Final Report

Impact of Non-Freeway Rumble Strips
Phase 1

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16. Abstract

In an effort to reduce lane-departure crashes, in 2008 the Michigan Department of Transportation (MDOT) began a three-year statewide non-freeway rumble strip installation initiative. This initiative called for the installation of milled centerline rumble strips on all rural non-freeway highways with a posted speed limit of 55 mph and a paved roadway width greater than 20 ft and shoulder rumble strips on roadways with paved shoulders that were at least 6 ft wide. Approximately 5,400 miles of non-freeway roadways were ultimately included in this rumble strip installation initiative. As this initiative was believed to be the largest of its kind in the United States at the time, it was important for MDOT to evaluate the impacts associated with the rumble strip installations to provide guidance for future implementation both within Michigan and other states. The objectives of this study included:

- Identification and analysis of “Before” traffic crashes
- Assessment of impact of rumble strips on driver behavior, bicyclist safety, roadside noise, and short-term pavement performance.

Several field data collection efforts were undertaken in order to accomplish the objectives. Based on the results of the evaluation, it is concluded that rumble strips on high-speed non-freeway highways improves driver performance on most highways and traffic scenarios. Vehicles produced higher levels of roadside noise when traveling over the rumble strips compared to normal passbys. The rumble strip noise typically did not exceed the roadside noise level produced by tractor trailer trucks traveling on normal highways. Finally, centerline rumble strips did not contribute to short-term transverse cracking are in asphalt pavements. Three years of “Before” crash data were analyzed to identify the target crashes that is expected to be alleviated by the installation of centerline rumble strips on MDOT’s high-speed trunkline (non-freeway) system.

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Traffic crashes on high-speed undivided highways often present safety challenges involving lane departure-related crashes and injuries. The use of continuous rumble strips along such highways on the edges of travelways provide a warning to drivers resulting in either appropriate corrective action or a reduction in speed, which are often associated with crash avoidance or severity reduction.

A search of traffic crashes on state [Michigan Department of Transportation (MDOT)] maintained non-freeway high-speed (55 mph) roadways, excluding intersection crashes, indicated that in 2007, approximately 23,751 crashes occurred in Michigan, including 122 fatal crashes *(1)*. In 2008, total crashes and fatal crashes on non-freeway state maintained roads were 24,288 and 111, respectively. Among the most severe of these types of crashes are those involving lane departure where vehicles cross over either the centerline or edge line, resulting in head-on, opposite direction sideswipe, or run-off-the-road collisions. Lane departure crashes totaled 20.7 percent (4,910) of all crashes that occurred on these types of roads and comprised 69 percent (84) of fatal crashes in 2007 and in 2008; they were 23 percent (5,565) of all crashes and 77 percent (86) of fatal crashes *(1)*. Historically, crashes involving lane departure are often over-represented in severity since these crashes are generally associated with higher vehicle speeds. Some of the primary causes of lane departure crashes also include distracted or drowsy driving.

Continuous longitudinal rumble strips placed along the roadway edge or centerline are used by transportation agencies as a means of reducing lane departure crashes and injuries. When encountered by distracted or drowsy drivers, they provide both a tactile and audible warning to the driver. In 2008, MDOT began a major rumble strip installation program to help prevent lane departure crashes on rural non-freeway state trunklines in Michigan. This initiative continued through 2010. This program includes the installation of both shoulder rumble strips (SRS) and centerline rumble strips (CLRS) on MDOT rural non-freeway highways with posted speed limits of 55 mph. CLRS were installed at all such highways, except at the intersections and through urbanized areas. SRS however, were installed only on highway segments where the shoulder width was six feet or greater. This program is the largest of its kind in the United States. As such, it is important for MDOT to carefully evaluate the impacts of the program on both traffic safety operations and pavement durability. If significant crash reduction and improvement in driver behavior due to the presence of continuous rumble strips are confirmed, this evaluation will set the standard for future implementation within Michigan and nationwide. Also under consideration are impacts on non-motorized users (i.e., bicycles) and the adjacent community (e.g., noise). In conjunction with the noted evaluations, impacts on pavement condition due to CLRS installations will be examined. Specifically, if pavement deterioration is caused or accelerated by the installation of rumble strips, alternate installation methods or specific preventive maintenance treatments need to be considered. All these elements must be critically examined in order to provide MDOT with a comprehensive assessment of the rumble strip program.

Study Objectives

The objectives of this research included:

1. Preparation of a Geographic Information System (GIS) database and map that identifies the locations of MDOT's non-freeway rumble strip installations.
2. Development of a comprehensive crash database for the "Before" period (for use in Phase 2 "Before-and-After" crash analysis).
3. Collection of "Before" and "After" field data for driver behavior, including: lateral placement within the lane, centerline and edgeline encroachments, speed, relevant passing maneuvers characteristics, and others at roadway segments where rumble strips have been installed.
4. Evaluation of sample "Before" and "After" driver behavior in the presence of bicyclists and bicyclist behavior, including: vehicular lateral placement when passing a bicyclist riding on the shoulder; edgeline encroachments, centerline encroachments, and others.
5. Identification of rumble strip related safety and mobility issues for bicyclists.
6. Use of MDOT's pavement management system video logs to evaluate short-term pavement performance impacts due to CLRS installations ("Before" and "After" condition data).
7. Perform a comparison of sample speeds before and after the CLRS installations.

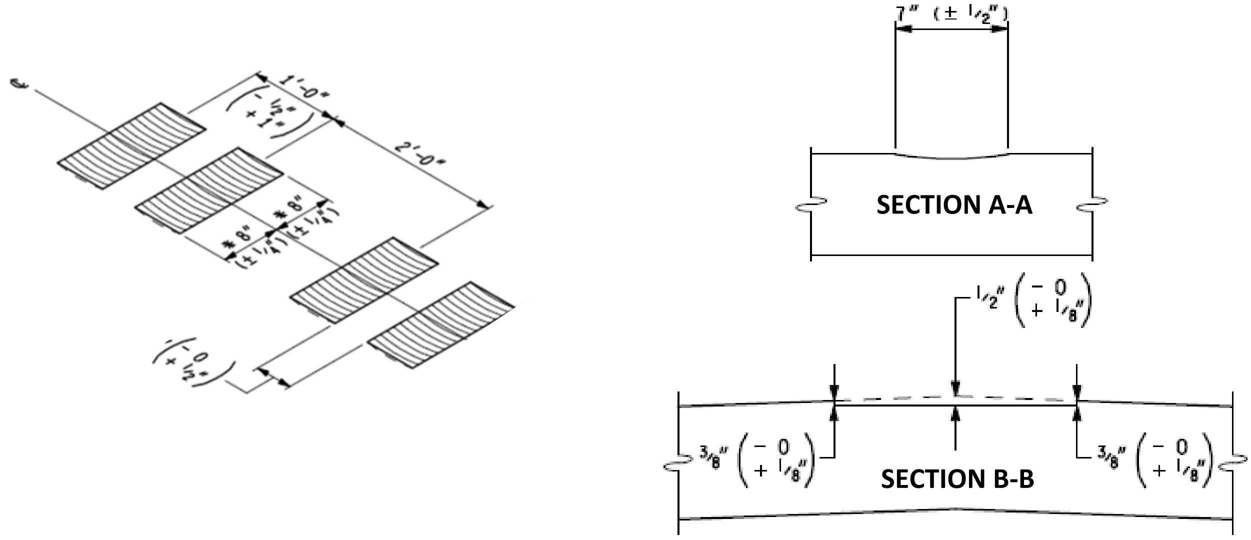
II. BACKGROUND AND PAST RESEARCH STUDIES

The centerline rumble strips (CLRS) were installed on approximately 5,400 miles of non-freeway high-speed rural highways in Michigan. The shoulder rumble strips (SRS) were also installed on roadways where there were at least 6 ft wide shoulders. The rumble strips corrugations were ground (i.e., milled) into the pavement per MDOT specifications. MDOT standard installation details *(2)* for both CLRS and SRS installations are shown in Figure 1, and are summarized as follows:

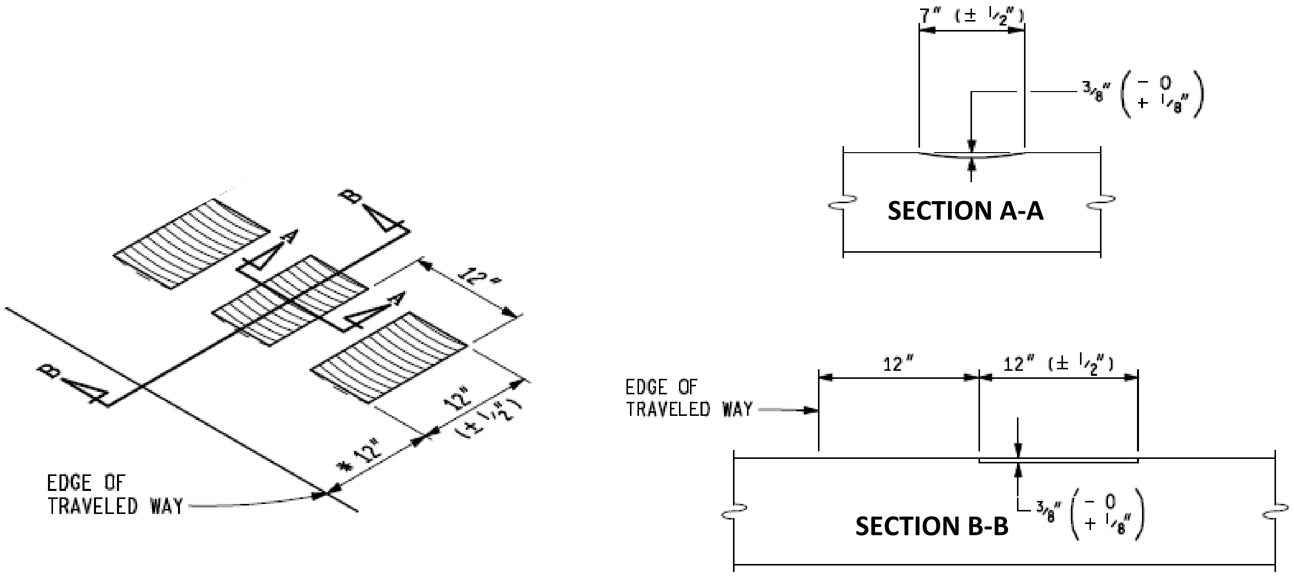
- Centerline Rumble Strips
  - Transverse dimension of corrugation (tolerance): 16 in (± ½ in),
  - Longitudinal dimension of corrugation: 7 in (±½ in)
  - Spacing between corrugations: 5 in (- ½ in, +1 in)
  - Longitudinal gap between corrugation pairs: 17 in
  - Depth of corrugation at outer edges: 3/8 in (-0, +1/8 in); at centerline: ½ in (-0, +1/8 in)
- Shoulder Rumble Strips
  - Transverse dimension of corrugation (tolerance): 12 in (± ½ in),
  - Longitudinal dimension of corrugation: 7 in (±½ in)
  - Spacing between corrugations: 5 in (±½ in)
  - Offset from edge of traveled way to near edge of corrugation: 12 in
  - Longitudinal installation cycle: 48 ft of rumble strips followed by a 12 ft gap
  - Depth of corrugation: 3/8 in (-0, +1/8 in)

The rumble strip dimensions at each field study location were verified with field measurements at sample locations to determine compliance with the implementation tolerances as per the MDOT specification.

The installation of CLRS and SRS was performed during the construction seasons of years 2008, 2009 and 2010. This provided an opportunity to build a traffic crash database for three years of “Before” data for each segment of highways, and allowed a “Before” and “After” evaluation of driver operational characteristics at sample of locations where the rumble strips were not installed at the time this study began.



a. Centerline Rumble Strips



b. Shoulder Rumble Strips

Figure 1. MDOT Rumble Strip Standards for Rural Non-Freeway Roadways ***(2)***

Past Research Studies

Rumble strips have been used by transportation agencies along the edge/shoulder of the roadway for many years as a means of reducing single vehicle run-off-the-road crashes involving drowsy or distracted drivers. Shoulder rumble strip installations were first utilized along rural freeways many years ago. Evaluations of the safety and/or driver behavioral effectiveness of these installations showed favorable results and prompted their use along the edge/shoulder of non-freeway high-speed rural roadways, including undivided two-lane and four-lane roadways. More recently, several transportation agencies have installed rumble strips along the centerline of two-lane and multilane undivided roadways. Centerline rumble strips are designed to reduce cross-centerline crashes, including head-on, sideswipe, and run-off-the-road (left-side) crashes. A wide variety of design and installation specifications are utilized across the United States for centerline and shoulder rumble strips installations on non-freeways, particularly regarding the size and spacing of the rumble strips, the offset from the centerline/edgeline markings, the types of roadways where CLRS and/or SRS are installed, and whether CLRS are terminated through passing zones.

