver. The vehicle was heading south bound into a curve on a hill and the tire tracks showed the vehicle travelled 118 ft. before striking the culvert.	yes	yes	no
1.88	Animal				Animal	Normal	Non-collision	Vehicle hit a deer.	yes	yes	no
2.12	Animal				Animal	Normal	Non-collision	Driver was prepared to negotiate on sharp turn, a large black dog appeared, and the car hit the dog.	yes	yes	no
3.1	Ran off the road to right	Traffic sign support			Traffic sign support	Unknown	Non-collision	Driver was not in contact. Vehicle knocked down a traffic sign.	yes	yes	no

Log mile	1st harmful event (from report)	2nd harmful event	3rd harmful event	4th harmful event	Most Harmful Event	Condition of Driver (vehicle 1)	Manner of Collision	Narrative	Travel Lane Departure	Complete Roadway Departure	Target Crash
9.01(1)	Ran off the road to right	Culvert	Ditch	Utility pole	Utility pole	Unknown	Non-collision	Driver said a deer ran out in front of him and he tried to avoid the deer. Then the driver felt like he hydroplaned and ran off the road.	yes	yes	no
3.75	S	Equipment failure			Equipment failure	Normal	Non-collision	Tire fell of the trailer while driving.	yes	yes	no
1.44	Animal				Animal	Normal	Other	Driver struck the deer with the front of her vehicle.	yes	yes	no
4.12	S				S	Normal	Rear end	Vehicle 1 ran into the back of her vehicle 2 at stop.	yes	yes	no
8.44	Animal				Animal	Normal	Non-collision	Driver struck the deer with front of his vehicle.	yes	yes	no
10.38	Animal				Animal	Normal	Non-collision	Driver hit the deer on the road.	yes	yes	no

Note: s – motor vehicle in transport

This public document is published at a total cost of $200.
29 copies of this public document were published in this first printing at a cost of $200. The total cost of all printings of this document including reprints is $200. This document was published by Louisiana Transportation Research Center to report and publish research findings as required in R.S. 48:105. This material was duplicated in accordance with standards for printing by state agencies established pursuant to R.S. 43:31. Printing of this material was purchased in accordance with the provisions of Title 43 of the Louisiana Revised Statutes.