Measures of Effectiveness Used in Prior Research

Although direct measurement of the reduction in target crashes or crash severity would ultimately provide the most valuable evidence of the effectiveness of a safety countermeasure such as rumble strips, these evaluations are often difficult to perform due to time and/or cost constraints. Consequently, evaluations of targeted surrogate measures of effectiveness (MOEs) are often used as a proxy for crash evaluations *(3)*. Surrogate MOEs are selected based on driver behavior or performance measures that are associated with specific crash types that the countermeasure is targeted to reduce *(4)*. As rumble strips are designed to reduce run-off-the-road, head-on, and sideswipe type of crashes, appropriate surrogate MOEs include those related to lateral placement within the travel lane, encroachment onto the centerline or edgeline, and vehicular speeds. In addition to their use in rumble strip related research *(5,6,7,8)*, these MOEs have also been previously utilized to evaluate the effects of other lane departure countermeasures, such as post-mounted delineators, chevrons, wider and/or brighter pavement markings, and retroreflective raised pavement markers *(9,10,11,12)*. In addition to safety-related measures of effectiveness, previous research has also evaluated potentially negative impacts produced by the use of rumble strips on non-freeways, including the impacts on bicyclists *(13,14,15,16)*, roadside noise *(17,18)*, and passing maneuvers *(5).*

Crash Reductions

Shoulder Rumble Strips

As shoulder rumble strips exist on both divided and undivided roadways, several effectiveness evaluations of the safety effectiveness of SRS have been completed in the US. The research literature provides conclusive evidence that shoulder rumble strips significantly reduce single vehicle run-off-the-road crashes *(19,20,21,22,23)*. A recent synthesis of Illinois and California data estimated shoulder rumble strips to reduce run-off-the-road crashes on rural freeways by 21 percent *(22)*. Similar results were found on rural freeways in Montana, as a 14 percent reduction run-off-the-road crashes was observed after the installation of shoulder rumble strips *(21)*. The greatest crash reductions have been observed on roadways with higher traffic volumes, wider shoulders, and higher speeds *(19)* and the benefit/cost ratio for shoulder rumble strips has been estimated to be at approximately 20 *(21)*. Few evaluations have focused specifically on the effectiveness of non-freeway installations of shoulder rumble strips. A Minnesota study of shoulder rumble strips on two-lane roadways found results that were similar to those found on freeways as single vehicle run-off-road crashes were reduced by 13 percent for all crashes and 18 percent for injury crashes *(52)*. A recent NCHRP study estimated existence of shoulder rumble strips to reduce run-off-road crashes on two-lane roadways by 15 percent and run-off-road fatal crashes by 29 percent *(24)*.

Centerline Rumble Strips

Centerline rumble strips have not experienced the level of implementation as shoulder rumble strips. Many pilot installations and subsequent evaluations have been performed showing various degrees of crash reductions for cross-centerline crashes *(25,26,27,28,29,30,31)*. Two larger evaluations have shown a reduction in cross-centerline crashes, such as head-on and sideswipe collisions after the installation of centerline rumble strips *(24,32)*. Analysis of crash data from 210 miles of roadway with centerline rumble strips installed in seven states found a 14 percent reduction in all crashes, a 15 percent reduction in injury crashes, a 21 percent reduction in head-on and sideswipe opposite crashes, and a 25 percent reduction of injury crashes that involved head-on and sideswipe opposite crashes *(32)*. A recent NCHRP study estimated a reduction in head-on and sideswipe opposite direction crashes due to the installation of CLRS on two-lane roadways at 30 percent and 44 percent for total and fatal crashes, respectively *(24)*.

Driver Behavior and Performance

Behavioral changes associated with rumble strip installations on non-freeways have been assessed in a limited number of evaluations. An evaluation in Texas investigated the effects of CLRS and SRS on undivided rural roadways *(5).* The driver behavior/performance MOEs included: vehicular lateral placement within the lane, percent of vehicles completing a passing maneuver, percent of vehicles encroaching onto the centerline or shoulder, and percent of vehicles committing erratic maneuvers. Vehicles were found to shift away from the centerline after the CLRS were installed and fewer centerline encroachments were observed, indicating a reduced risk of cross-centerline events. Shoulder encroachments were also reduced at locations where shoulder rumble strips were installed. An investigation of 479 vehicle passing maneuvers (forced by a test vehicle), showed little change in the percent of vehicles attempting a pass when rumble strips were present. In addition, no vehicles were observed making a wrong-way correction (i.e., shifting farther left when initially encountering a CLRS) nor were any vehicles observed avoiding CLRS by straddling them.

A Pennsylvania study by Mahoney, et al, *(6)* investigated the effects of CLRS on lateral placement with respect to the centerline of the roadway. Vehicles were found to shift away from the centerline when they were present. A decrease in the lateral placement variance was also observed, suggesting that vehicles are more uniformly positioned in the presence of CLRS. Vehicular speeds were not impacted.

Bicyclist Impacts

Although there is no evidence of increases in bicycle-involved crashes associated with centerline and/or shoulder rumbles strips, a review of the several literature sources have found some concerns from the bicyclist community. They include:

- Vehicles crowd along the right side of the roadway while trying to avoid contact with the CLRS *(14).*
- Safety concerns when traversing over rumble strips, particularly along the shoulder *(13,14,15).*
- Reduction of the rideable width of the shoulder due to improper placement of SRS *(16).*

Attempts have been made to develop rumble strip configurations that are more bicycle-friendly *(13,14,15)*. Continuous sections of 40 to 60 ft have been recommended *(13,14)* with a gap spacing of 12 ft *(13)* and a corrugation depth of 0.375 – 0.4 inches *(14,15)* with 6-inch spacings between corrugations *(15)*. A usable paved shoulder width of 4 ft has also been recommended *(33)*.

Noise Impacts

Although rumble strips provide benefits to roadway safety, the noise produced by vehicles contacting the rumble strips may be undesirable for local residents. Previous research has investigated the exterior roadside noise produced by rumble strips utilizing the controlled pass-by method *(17,18)*. The controlled pass-by method measures the A-weighted decibels (dBA) generated by passes of a test vehicle traveling at a known speed past a noise meter located 5 feet above the roadway, and within a distance of 100 feet of the roadway, based on the Federal Highway Administrations (FHWA) guidelines for measuring highway related noise *(34)*. Past research using the controlled pass-by method has consistently shown a marked increase in decibels when vehicles make contact with rumble strips. Collectively, previous research found increases in roadside noise ranging from 3 to 12 dBA when a vehicle travels over the rumble strip compared to instances where no rumble strip contact is made. Higher vehicle speeds result in larger increases in exterior noise. It was also shown that vehicle type has an effect on exterior noise level; heavier vehicles produce higher level of noise.

Conclusions

Collectively, results from previous research have allowed for the following conclusions pertaining to the effectiveness of shoulder and centerline rumble strips:

- Shoulder rumble strip effectiveness
    - Single vehicle run-off-the-road crashes are reduced
    - Drivers are less likely to encroach onto the shoulder
    - Drivers are more likely to position themselves away from the shoulder in the presence of SRS
    - Much of the research has been conducted on freeways, with some research on non-freeway locations.

- Centerline rumble strip effectiveness
    - Evaluation of several pilot installation in many states have shown evidence of a reduction in cross-centerline crashes, including head-on and sideswipe opposite type of crashes
    - Drivers are less likely to encroach onto the centerline in the presence of CRS
    - Drivers are more likely to position themselves away from the centerline
    - An evaluation of a limited sample of forced passing maneuvers in Texas showed negligible impact on passing maneuvers
    - Behavioral impacts associated with centerline and shoulder rumble strips used in combination on non-freeways require further study
    - Crash effectiveness requires a comprehensive evaluation as only pilot installations have been evaluated.
- Impact on bicyclists
    - No evidence exists of increases in bicycle-involved crashes associated with centerline and/or shoulder rumbles strips
    - Prior research suggests the following rumble strip dimensions allow for safe maneuverability for bicyclists:
        - Rumble strip sections of 40 to 60 ft followed by a gap spacing of 12 ft
        - Corrugation depths of 0.375 – 0.4 in, spaced 6-inches on center
        - A minimum usable paved shoulder width of 4 ft
    - Concerns from bicyclists have suggested the need for further study on behavior of motorists while passing bicyclists positioned along on the edge of the roadway or within the shoulder.
- Roadside noise impacts
    - Prior research using controlled pass-by test vehicles have consistently shown an increase ranging from 3 to 12 decibels of noise when the vehicle travels over the rumble strip, compared to instances where no contact is made rumble strips
    - High speeds yield larger increases in roadside noise when contact occurs with rumble strips
    - Additional research is needed to investigate roadside noise impacts associated with varying depths of rumble strip corrugations.

III. IMPACT OF RUMBLE STRIPS ON NON-FREEWAY HIGHWAYS IN MICHIGAN

This research consists of a number of independent studies, which collectively are part of the comprehensive effectiveness evaluation of the MDOT non-freeway rumble strip installation program. Each study tests a different aspect of safety and operational consequences related to their installation on high-speed non-freeways.

The following sections present a number of studies that address the study objectives presented earlier. Each of these studies includes background information such as a review of prior research, field study where applicable, description and methods used in data collection, analysis, statistical testing, and conclusions.

GIS Map

A GIS map was developed using ArcGIS based on non-freeway rumble strip installation information provided by MDOT that included installations occurring between 2008 and 2010 as a part of the annual restriping contracts in addition to installations associated with new construction or repaving projects. The rumble strip installation segments were mapped in ArcGIS based on Physical Road (PR) codes along with the approximate begin and end milepoints that were provided by various MDOT Transportation Service Centers (TSC) or regional offices. The rumble strip installations were color-coded based on the rumble strips installation year, and were overlaid onto the geocoded MDOT roadway base map. The map depicting MDOT's non-freeway rumble strip installations performed between 2008 and 2010 is shown in Figure 2. Note that the map only includes installation information that was provided to the research team by MDOT and was not verified through field inspection by the research team.

It is important to note that a small number of offices did not report their CLRS and SRS installation mileages and route descriptions, or provided inconsistent or inaccurate information. Nevertheless, a geocoded database was established for a total of 5,326 miles of non-freeway highway segments, which is only slightly less than the approximately 5,400 miles of high-speed non-freeway highway segments that are typically reported by MDOT as possessing CLRS. The GIS database is included through a link (https://docs.wayne.edu/4fad86f4e3191/) for further use and updating, as additional data became available.

Figure 2. Non-Freeway Rumble Strip Installations Reported by MDOT for 2008–2010

IV. DRIVER BEHAVIOR AND PERFORMANCE STUDY

While past research has provided substantial evidence that shoulder rumble strips *(19,20,21,22,24)* and centerline rumble strips *(24,32,25)* provide significant reductions in targeted lane departure crashes on two-lane roadways by as much as 15 percent and 30 percent, respectively *(24)*, work has been limited with respect to the relative difference in safety performance between roadways with both as compared to CLRS-only. More broadly, there is limited literature focused on the impacts of rumble strips on driver behavior characteristics that contribute to the relevant target crash reductions on two-lane roadways.

This research aims to gain important insight into these issues by assessing the impacts of centerline rumble strips on driver behavior characteristics related to lane departure crashes, including vehicular lateral placement within the travel lane, edgeline encroachments, and centerline encroachments *(3)*. Such MOEs have been utilized in past research to evaluate the driver behavior impacts of rumble strips installed on rural undivided highways *(5,6)*. These MOEs have also been previously utilized to evaluate other lane departure treatments, such as post-mounted delineators, chevrons, wider and/or brighter pavement markings, and retro reflective raised pavement markers *(35,9,10,11).* Indication of any behavioral improvements generally provide preliminary evidence to potential safety impacts, in addition to providing insight into changes in driver behavior that often contribute to the targeted safety improvements. Also of interest is the determination of potential impacts that may be caused by the existence of rumble strips, such as a reduction in passing attempts, which often lowers the risk associated with passing-related crashes.

A “Before” and “After” evaluation study was initiated in June 2010, prior to completion of the rumble strip installations included in the MDOT program. The specific objectives of this study were to assess the impact of centerline and shoulder rumble strips on:

- Vehicular lateral placement within the travel lane,
- Vehicular encroachment onto or over the centerline or edgeline, and
- Attempted passing maneuvers.

Field Study

A “Before” and “After” (B&A) field study was performed to assess the impacts of CLRS and SRS on driver behavior along a rural two-lane highways in Michigan. The study segments included both horizontal curves and tangent sections, with and without passing zones. The following driver performance characteristics were captured during the field study:

- Vehicular lateral placement in the travel lane,
- Encroachments onto or across the centerline,
- Encroachments onto or across the edgeline,
- Passing attempts, and
- Aborted passing attempts.

Ten roadway segments were selected for use. The segments were selected from the statewide population of two-lane rural highways with 55 mph speed limits where rumble strips were scheduled for installation during late summer 2010. The segments were evenly split between locations where both centerline and shoulder rumble strips were to be installed and sites where only centerline rumble strips were to be installed. The average daily traffic volumes at the 10 study segments ranged from 1,500 to 6,000 vehicles per day.

Prior to data collection, a preliminary investigation was performed along each roadway segment to identify at least one location where passing was permitted in both directions of travel, and one horizontal curve location that was suitable for field data collection. A total of 18 passing zone locations and 12 horizontal curve locations were selected for data collection from the segments. The characteristics of the roadways and the number of specific data collection locations are presented in Table 1.

Table 1. Roadway Site Characteristics

RUMBLE STRIPS INSTALLED	HIGHWAY	LANE WIDTH (FT)	PAVED SHOULDER WIDTH (FT)	AVERAGE DAILY TRAFFIC (2009)	NUMBER OF DATA COLLECTION LOCATIONS	
CENTERLINE AND SHOULDER	M-19 - Site 1	12	6	5,500	Passing Zones	3
					Curves	2
	M-25	12	8	3,300	Passing Zones	2
	M-136 - Site 2	11	8	6,000	Passing Zones	1
	US-41 - Site 1	12	8	4,100	Passing Zones	1
					Curves	1
	US-41 - Site 2	12	8	4,500	Passing Zones	1
					Curves	1
CENTERLINE	M-19 - Site 2	11	3	5,300	Passing Zones	1
					Curves	3
	M-46	11	3	4,900	Passing Zones	2
	M-136 - Site 1	11	3	1,500	Passing Zones	3
					Curves	2
	M-93	12	5	2,900	Passing Zones	1
					Curves	2
	M-81	12	3	4,800	Passing Zones	3
					Curves	1

Note: Rumble strips were not present in the "Before" period at any of the locations.

Data Collection

Video data were collected at the study sites both before and after installation of the rumble strips. "Before" period data were collected between June 2010 and August 2010. Data were again collected at the same locations in November 2010 and/or May - June 2011 after, the rumble strips had been installed for a minimum of 30 days during normal weekdays. All data were collected during daylight hours under dry pavement conditions. Geometric data, including lane width, shoulder width, lateral offset of the rumble strips from the centerline and/or shoulder, and the rumble strip dimensions were measured at each field sites.

Elevated high definition video cameras were installed on existing roadside poles at each study site to stealthily record the behavior of vehicles traveling through the study roadway segments. Each camera was mounted on top of a lightweight aluminum pole that telescoped from 7 to 20 feet and securely strapped to a rigid roadside sign post or a utility post. Between four and ten hours of video were typically recorded at each location during the "Before" and "After" data collection periods.

A single camera setup was utilized at the curve locations and was mounted in a position that maximized the field-of-view of vehicles traveling through the curve and the adjacent tangent segment of the highway. The maximum clear viewing distance along a roadway for a single camera location was approximately 1,000 feet. The passing zone locations utilized two cameras mounted at the same telescopic pole location, but the cameras were aimed in the opposite directions. The two-camera setup doubled the effective viewing distance and greatly increased the likelihood of capturing all passing events. Examples of the video camera setups for both passing zones and curve locations are shown in Figure 3. These camera setups on existing roadside posts created a concealed environment to capture driver behavioral data and retrieve quality data for verification.

a. Passing Zone (two cameras in opposing directions) **b. Curve (single camera aimed towards curve)**

Figure 3. Typical Elevated Video Camera Setup

Extraction of Driver Behavioral Performance Data

After completion of the field data collection, videos were manually reviewed using Quicktime video players by a team of trained researchers to assess various characteristics of driver behavior. Each vehicle was monitored through the entire field-of-view of the camera(s). Behavioral characteristics that were collected for each observed vehicle depending on whether the location was a passing zone or a horizontal curve location.

Passing Zones

Videos recorded 18 passing zone sites and were reviewed to capture various driver behavioral characteristics related to passing maneuvers by vehicles traveling through each study site. Synchronization of the time clocks between the two cameras used in each passing zone setup simplified the review process by allowing vehicles to be continuously tracked between the two. During a review of the dual-camera passing zone videos, several important characteristics were assessed, that included:

- Type of vehicle (passenger vehicle, truck/RV/bus, motorcycle)
- Direction of travel
- Was the vehicle within 150 ft of the previous vehicle (i.e., in passing position)?
- Was a pass attempted?
- Was the pass aborted?

Vehicles were considered to be in a position to pass if they were within 150 ft of the previous vehicle. For vehicles traveling at 55 mph, a 150 ft following distance represents an approximately two second headway between the leading vehicle and the following vehicle. The distance between successive vehicles was estimated based on the number of centerline skip pavement markings, which were installed at 50 ft intervals per MDOT standard.

A passing attempt was defined as a vehicle that crossed the centerline and began to overtake another vehicle that was traveling within the same lane and same direction. Aborted passing attempts were defined as cases where a vehicle initially touched or crossed over the centerline while attempting to overtake another vehicle, but moved back into the original lane without completing the passing maneuver. It was not possible to distinguish and subsequently exclude unintentional shifts that resulted in contact with the centerline. Figures 4 a-b, page 17, show an example of the vehicular assessments performed during the data extraction of the passing zone videos.

Curves and Adjacent Tangent Sections

The videos recorded at the 12 horizontal curve locations were reviewed to assess the lateral lane position and encroachments onto or over the centerline and edgeline for each vehicle. The type and travel direction for each vehicle was recorded, as well as whether the vehicle was traveling through a curve to the left or curve to the right. Figures 4 c-d, page 18, show an example encroachment and lateral position assessment.

The lateral position of each vehicle was assessed at the apex of the curve and at the tangent section adjacent to the curve. Each vehicle was assessed at the same location for curve or tangent section in the "Before" and "After" periods. It was occasionally not possible to assess the lateral position of a given vehicle in both the curve and adjacent tangent, resulting in a slight imbalance between the number of vehicular observations for the curve and tangent data sets.

The lateral placement position was assessed based on the center of the vehicle with respect to the center of the travel lane. A vehicle was considered centered unless the vehicle had shifted to the left or right of the center of the lane by more than approximately 6-inches. The vehicle's license plate was often used as a reference point to assess lateral placement position. This data extraction procedure was used in a vehicular lateral placement evaluation for work zones *(36)* and other similar research.

Each vehicle was monitored to determine if a centerline or edgeline encroachment occurred at any point along the visible portion of the tangent section or curve section. Encroachments were categorized based on whether the vehicle's near tire either touched or completely crossed over the centerline or edgeline at the most extreme point. Tangent encroachments and curve encroachments were counted separately for each vehicle traveling through the study section.

a. Passing Position **b. Passing Attempt**

Figure 4. Example Driver Behavior Assessment

c. Centerline Encroachment (Curve) **d. Lateral Lane Placement Assessment (Tangent)**

Figure 4. Example Driver Behavior Assessment (Continued)

Measures of Effectiveness and Statistical Analysis

Several MOEs were utilized to quantify driver behavioral characteristics in the presence and absence of rumble strips, which included:

- Passing Maneuvers
  - Percent of vehicles that attempted a passing maneuver;
  - Percent of vehicles that were in a position to pass and attempted a passing maneuver;
  - Percent of vehicles that aborted a passing maneuver after an initial attempt;

- Lateral Position within Travel Lane
  - Percent of vehicles centered in the lane;
  - Percent of vehicles in the right lane position;
  - Percent of vehicles in the left lane position;

- Encroachments
  - Percent of vehicles encroaching onto or across the centerline; and
  - Percent of vehicles encroaching onto or across the edgeline.

Each of the MOEs were expressed as dichotomous rates of occurrence, and as such, two sample z-tests of proportions were utilized to determine the statistical significance of change in the MOEs between the "Before" and "After" rumble strip installation periods. Two-tailed tests were utilized for all statistical testing and the null hypothesis for all tests was that the rumble strips produced no change in the MOE. The lateral position and encroachment MOEs were analyzed both separately by vehicle type and overall for curves to the left, curves to the right, and tangent sections. MOEs related to passing maneuvers were analyzed independently by site and overall.

Since several hypothesis tests were performed simultaneously on the same family of data for each MOE, it was necessary to apply a multiple comparison correction to correct for errors in inference that may occur *(37)*. The Bonferroni Multiple Comparison Correction was utilized in the analyses for this study as it is a conservative method of correcting erroneous rejection of the null hypothesis based on chance alone that is typically encountered during individual testing of several hypotheses from the same family of data. The Bonferroni Correction assumes the selected significance level, 100-α (percent), to relate to inference on the family of data, where α is the selected probability of Type 1 error for the entire family of data. The corresponding significance level used for each individual hypothesis test is equal to "(100-α)/n" (percent), where "n" is the number of simultaneous tests being performed per MOE (e.g., one test for each of the individual study locations plus one overall test). Critical z-values (or t-values) for rejection of the null hypothesis were determined accordingly from the standard normal probability table.

Results of Driver Behavioral Study

Passing Maneuvers

Review of the passing zone videos yielded a total of 39,664 and 38,094 vehicles in the "Before" and "After" periods, respectively. A total of 1,188 passing attempts were observed, which included 620 during the "Before" period and 568 during the "After" period. Twenty-seven (27) of these passing attempts were aborted that included 14 in the "Before" period and 13 in the "After" period. The descriptive statistics resulting from review of the passing zone videos are shown in Table 2.

Table 2. Descriptive Statistics for Passing Maneuvers

DATA COLLECTION LOCATION	TOTAL OBSERVATION TIME (HRS)		TOTAL NO. OF VEHICLES OBSERVED		NO. OF VEHICLES IN PASSING POSITION		TOTAL PASSING ATTEMPTS		ABORTED PASSING ATTEMPTS	
	Before	After	Before	After	Before	After	Before	After	Before	After
M-136 - Site 1, PZ 1	5.0	9.3	588	1,103	56	79	19	21	0	0
M-136 - Site 1, PZ 2	6.4	5.5	2,657	1,581	392	158	23	18	0	2
M-136 - Site 1, PZ 3	5.9	8.6	767	1,193	52	71	10	15	0	0
M-136 - Site 2, PZ 1	5.1	7.6	2,403	3,527	460	565	22	18	2	0
M-19 - Site 1, PZ 1	4.7	8.6	1,926	2,684	375	456	19	30	0	1
M-19 - Site 1, PZ 2	4.6	7.8	1,811	2,513	299	419	25	38	1	2
M-19 - Site 1, PZ 3	8.4	8.6	3,037	2,636	542	438	57	57	4	2
M-19 - Site 2, PZ 1	6.2	8.8	1,920	3,016	373	427	42	34	1	2
US-41 - Site 1, PZ 1	6.5	10.0	1,661	2,508	197	318	7	21	0	1
US-41 - Site 2, PZ 1	3.9	7.9	1,011	2,498	138	393	13	36	0	1
M-93 - PZ 1	8.2	9.3	1,935	1,835	162	133	15	21	0	1
M-46 - PZ 1	9.4	2.2	3,258	608	545	91	67	13	0	0
M-46 - PZ 2	9.0	7.1	3,166	2,352	445	297	20	15	0	0
M-25 - PZ 1	6.4	8.3	2,436	2,150	408	321	41	60	1	0
M-25 - PZ 2	5.3	8.6	2,730	2,530	553	356	34	43	0	1
M-81 - PZ 1	8.7	7.4	2,728	1,915	457	331	113	46	2	0
M-81 - PZ 2	8.4	2.1	3,151	653	484	65	48	6	2	0
M-81 - PZ 3	7.3	8.4	2,479	2,782	353	464	45	76	1	0
TOTAL	**119.4**	**136.0**	**39,664**	**38,084**	**6,291**	**5,382**	**620**	**568**	**14**	**13**

A summary of the results of the statistical analyses for the MOEs related to passing maneuvers is presented in Table 3. The overall percent of vehicles attempting a passing maneuver decreased slightly from 1.56 percent to 1.49 percent after the rumble strips had been installed.

Table 3. Statistical Analysis Results for Passing-Related MOEs

DATA COLLECTION LOCATION	TOTAL PASSING ATTEMPTS AS % OF TOTAL VEHICLES			TOTAL PASSING ATTEMPTS AS % OF VEHICLES IN PASSING POSITION			ABORTED PASSING ATTEMPTS AS % OF TOTAL PASSING ATTEMPTS		
	Before	**After**	**Significant Difference?**	**Before**	**After**	**Significant Difference?**	**Before**	**After**	**Significant Difference?**
M-136 - Site 1, PZ 1	3.23%	1.90%	No	33.93%	26.58%	No	0.00%	0.00%	No
M-136 - Site 1, PZ 2	0.87%	1.14%	No	5.87%	11.39%	No	0.00%	11.11%	No
M-136 - Site 1, PZ 3	1.30%	1.26%	No	19.23%	21.13%	No	0.00%	0.00%	No
M-136 - Site 2, PZ 1	0.92%	0.51%	No	4.78%	3.19%	No	9.09%	0.00%	No
M-19 - Site 1, PZ 1	0.99%	1.12%	No	5.07%	6.58%	No	0.00%	3.33%	No
M-19 - Site 1, PZ 2	1.38%	1.51%	No	8.36%	9.07%	No	4.00%	5.26%	No
M-19 - Site 1, PZ 3	1.88%	2.16%	No	10.52%	13.01%	No	7.02%	3.51%	No
M-19 - Site 2, PZ 1	2.19%	1.13%	No	11.26%	7.96%	No	2.38%	5.88%	No
US-41 - Site 1, PZ 1	0.42%	0.84%	No	3.55%	6.60%	No	0.00%	4.76%	No
US-41 - Site 2, PZ 1	1.29%	1.44%	No	9.42%	9.16%	No	0.00%	2.78%	No
M-93 - PZ 1	0.78%	1.14%	No	9.26%	15.79%	No	0.00%	4.76%	No
M-46 - PZ 1	2.06%	2.14%	No	12.29%	14.29%	No	0.00%	0.00%	No
M-46 - PZ 2	0.63%	0.64%	No	4.49%	5.05%	No	0.00%	0.00%	No
M-25 - PZ 1	1.68%	2.79%	No	10.05%	18.69%	Yes	2.44%	0.00%	No
M-25 - PZ 2	1.25%	1.70%	No	6.15%	12.08%	Yes	0.00%	2.33%	No
M-81 - PZ 1	4.14%	2.40%	Yes	24.73%	13.90%	Yes	1.77%	0.00%	No
M-81 - PZ 2	1.52%	0.92%	No	9.92%	9.23%	No	4.17%	0.00%	No
M-81 - PZ 3	1.82%	2.73%	No	12.75%	16.38%	No	2.22%	0.00%	No
TOTAL	**1.56%**	**1.49%**	**No**	**9.86%**	**10.55%**	**No**	**2.26%**	**2.29%**	**No**

Note: Statistical significance was assessed based on a 95 percent confidence level using a Bonferroni corrected critical z-score of ± 3.00.

As shown in Table 3, the total passing attempts were also not found to change significantly when analyzed as a percent of vehicles in a position to pass. Similarly, no statistically significant changes were found in the rate of aborted passing attempts. Overall, passing maneuvers were aborted in 2.26 percent of all passing attempts before rumble strip installation and 2.29 percent of all passing attempts after rumble strip installation.

Lateral Lane Position

Review of the videos from the curve locations yielded a total of 30,202 and 20,673 vehicles in the "Before" and "After" periods, respectively. The lateral lane position data were aggregated based on the types of rumble strips installed, geometry, and vehicle type. The results of the vehicular lateral lane position analysis are shown in Tables 4 and 5 for locations with CLRS-only and CLRS and SRS, respectively.

Table 4. Vehicular Lateral Lane Position Results by Geometry and Type of Vehicle – Locations with CLRS Only

	VEHICLE TYPE	TOTAL NO. OF VEHICLES OBSERVED		% LEFT OF CENTER			% CENTERED IN LANE			% RIGHT OF CENTER		
		Before	After	Before	After	% Change	Before	After	% Change	Before	After	% Change
TANGENTS	Passenger	19,499	11,749	22.1%	18.5%	-16.3%*	36.5%	48.8%	33.8%*	41.4%	32.7%	-21.0%*
	Truck/Bus/RV	996	603	17.0%	15.4%	-9.1%	33.6%	44.1%	31.2%*	49.4%	40.5%	-18.1%*
	Motorcycle	384	143	42.7%	41.3%	-3.4%	34.1%	32.2%	-5.7%	23.2%	26.6%	14.7%
	ALL	**20,879**	**12,495**	**22.3%**	**18.6%**	**-16.3%***	**36.3%**	**48.4%**	**33.3%***	**41.4%**	**33.0%**	**-20.4%***
LEFT CURVES	Passenger	11,327	6,489	41.1%	19.0%	-53.7%*	33.0%	55.7%	68.5%*	25.8%	25.3%	-2.2%
	Truck/Bus/RV	560	348	31.3%	21.3%	-32.0%*	33.8%	47.1%	39.6%*	35.0%	31.6%	-9.7%
	Motorcycle	219	82	51.1%	41.5%	-18.9%	35.2%	28.0%	-20.2%	13.7%	30.5%	122.6%*
	ALL	**12,106**	**6,919**	**40.8%**	**19.4%**	**-52.5%***	**33.1%**	**54.9%**	**65.9%***	**26.1%**	**25.7%**	**-1.5%**
RIGHT CURVES	Passenger	8,175	5,230	6.1%	6.7%	9.3%	24.5%	45.4%	85.1%*	69.4%	47.9%	-30.9%*
	Truck/Bus/RV	434	259	5.3%	11.2%	111.3%	23.0%	45.6%	97.7%*	71.7%	43.2%	-39.7%*
	Motorcycle	165	57	18.2%	26.3%	44.7%	37.0%	40.4%	9.1%	44.8%	33.3%	-25.7%
	ALL	**8,774**	**5,546**	**6.3%**	**7.1%**	**12.6%**	**24.7%**	**45.3%**	**83.7%***	**69.0%**	**47.6%**	**-31.1%***

* Statistically significant at 95 percent confidence level based on a Bonferroni corrected critical z-score of ± 2.86
Note: The before-and-after percent change was computed as follows: (A-B)/B X 100%

Table 5. Vehicular Lateral Lane Position Results by Geometry and Type of Vehicle – Locations with CLRS and SRS

	VEHICLE TYPE	TOTAL NO. OF VEHICLES OBSERVED		% LEFT OF CENTER			% CENTERED IN LANE			% RIGHT OF CENTER		
		Before	After	Before	After	% Change	Before	After	% Change	Before	After	% Change
TANGENTS	Passenger	8,567	7,560	32.8%	9.7%	-70.3%*	34.9%	68.5%	96.6%*	32.4%	21.7%	-32.9%*
	Truck/Bus/RV	603	559	30.2%	7.0%	-76.9%*	35.7%	71.0%	99.2%*	34.2%	22.0%	-35.6%*
	Motorcycle	145	59	49.0%	20.3%	-58.5%*	35.9%	72.9%	103.2%*	15.2%	6.8%	-55.3%
	ALL	**9,315**	**8,178**	**32.9%**	**9.6%**	**-70.7%***	**34.9%**	**68.7%**	**96.8%***	**32.2%**	**21.6%**	**-32.9%***
LEFT CURVES	Passenger	5,516	4,644	19.9%	4.4%	-78.0%*	33.9%	72.5%	113.7%*	46.1%	23.1%	-49.9%*
	Truck/Bus/RV	375	337	14.1%	3.6%	-74.8%*	32.0%	73.9%	130.9%*	53.9%	22.6%	-58.1%*
	Motorcycle	110	38	42.7%	28.9%	-32.3%	30.9%	63.2%	104.3%*	26.4%	7.9%	-70.1%
	ALL	**6,001**	**5,019**	**20.0%**	**4.5%**	**-77.4%***	**33.8%**	**72.5%**	**114.9%***	**46.2%**	**22.9%**	**-50.4%***
RIGHT CURVES	Passenger	3,055	2,915	20.3%	1.9%	-90.7%*	35.1%	66.8%	90.3%*	44.6%	31.3%	-29.7%*
	Truck/Bus/RV	227	208	37.4%	0.5%	-98.7%*	26.4%	75.0%	183.8%*	36.1%	24.5%	-32.1%
	Motorcycle	39	21	17.9%	4.8%	-73.5%	46.2%	85.7%	85.7%*	35.9%	9.5%	-73.5%
	ALL	**3,321**	**3,144**	**21.5%**	**1.8%**	**-91.6%***	**34.6%**	**67.5%**	**94.8%***	**43.9%**	**30.7%**	**-30.0%***

* Statistically significant at 95 percent confidence level based on a Bonferroni corrected critical z-score of ± 2.86
Note: The before-and-after percent change was computed as follows: (A-B)/B X 100%

It can be observed from Tables 4 and 5 (page 22) that the presence of rumble strips had a statistically significant impact on the lateral lane position of vehicles in both curve and tangent sections. In general, vehicles tended to be more centrally positioned within the lane when rumble strips were present as drivers tended to shy away from both the centerline and the edgeline. This was especially evident for locations with both as the percent of vehicles positioned in the center of the lane approximately doubled in both curve and tangent sections after rumble strip installation. Although central lane positioning was found to increase after rumble strip installation for locations with centerline rumble strips only, the increases were of a lower magnitude and less consistent compared to locations with both centerline and shoulder rumble strips.

The results were found to vary somewhat based on vehicle type. Both passenger vehicles and large vehicles such as trucks, buses, and RVs showed significant increases in center lane positioning when rumble strips were present – particularly at locations where both centerline and shoulder rumble strips were present. Large vehicles showed the greatest changes in lateral position when rumble strips were present, particularly on curves to the right as the percent of vehicles positioned in the center doubled at locations where only centerline rumble strips were installed and nearly tripled where both were installed. The central lane positioning tendencies of motorcyclists were improved by the presence of rumble strips only at locations where both centerline and shoulder rumble strips were installed. The presence of centerline rumble strips alone did not significantly impact the lane position of motorcyclists.

Encroachments

Centerline and edgeline encroachments were assessed within the curve and along the adjacent tangent section for each vehicle observed during review of the curve videos. Only locations where both SRS were installed between the "Before" and "After" periods were included in the assessment of edgeline encroachments. Similar to the lateral lane position data, the encroachment data were aggregated based on geometry and vehicle type. The results of the encroachment analysis are shown in Table 6.

Table 6. Encroachment Results by Geometry and Type of Vehicle

	VEHICLE TYPE	% ENCROACHING ONTO OR ACROSS EDGELINE			% ENCROACHING ONTO OR ACROSS CENTERLINE		
		Before	After	% Change	Before	After	% Change
TANGENTS	Passenger	9.1%	5.4%	-41.2%*	1.5%	0.6%	-63.7%*
	Truck/Bus/RV	27.7%	31.0%	11.8%	2.0%	1.4%	-31.2%
	Motorcycle	0.0%	0.0%	0.0%	0.8%	1.0%	30.9%
	ALL VEHICLES	**10.5%**	**6.6%**	**-37.1%***	**1.5%**	**0.6%**	**-60.7%***
LEFT CURVES	Passenger	11.2%	3.7%	-67.2%*	12.0%	1.3%	-88.8%*
	Truck/Bus/RV	36.7%	26.5%	-27.9%	13.6%	4.1%	-69.9%*
	Motorcycle	0.0%	0.0%	0.0%	3.3%	0.0%	-100.0%
	ALL VEHICLES	**13.2%**	**4.5%**	**-65.7%***	**11.9%**	**1.5%**	**-87.5%***
RIGHT CURVES	Passenger	10.3%	5.4%	-47.5%*	0.5%	0.4%	-28.6%
	Truck/Bus/RV	28.8%	27.1%	-6.0%	1.8%	1.1%	-41.0%
	Motorcycle	0.0%	0.0%	0.0%	0.5%	0.0%	-100.0%
	ALL VEHICLES	**11.6%**	**6.6%**	**-43.7%***	**0.6%**	**0.4%**	**-31.4%**

* Statistically significant at 95 percent confidence level based on a Bonferroni corrected critical z-score of ± 2.86
Note: Only locations where SRS were installed between the "Before" and "After" periods were included in the assessment of edgeline encroachments. The before-and-after percent change was computed as follows: (A-B)/B X 100%

It can be observed from Table 6 that the presence of rumble strips had a statistically significant reduction in both centerline and edgeline encroachments in curve and tangent sections. The greatest reduction in centerline encroachments were observed within curves to the left as encroachments reduced from 11.9 percent to 1.5 percent. Similarly, the greatest reduction in edgeline encroachments were observed within curves to the right as encroachments were reduced from 11.6 percent to 6.6 percent. These findings suggest that rumble strips tend to reduce the tendencies for drivers to laterally shift to the inside (i.e., "corner cutting") while maneuvering through curves. Both centerline and edgeline encroachments were also reduced in tangent sections.

The encroachment results were found to vary based on vehicle type. Passenger vehicles showed consistent and significant reductions in both centerline and edgeline encroachments after the installation of rumble strips for nearly all geometric conditions. Large vehicles showed mostly marginal decreases in encroachments after the rumble strips were installed, although centerline encroachments were significantly reduced on curves to the left. Encroachments by motorcyclists onto the centerline and particularly the edgeline were rare and were not significantly impacted by the presence of rumble strips.

Major encroachments across the centerline decreased significantly after installation of rumble strips for both tangent sections and curves to the left. Major centerline encroachments were not impacted by rumble strips for curves to the right. Summaries of all data related to this study are included in Appendices I and II.

V. STUDY OF VEHICLE LATERAL PLACEMENT CHARACTERISTICS IN PRESENCE OF BICYCLISTS

Rumble strips have been installed in many states, including Michigan, as a countermeasure on the shoulders of high-speed roads and highways for reducing run-off-the-road crashes. Several studies have shown that continuous shoulder rumble strips can significantly reduce such crashes *(19,20,21,22)*, with a recent National Cooperative Highway Research Program (NCHRP) Report estimating a 21 percent reduction in run-off-the-road crashes on rural freeways *(38)*. In more recent years, rumble strips have been installed along the centerline of two-lane highways, where they have been shown to reduce cross-centerline crashes *(32,25)*. Other research has demonstrated positive impacts of rumble strips with respect to driver behavioral measures, such as motor vehicle lateral placement *(5,6,39)*.

While crash and driver behavioral metrics generally support use of both shoulder and centerline rumble strips, there are several potential concerns associated with their use. Recent technical advisories issued by the Federal Highway Administration *(40,41)* list three potential adverse impacts of rumble strips: (1) noise to adjacent residents, (2) bicycle compatibility, and (3) maintenance issues. While some research has been conducted with respect to safety issues associated with bicycle traffic on highways with shoulder rumble strips *(42,13,14,15)*, research related to the effects of centerline rumble strips on bicycle safety is minimal.

Bicyclists tend to ride on paved shoulders rather than in the travel lane when possible as this provides a safety buffer and allows for convenient overtaking by faster-moving motor vehicles. However, the rideable area can sometimes be reduced due to debris that has collected on the edge of the pavement. It is further limited when shoulder rumble strips are installed, sometimes forcing bicyclists to travel over the rumble strips. While contact with rumble strips may not cause the bicyclist to lose control, vibrations produced can be uncomfortable to the rider *(42)*. This effect may cause some bicyclists to ride in the travel lane, potentially increasing their safety risk.

Several past studies have attempted to develop rumble strip configurations that are tolerable for the bicyclists *(13,14,15)*. An Arizona study sought to identify the optimum spacing of gaps in continuous shoulder rumble strips that would allow bicyclists to cross between the shoulder and travel lane without riding over the rumble strips *(13)*. The study recommended gap spacing of 12 ft, with gaps located after continuous rumble strip sections of 40 or 60 ft. A Colorado study evaluated three different rumble strip installation configurations using rideability ratings provided by a group of bicyclists who each individually traversed the rumble strips *(14)*. The study concluded that the typical milled application, with a depth of 0.375 inches and a 60-ft continuous section length, was the optimal design for both bicycle and motor vehicle safety. A Pennsylvania study utilized a simulation model to evaluate rumble strip configurations for their potential to be bicycle-tolerable *(15)*. Configurations with the greatest potential were then installed on a test track for field evaluation to rank bicycle ride quality and the ability to alert motorists. The study resulted in recommended configurations for use on non-freeway segments. For segments with operating speeds of 55 mph and above, this configuration included a groove width of 5 inches and a depth of approximately 0.4 inches, with a 6-inch flat portion between the cuts.

Driver Behavior in the Presence of Bicyclists

Several studies have examined interactions between motor vehicles and bicycles on shared use facilities *(43,33)*. One such study investigated the effects of bicycle lanes on motor vehicle and bicycle lateral placement, concluding that the separation distance between bicycles and motor vehicles was related to the amount of total travel space available and was not a function of the presence of a bike lane *(43)*. A Florida Department of Transportation study *(33)* determined that average motorists attempt to keep their vehicles 5.9 ft to 6.4 ft lateral separation distance from the bicyclists as they perform a passing maneuver.

In the case of rumble strips, *NCHRP Synthesis 339* reported that bicyclists in Colorado, Pennsylvania, and Wyoming complained of being crowded to the right side of the roadway by motor vehicles trying to avoid contact with the centerline rumble strips *(25)*.

Field Study

In order to evaluate the driver behavior in the presence of bicyclists, a field study was conducted on Michigan Highway 109 (M-109), shown in Figure 5. It is a two-lane rural section of MDOT trunkline in the northwestern Lower Peninsula and serves as a popular bicyclist route, particularly during the summer.

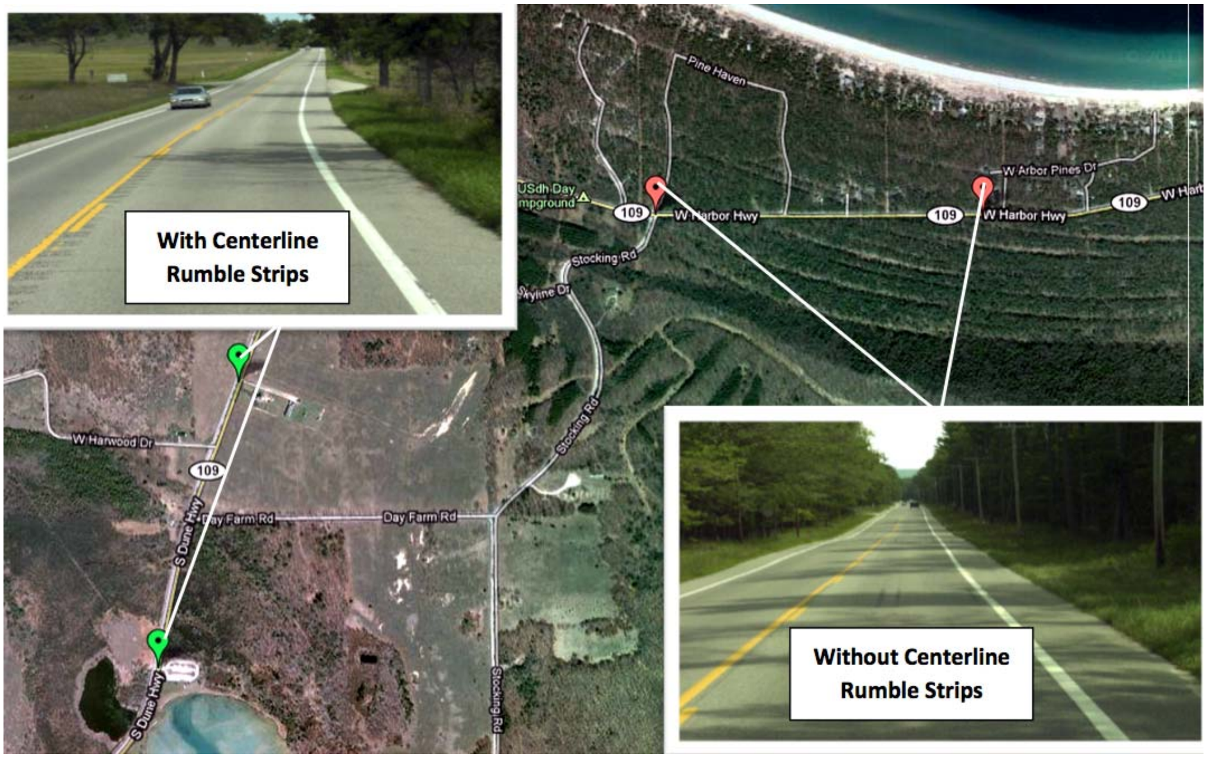


Figure 5. Study Segments

M-109 is unique in that it includes one stretch where there are consecutive segments that are identical, with the exception of centerline rumble strips. This feature creates an appropriate setting for a controlled comparison of driver behavior when passing bicyclists with respect to the presence of centerline rumble strips. Two 0.5-mile long segments of M-109 were selected for the purposes of this field study. These segments were separated by a distance of approximately 1.1 mile distance and were selected to control for two factors: (1) roadway geometry and (2) individual driver behavioral characteristics. Selecting two locations in close proximity to one another, along the same route, allowed for both of these concerns to be addressed in this study. Each segment consisted of a relatively straight, level alignment, with identical posted speed limits (55 mph), lane widths (11 ft), and shoulder widths (4 ft). Neither of the two segments included shoulder rumble strips. Furthermore, given their close proximity, most of the drivers that were observed, passed over both study segments during the analysis period. Centerline rumble strips were installed on the southernmost of these two segments and their presence was the only substantive difference between the two. The centerline rumble strip dimensions were as follows:

- Corrugation depth = 0.4375 in.
- Transverse dimension of corrugation = 16.0 in.
- Longitudinal dimension of corrugation = 7.0 in.
- Gap between corrugations = 5 in.
- Gap between corrugation pairs = 17 in.

Field Data

The principal focus of this study was to determine the impacts of centerline rumble strips on the lateral placement of motor vehicles as they pass bicyclists along two-lane highways. However, there are several key factors that affect lateral placement under such a setting besides the presence or absence of rumble strips. They include the following:

- Lateral placement of nearest bicyclist to travel lane – Bicyclists traveling nearer to, or within, the travel lane are likely to lead to a greater lateral shift by a motor vehicle in comparison to bicyclists traveling farther from the travel lane on the shoulder.

- Number of bicyclists encountered by a passing vehicle – Bicyclists riding in a group may be more conspicuous or elicit a different response from motorists than a bicyclist riding alone.

- Type of motor vehicle – Larger vehicles require greater lane widths and, as such, may tend to shift over further in their lane when encountering a bicyclist.

- Presence of opposing traffic – If traffic is present in the opposing lane, motor vehicles are inhibited from shifting over into that lane and may be forced to crowd an adjacent bicyclist.

As these factors are a function of the bicyclist and driver population interactions, it is difficult to evaluate their impacts solely based upon observations under a natural setting. To address this issue, as a part of this field study, research team members participated as bicyclists, and were assigned one of three specific lateral positions (in the center of the shoulder, on the left edge of the shoulder, on the right edge of the travel lane) for a predetermined amount of time through each study segment. The design allowed for an assessment of the effects of bicyclist lateral position on driver behavior. Additional data were also collected for all other bicyclists who traveled the study segments during this observation period.

In order to assess the lateral placement of each motor vehicle observed, a series of four pole-mounted, high-definition cameras were setup on each side of the roadway throughout each 0.5-mile study segment. These cameras were mounted on top of 20-ft tall poles that were secured to roadside signposts. An example of this elevated camera installation, which has been used previously in a series of field studies of road user behavior *(39,36,44)*, is shown in Figure 6. This data collection method was completely unobtrusive, involved no interaction with road users, and allowed for data collection without influencing driver or bicyclist behavior.

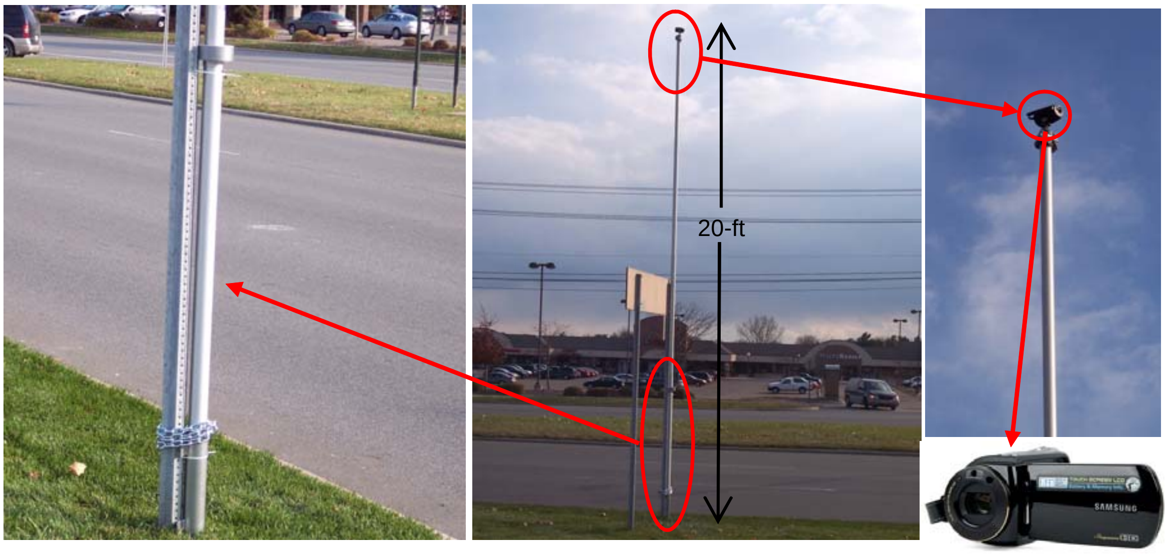


Figure 6. Field Setup for Elevated Video Recording of Road User Behavioral Data

Data were collected during a typical Saturday in summer 2011, as traffic volumes are generally higher in the summer; tend to increase during this time given the scenic nature and attraction of this roadway segment. The weather was comfortable and clear with temperatures in the mid-80's. Pairs of bicyclists from the research team rode continuous loops around each of the study segments. The bicyclists were staggered such that a bicyclist was on each side of the roadway at all times. The ends of each loop were clearly marked on the shoulder in order to provide visual cues for bicyclists during data collection. All bicyclists rode in the prescribed lateral position for approximately one hour before taking a break and continuing in a different lateral position during the subsequent loop. The loops were evenly distributed among three predetermined lateral positions, which included: (1) within the center of the shoulder; (2) on the left edge of the shoulder; and (3) on the right edge of the travel lane. A schematic of the data collection plan is shown in Figure 7.

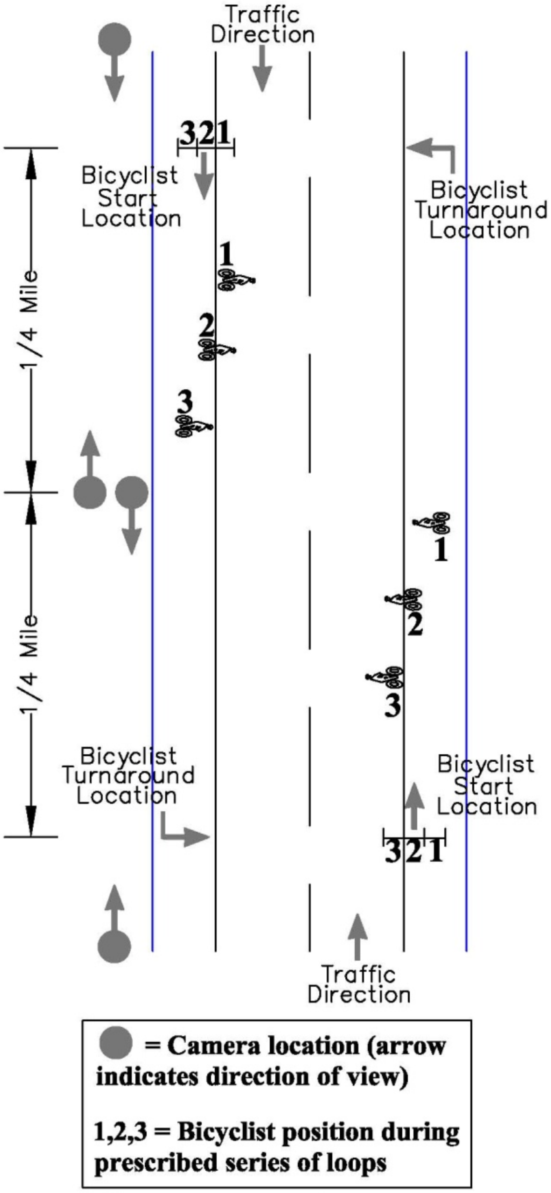


***Diagram not to scale**

Figure 7. Schematic Diagram of Data Collection Plan

After completion of the field data collection, the videos were transferred to a computer for review and data extraction. During the video review, data were randomly checked to ensure continued consistency and precision among observers, as well as compliance with the review protocol. Figure 8 shows an example screenshot from a video review.

Figure 8. Example Screenshot of Video Review

Field data collection was performed under two separate conditions. The first condition of data was collected at both of the segments, one segment with CLRS and the similar segment that did not have CLRS. This was performed with all existing traffic control devices along both of the study segments. Table 7 shows the raw data of the field study without the "Share the Road" sign.

Table 7. Vehicular and Bicycle Volumes – Without Signs – 7/16/11

PERIOD	WITH RUMBLE STRIPS			WITHOUT RUMBLE STRIPS		
	MINUTES	VEHICLES	BICYCLES	MINUTES	VEHICLES	BICYCLES
1	64	196	35	61	160	35
2	64	227	39	65	225	52
3	65	269	47	65	253	59
4	65	276	19	65	249	30
5	65	248	38	65	249	44
TOTAL	**323**	**1216**	**178**	**321**	**1136**	**220**
AVERAGE HOURLY VOLUMES	**-**	**226**	**33**	**-**	**212**	**41**

The second wave of data collection was performed at the same highway locations, however with a "Share the Road" sign installed for both directions of flow in the study segment. Table 8 displays this summary of field data.

Table 8. Vehicular and Bicycle Volumes – With Signs – 8/20/11

PERIOD	WITH RUMBLE STRIPS			WITHOUT RUMBLE STRIPS		
	MINUTES	VEHICLES	BICYCLES	MINUTES	VEHICLES	BICYCLES
1	20	60	4	18	68	1
2	65	302	47	68	257	65
3	66	368	44	68	328	66
4	65	159	41	65	313	41
5	36	218	16	12	58	6
TOTAL	**252**	**1107**	**152**	**231**	**1024**	**179**
AVERAGE HOURLY VOLUMES	**-**	**264**	**36**	**-**	**266**	**46**

Statistical Analysis for Impacts of CLRS on Vehicular Lateral Positioning When Passing a Bicyclist

A statistical analysis was performed to investigate the impacts on CLRS on the rate at which motor vehicles rode onto or over the centerline while passing a bicyclist. Two measures of effectiveness were considered:

- Percent of vehicles that contacted the centerline when passing a bicyclist
- Percent of vehicles that crossed at least halfway into the opposing lane when passing a bicyclist

Because each of the MOEs were expressed as a dichotomous rate of occurrence (e.g., crossed the centerline vs. did not cross the centerline), a two sample z-test of proportions was utilized to determine the statistical significance of any differences in the MOEs between the two study locations (i.e., segment with CLRS vs. segment without CLRS). The calculated z-statistic for the difference in the two proportions is computed as follows:

$$z = \frac{p_2 - p_1}{\sqrt{p(1-p)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

Where:

z = calculated z-statistic from standard normal distribution

p_1 = sample MOE for location with CLRS

p_2 = sample MOE for location without CLRS

p = combined sample rate across both locations = $\frac{n_1 p_1 + n_2 p_2}{n_1 + n_2}$

n_1 = sample size (i.e., number of vehicle/bicycle passing events) for location with CLRS

n_2 = sample size (i.e., number of vehicle/bicycle passing events) for location without CLRS

The null hypothesis (h_0) was that the CLRS produced no change in the MOE (i.e., $p_1 = p_2$). The alternative hypothesis was that the CLRS produced a change in the MOEs. As such, two-tailed tests were utilized. The z-test of proportions assumes a normal sampling distribution for the proportion, p_i, for each i^th population. The assumption of normality is generally valid as long as p_i is not too close to either 0 or 1 and the sample, n_i, is relatively large. The normality assumption is typically valid if $n_i p_i$ and $n_i(1-p_i)$ are both greater than or equal to 5. This condition is met for the data reported herein and the assumption of normality is valid for the sampling distributions of p_i. The results of the z-test of proportions are shown in Table 9.

Table 9. Statistical Results for Impacts of CLRS on Vehicular Lateral Positioning When Passing a Bicyclist

MOE	W/O CLRS	W/ CLRS	ARITHMETIC DIFFERENCE	Z-SCORE	STATISTICALLY SIGNIFICANT DIFFERENCE?
Percent of Vehicles Contacted the Centerline when Passing a Bicyclist	79.0%	71.1%	-7.9	-3.16	**Yes**
Percent of Vehicles Crossed at Least Halfway into Opposing Lane when Passing a Bicyclist	17.9%	14.9%	-3.0	-1.40	**No**

Note: Total vehicle/bicycle passing events = 626 w/o CLRS and 571 w/ CLRS. The critical z-score for the two-tailed test of proportions was ±1.96, representing a 95 percent confidence level.

The presence of centerline rumble strips was found to decrease the percentage of motor vehicles making contact with the centerline from 79.0 percent to 71.1 percent, which was statistically significant at 95 percent confidence. Motor vehicles were also less likely to cross at least halfway over the centerline when bicyclists were present, though this effect was not significant at 95 percent level of confidence. Overall, these findings show that while drivers generally tended to ride onto or across the centerline when passing bicyclists, they did so less frequently when centerline rumble strips were present.

Table 10 shows the results of a comparison of driver performances with and without the "Share the Road" sign. There was a slight decrease in the MOE "vehicle contacted the centerline" (75.4 percent without sign to 74.1 percent with sign); however this change was not statistically significant. The percent of vehicles that crossed at least halfway into the opposing lane was also insignificant with the "Share the Road" sign, as compared to the condition without it. However, this static sign can be used in such locations, even if it has only limited effect, since it is a relatively inexpensive device.

Table 10. Results of the Impacts of Share the Road Sign on Vehicle Lateral Placement

MOE	WITHOUT "SHARE THE ROAD" SIGN	WITH "SHARE THE ROAD" SIGN	ARITHMETIC DIFFERENCE	PERCENT DIFFERENCE
Percent of Vehicles Contacted the Centerline	75.4%	74.1%	-1.3	-1.7%
Percent of Vehicles Crossed at Least Halfway Into Opposing Lane	16.4%	15.9%	-0.5	-3.0%

Note: Differences were not statistically significant.

Bicyclist Opinion Survey

An online survey pertaining to non-freeway rumble strips was developed by the WSU-TRG and distributed to members of the Michigan bicycling community in May 2011. The purpose of the survey was to obtain feedback from bicyclists regarding their perceptions and experiences related to centerline and shoulder rumble strips on high-speed, non-freeways in Michigan. Of particular interest were their perceptions of the impact of centerline and shoulder rumble strips on safety and comfort of bicyclists. The survey was distributed through the League of Michigan Bicyclists (LMB), which is a non-profit group that serves to promote bicycling and bicyclist safety in Michigan.

A total of 213 completed survey responses were received. In terms of exposure to non-freeway rumble strips, a majority of responding bicyclists had encountered rumble strips in Michigan. Greater than 80 percent of these respondents claimed to ride differently on roadways with rumble strips installed, and approximately one-half of respondents avoid roadways with rumble strips completely. Approximately one-quarter of respondents felt less safe on roadways with only centerline rumble strips, while nearly half of respondents felt less safe on roadways with both centerline and shoulder rumble strips.

In terms of suggestions for improving safety on non-freeway roadways with rumble strips, approximately two-thirds of respondents agreed that a special sign or pavement markings in advance of rumble strips sections would be helpful to bicyclists. Approximately 60 percent of all respondents believed that MDOT's current shoulder width standard of 6 feet for shoulder rumble strip installation was appropriate, while approximately 40 percent suggested that this minimum shoulder width be increased beyond 6 feet. The responses also indicated that the current MDOT standard 12 foot gap between continuous shoulder rumble strip installation cycles was not long enough to allow for safe navigation – particularly on steep downgrades. The responses to the primary safety and/or comfort issues for bicyclists were summarized as follows, with complete responses listed in Appendix III.

- 88% ride differently on roadways with rumble strips
- 52% avoid roadways with rumble strips
- 60% believe 6-ft is appropriate minimum shoulder width for SRS

- 23% believe 12-ft is appropriate gap length on normal section for bicyclist maneuverability
- 6% believe 12-ft is appropriate gap length on steep downgrade for bicyclist maneuverability
- 27% feel less safe on roadways with centerline rumble strips only
- 47% feel less safe on roadways with centerline and shoulder rumble strips
- 67% believe that special signs or pavement markings in advance of rumble strip sections would be helpful to bicyclists

It is important to note that this “Bicyclist Opinion Survey” was not intended to capture opinion about alternative design standards.

VI. IMPACT OF SHORT-TERM PAVEMENT PERFORMANCE DUE TO INSTALLATION OF CLRS

If left untreated or not maintained, all pavements will deteriorate over time. The rate of deterioration is often affected by several factors, including the applied load cycle due to automobile traffic volume, temperature, moisture, and age *(45)*. Pavement performance is often quantified by roadway agencies using direct measurement of distress in the pavement surface. These measures may include quantity (i.e., frequency), extent (i.e., length), or severity (width or size). Cracking specifically is one of the most common distresses that affect performance *(46)*. Past research has examined the effects of various factors on crack propagation, including the pavement structure, materials, traffic volumes, environmental factors, and age *(46)*.

In Michigan, the non-freeway rumble strip installations have generally been milled into the existing pavement surface. This milling process causes the effective pavement surface thickness to be reduced in the milled areas that may allow moisture to infiltrate to the bottom of the pavement surface on a thinner asphalt layer. Limited research exists pertaining to quantitative assessment of pavement deterioration caused or accelerated by the installation of rumble strips.

In 2001, the Colorado Department of Transportation performed an in-house evaluation of a pilot implementation of centerline rumble strips *(26)*. This evaluation involved subjective visual field assessments conducted on an annual basis, to identify whether any distress had developed in the rumble strip grooves. After monitoring for a period of five years, it was determined that the rumble strips did not have any significant detrimental effect on pavement life.

In 2004, Russell, et al. conducted a nationwide survey of issues related to centerline rumble strips, which solicited information regarding pavement deterioration problems or maintenance concerns *(25)*. Of 24 responding states, 15 indicated that there was no effect on pavement deterioration or problems for drivers because of water accumulation in the rumble strips. Two states indicated that they had experienced problems and seven states were unsure. The two states that had experienced issues were Alaska and Oregon. Alaska noted pavement deterioration only when rumble strips were installed in chip seals or otherwise compromised pavements. They also commented that snow or ice could become compacted into the rumble strips and persist for a short time after a storm, although this problem typically resolved itself as the compaction was cleared by passing traffic. The State of Oregon noted that water accumulation could also lead to premature pavement deterioration.

In 2008, the Minnesota Department of Transportation released a report on the long-term maintenance effects of rumble strips on asphalt concrete pavements *(47)*. This research involved the implementation of a state-of-the-practice survey among all Minnesota counties and state DOT district offices. Respondents were asked about the type and quantity (length) of rumble strips installed in their jurisdiction, as well as whether they observed the presence of any pavement distresses in the rumble strips and what kind of treatments were being used to address pavement issues. A similar survey was sent to all state DOT's to collect data on a national level. The results showed that all Minnesota counties and 67 percent of the state DOT district offices observed the development of distress in the rumble strips while only 10 of the 24 State DOT's who replied to the survey reported a similar finding. The study concluded there is a general concern that pavement damage can be caused by grinding in rumble strips on an HMA pavement surface. However, a 2003 study in Texas contradicts some of these claims as rumble strips were found to have minimal effect on pavement deterioration *(7)*. This study reports that field tests showed the vibration created by wheels passing over the rumble strips were strong enough to remove debris, ice, and water.

Overall, there is a gap in the knowledge pertaining to the impacts of rumble strips on pavement condition. In order to address this need, this study involved a visual review of pavement imagery data from high-speed, two-lane rural highways throughout the State of Michigan. The effects of centerline rumble strips were assessed by comparing the rate of crack propagation between road segments where rumble strips were installed, and similar control segments where rumble strips were not installed.

Review of Pavement Imagery Data

As a part of the pavement management program, MDOT conducts an annual inventory of the pavement condition (video of the pavement surface) on all state-maintained roads. Data are collected in a cyclical manner such that each road segment is observed once every three years. Data collection vans used as a part of the initiative are equipped with sensors to collect information regarding the roughness of the pavement surface, as well as having cameras mounted on the same vehicle collect images of the pavement from various perspectives. Each set of images covers a distance of 26.4 ft of pavement length, resulting in a total of 200 images per mile.

Imagery data for the years 2006 to 2010 were obtained for the purposes of this study. In order to determine the impacts of centerline rumble strips on short-term pavement performance, the change in the number of cracks intersecting the centerline over a two-year period (also referred to as crack propagation) was used as the performance measure. In order to allow for a controlled comparison to isolate the effects of rumble strips on crack propagation, a database was created that disaggregated all MDOT, high-speed, rural non-freeways into 0.1-mile segments. This database included information on the roadway geometry, traffic volume, and geographic location, as well as whether centerline rumble strips had been installed at the location. These segments were subsequently combined into larger, longer one mile segments, each of which shared similar geometric, traffic, and geographic characteristics. Figure 9 provides a statewide map that illustrates the locations of rumble strip and control sections that was used in the study of short-term pavement performance study.

Figure 9. Map of Rumble Strip and Control Sections

Factors Affecting Crack Propagation

It is important to note that the development of transverse cracks in the pavement is a function of many factors, including annual average daily traffic (AADT), regional effects, and pavement age. To allow for an appropriate comparison between rumble strip and control sections, these factors were controlled for as a part of the subsequent statistical analysis, which involved a multi-factor analysis of variance (ANOVA).

Crack propagation was analyzed with respect to AADT and differences were observed between segments with AADT values above and below 4,000 vehicles per day. The road segments were also disaggregated into one of three geographic regions. This would theoretically capture unique regional effects, such as temperature, precipitation, and local maintenance practices. The state was divided into three regions: the Upper Peninsula (Region 1), the

Northern Lower Peninsula (Region 2), and the Southern Lower Peninsula (Region 3) as shown in Figure 10. These regions were selected largely based upon similarities in weather, as differences in Michigan's freeze-thaw cycles are likely to impact pavement performances.

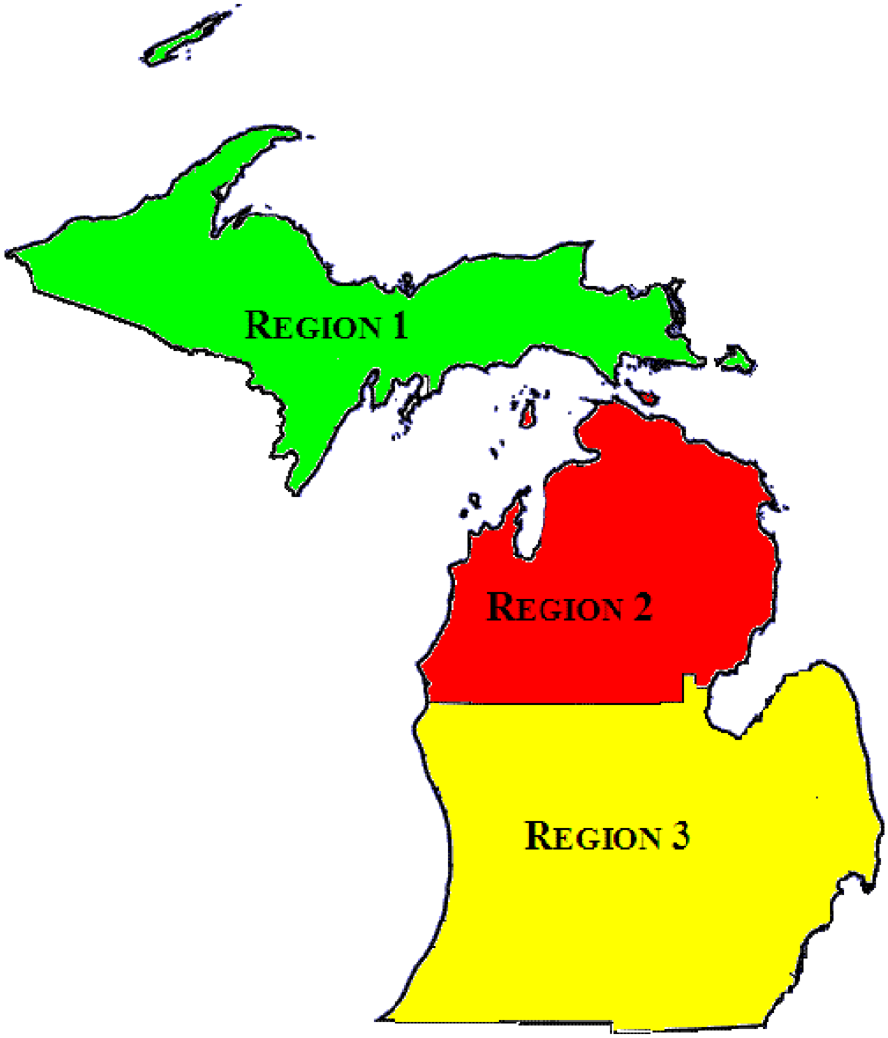


Figure 10. Map of Michigan Geographic Regions

Sampling Strategy for Pavement Condition Data

A representative sample of roadway segments was used to collect data. Random sampling provided an adequate sample of data to assess differences in pavement condition before and after, CLRS installation with a high degree of confidence in results that can be used to make generalized statewide conclusions.

As a part of this process, it was first necessary to estimate an appropriate number of 0.1-mile roadway segments to allow for determination of whether the rumble strips have a significant impact on pavement surface cracking. The target number of 0.1-mile roadway segments was determined based on the following equation:

$$n \cong \frac{\left(Z_{\alpha} Z_{\beta}\right)^{2}\left(\sigma_{1}^{2}+\sigma_{2}^{2}\right)}{\Delta^{2}},$$

where *n* is the minimum sample size of 0.1-mile pavement segments, z_α and z_β are probability-based factors that represent the confidence level (95% for a one-tailed test) and power (80%) of subsequent statistical tests, σ_1^2 and σ_2^2 are estimates of the variances of cracks per 0.1-mile segment with and without rumble strips (i.e., "Before" and "After"), and Δ is difference in the number of cracks per 0.1-mile segment after rumble strips are installed.

In order to estimate the target sample size, preliminary pavement condition data were collected from the pavement surface imagery for 56 randomly selected roadway segments, each of which was 1.0 mile in length. To help control for externally biasing environmental factors, the segments were separated into three zones prior to sampling: Upper Peninsula (MDOT Region 6), Northern Lower Peninsula (MDOT Region 4), and Southern Lower Peninsula (all other MDOT regions).

These preliminary segments were randomly selected from the list of non-freeway high-speed roadway segments for which 2007 imagery was available. Between 17 and 21 miles of roadway segments were selected from each of the three zones. The 2007 pavement surface imagery was reviewed for approximately 56 miles of roadway segments. Similar centerline rumble strips were not installed on these roadways until 2008, the reviewed sample pavement imagery represented the "Before" condition. Each pavement surface image was visually reviewed to provide a numerical count of visible cracks that intersected the roadway centerline. The cracking data were summarized for each 0.1 mile segment. The basic descriptive statistics for pavement surface cracking is summarized in Table 11.

Table 11. Descriptive Statistics for Sample Centerline Surface Cracking Data

ZONE	NO. OF 0.1-MILE SAMPLE SEGMENTS REVIEWED	AVERAGE SURFACE CRACKS	STANDARD DEVIATION (Σ) PER SEGMENT
Upper Peninsula	180	8.26	10.29
Northern Lower	207	6.13	9.01
Southern Lower	171	9.57	9.34
STATEWIDE	**558**	**7.87**	**9.63**

The standard deviation of the sample data were then utilized to compute the estimated target sample sizes required in order to detect specific increases (Δ) in the mean number of cracks, per 0.1 mile between the “Before” and “After” periods. These sample size estimates, computed for each zone and overall, are shown in Table 12.

Table 12. Target Sample Sizes for Analysis of Pavement Distress Data by Zone and Statewide

INCREASE IN THE NUMBER OF CRACKS (Δ) BETWEEN "BEFORE" AND "AFTER" PERIOD (PER 0.1 MILE)		MINIMUM SAMPLE SIZE OF 0.1 MILE HIGHWAY SEGMENTS			
		UPPER PENINSULA	NORTHERN LOWER	SOUTHERN LOWER	STATEWIDE
NUMBER OF CRACKS	PERCENT OF OVERALL MEAN*	$\Sigma = 10.29$ CRACKS/ SEGMENT	$\Sigma = 9.01$ CRACKS/ SEGMENT	$\Sigma = 9.34$ CRACKS/ SEGMENT	$\Sigma = 9.63$ CRACKS/ SEGMENT
0.98	**12.5%**	1,357	1,040	1,118	1,188
0.79	**10.0%**	2,120	1,625	1,747	1,857
0.59	**7.5%**	3,769	2,889	3,105	3,301
0.39	**5.0%**	8,479	6,501	6,986	7,427
0.20	**2.5%**	33,918	26,005	27,944	29,707

*Overall Sample Mean = 7.87 cracks per 0.1 mile

This analysis indicates larger sample sizes are necessary to detect smaller differences between the "Before" and "After" periods. It is also evident that relatively little difference exists in the sample standard deviations for comparing cracking between each of the three zones.

Ultimately, a sample of 457 miles of pavement sections was selected for analysis. This included 275 miles of highways where rumble strips had been installed, and 182 miles of control sections where there were none, and in both cases, two sets of imagery were available that allowed the assessment for deterioration. The number of miles reviewed in each group was increased in some cases to provide more thorough coverage with respect to each of the factors previously described (geographic region, AADT, and pavement age). Table 13 provides summary statistics detailing the number of miles of pavement imagery that were reviewed within the various categories of the aforementioned factors with respect to whether the segment was from a road segment with rumble strip or control section. Two-sample Kolmogorov-Smirnov tests *(48)* were conducted and showed that there were not any significant differences between the roads with rumble strip and control section distributions with respect to these key factors.

Table 13. Data Summary

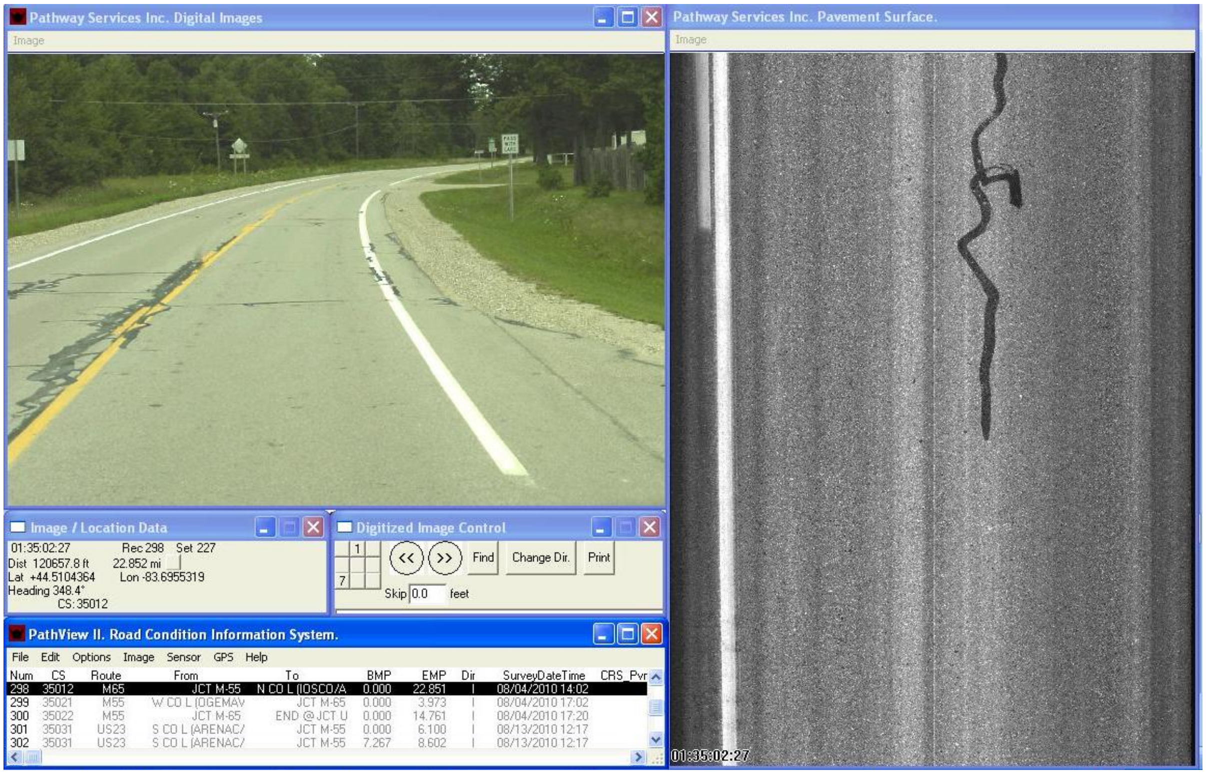
FACTOR	CLASSIFICATION	RS INSTALLED (MILES)	NO RS INSTALLED (MILES)	ALL (MILES)
REGION	Region 1	131	58	189
	Region 2	85	69	154
	Region 3	59	55	114
	Total	**275**	**182**	**457**
AADT	Under 4,000	165	109	274
	Over 4,000	110	73	183
	Total	**275**	**182**	**457**
PAVEMENT AGE (SECOND YEAR)	2 yrs old	28	26	54
	3 yrs old	43	36	79
	4 to 5 yrs old	105	64	169
	6+ yrs old	99	56	155
	Total	**275**	**182**	**457**

Procedure for Pavement Imagery Review

Imagery data were reviewed through a proprietary software program (Pathview II) used by MDOT as a part of the pavement management system. All personnel who reviewed the pavement imagery were trained on the use of this software. As a part of the training, a series of sample segments were independently reviewed by all participants. Each staff member was required to match the actual number of cracks intersecting the centerline on these segments, determined prior to the training. In addition, select pavement sections were randomly checked by a second observer during the course of this study to ensure consistency and precision of results. Figure 11 provides a screenshot of the software, which allows users to view multiple windows that include pavement images, and identifying information for each set of images.

When reviewing the imagery, the first step was to verify the information in the database, specifically whether the site had rumble strips installed or not, and whether the segment was a high-speed, two-lane, non-freeway. The numbers of transverse cracks intersecting the centerline of the roadway were counted for each analysis segment. For the sections where rumble strips were installed, pavement imagery was reviewed one year prior to installation and one year after installation. For the control sections, one set of imagery was reviewed for a baseline year and another set of images that were taken two years later. Examining the increase in the number of cracks over this two-year period allowed for a direct comparison of crack propagation between the rumble strip and the control sections.

For the purposes of this study, only transverse cracks that intersected the centerline were counted, as these are the types of cracks most directly related to the rumble strips. Longitudinal cracks or transverse cracks that did not intersect the centerline were assumed to be due to other factors. Figure 12 shows example imagery from a specific segment before and after rumble strip installation. It can be observed from this image that one new transverse crack had developed.



01:35:02:27 Rec 298 Set 227
Dist 120657.8 ft 22.852 mi
Lat +44.5104364 Lon -83.6955319
Heading 348.4°
CS: 35012

Skip 0.0 feet

Num	CS	Route	From	To	BMP	EMP	Dir	SurveyDateTime	CRS_Pvr
298	35012	M65	JCT M-55	N CO L (IOSCO/A	0.000	22.851	I	08/04/2010 14:02	
299	35021	M55	W CO L (OGEMAV	JCT M-65	0.000	3.973	I	08/04/2010 17:02	
300	35022	M55	JCT M-65	END @ JCT U	0.000	14.761	I	08/04/2010 17:20	
301	35031	US23	S CO L (ARENAC/	JCT M-55	0.000	6.100	I	08/13/2010 12:17	
302	35031	US23	S CO L (ARENAC/	JCT M-55	7.267	8.602	I	08/13/2010 12:17	

Figure 11. Pathview II Software – Display Windows

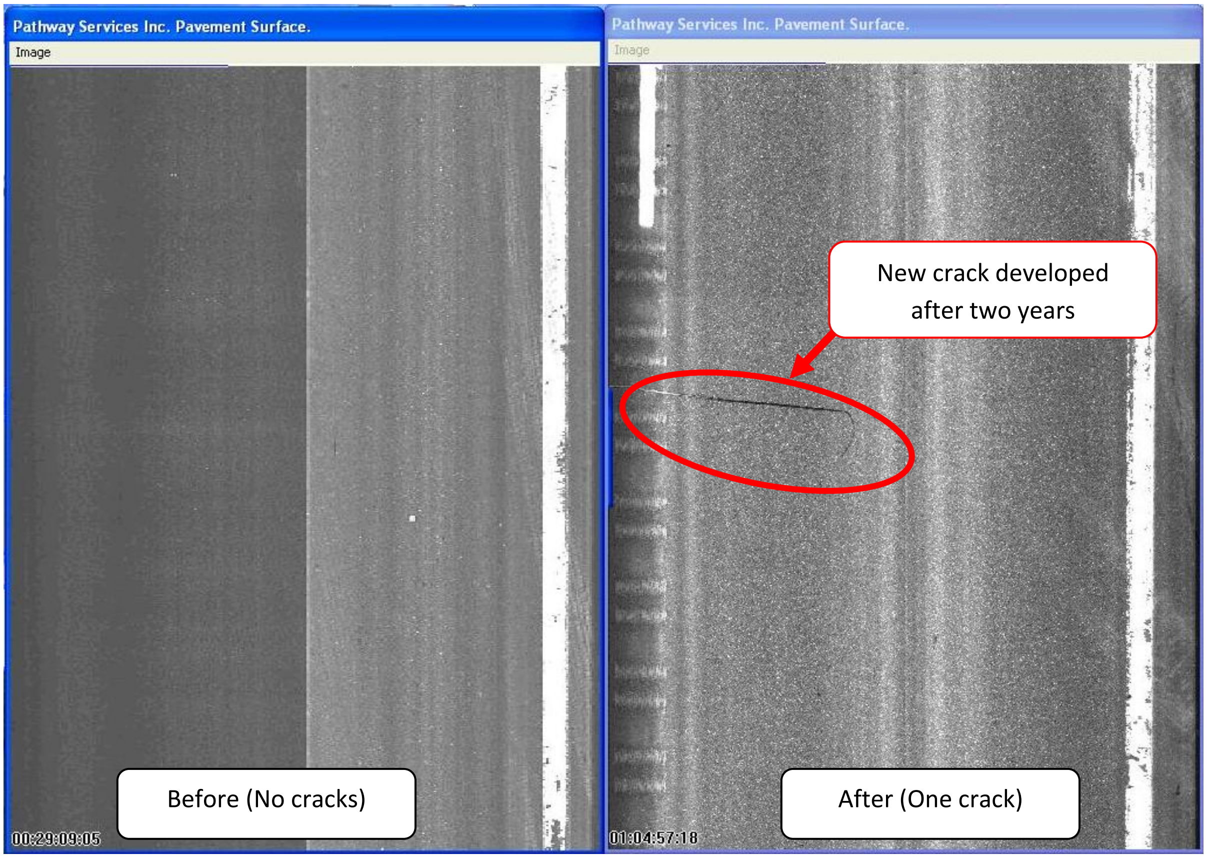


Figure 12. Example Pavement Imagery from Before and After Rumble Strip Installation

Results

Tables 14 and 15 present summary statistics detailing the number of transverse cracks that were found to intersect the centerline of the roadway for the rumble strip and control sections, respectively. In each table, these data were aggregated by geographic region and AADT as described previously. Within each region/AADT category, the number of 0.1-mile segments that were observed is presented, along with the mean number of cracks per segment observed during the "before" and "after" periods. Lastly, the increase in cracks per 0.1-mile segments is also presented.

The results show that crack propagation tended to be greater in the more urbanized southern regions of the state and less rapid in the Upper Peninsula. The increase also tended to be greater at higher traffic volume areas. These trends were observed in both the rumble strip and control sections.

Table 14. Cracking Results for the Rumble Strip Sections

REGION	AADT CATEGORY	SAMPLE SIZE (0.1 MILE SEGMENTS)	RUMBLE STRIP SECTIONS TRANSVERSE CRACKING DATA					
			NO. OF CRACKS BEFORE INSTALLATION		NO. OF CRACKS AFTER INSTALLATION		INCREASE IN CRACKS DURING TWO-YEAR PERIOD	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
I	**TOTAL**	**1,320**	**6.10**	**8.52**	**9.14**	**9.79**	**3.04**	**4.32**
	AADT ≤ 4,000	1,080	5.69	8.48	8.62	9.63	2.93	4.42
	AADT > 4,000	240	7.92	8.47	11.49	10.14	3.57	3.83
II	**TOTAL**	**870**	**8.68**	**10.82**	**11.98**	**11.70**	**3.30**	**5.07**
	AADT ≤ 4,000	350	8.74	11.18	11.19	12.18	2.45	4.69
	AADT > 4,000	520	8.64	10.58	12.51	11.35	3.87	5.24
III	**TOTAL**	**600**	**11.78**	**13.13**	**16.35**	**14.85**	**4.57**	**5.14**
	AADT ≤ 4,000	240	14.33	14.53	19.20	15.68	4.87	5.48
	AADT > 4,000	360	10.08	11.83	14.45	13.98	4.38	4.90
STATEWIDE SAMPLE	**TOTAL**	**2,790**	**8.12**	**10.62**	**11.58**	**11.96**	**3.45**	**4.78**
	AADT ≤ 4,000	1,670	7.57	10.58	10.68	11.81	3.11	4.70
	AADT > 4,000	1,120	8.95	10.62	12.91	12.07	3.97	4.87

Table 15. Cracking Results for the Control Sections

REGION	AADT CATEGORY	SAMPLE SIZE (0.1 MILE SEGMENTS)	CONTROL SECTIONS TRANSVERSE CRACKING DATA					
			NO. OF CRACKS INITIAL YEAR		NO. OF CRACKS AFTER TWO YEARS		INCREASE IN CRACKS DURING TWO-YEAR PERIOD	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
I	**TOTAL**	**580**	**6.19**	**9.08**	**9.45**	**10.78**	**3.26**	**5.77**
	AADT ≤ 4,000	440	4.12	6.73	6.35	8.19	2.23	3.81
	AADT > 4,000	140	12.70	12.01	19.21	12.09	6.51	8.88
II	**TOTAL**	**670**	**7.14**	**12.05**	**10.65**	**15.26**	**3.51**	**5.40**
	AADT ≤ 4,000	400	6.23	12.34	9.09	15.46	2.86	4.80
	AADT > 4,000	270	8.50	11.48	12.96	14.68	4.46	6.07
III	**TOTAL**	**550**	**6.03**	**8.41**	**10.73**	**10.20**	**4.70**	**4.92**
	AADT ≤ 4,000	230	4.50	7.43	9.76	9.95	5.25	5.56
	AADT > 4,000	320	7.13	8.89	11.43	10.33	4.30	4.36
STATEWIDE SAMPLE	**TOTAL**	**1,800**	**6.50**	**10.12**	**10.29**	**12.49**	**3.79**	**5.41**
	AADT ≤ 4,000	1,070	4.99	9.39	8.10	11.84	3.11	4.74
	AADT > 4,000	730	8.70	10.72	13.49	12.74	4.78	6.14

Table 16 presents a comparison of the increases in crack propagation between the test (i.e., rumble strip) and control sections by region. In each case, the increase in cracks during the two-year analysis period was marginally higher in the control sections in comparison to rumble strip sections. While these differences were not statistically significant, these data suggest that rumble strips did not create adverse impacts on pavement performance in the short-term.

Table 16. Comparison of Increase in Cracks Between Rumble Strip and Control Sections

REGION	INCREASE IN CRACKS PER 0.1 MILE DURING A TWO-YEAR PERIOD				T-TEST STATISTIC	P-VALUE	SIGNIFICANT DIFFERENCE?
	RUMBLE STRIP SECTIONS		CONTROL SECTIONS				
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION			
I	3.04	4.32	3.26	5.77	-0.82	0.41	No
II	3.30	5.07	3.51	5.40	-0.78	0.44	No
III	4.57	5.14	4.70	4.92	-0.44	0.66	No

VII. ROADSIDE NOISE STUDY

While the installation of rumble strips may provide a safety benefit, the noise produced by vehicles traveling over the rumble strips may create an undesirable level of noise for local residents *(49,50,51,52)*. A number of transportation agencies including MDOT, have received complaints about such noise after rumble strips were installed. In order to provide a quantitative assessment of noise levels produced by rumble strips when in contact by vehicles, research was performed to evaluate roadside noise produced by them on rural two-lane highways in Michigan.

Sound Fundamentals

The intensity of sound is measured using either Pascals (Pa) or decibels (dB), which is a logarithmic measure of the effective sound pressure level compared to a standard reference level. Not all frequencies of sound are detected by the human ear. Consequently, sound measurement is typically performed using the “A”-weighted decibel scale (denoted as dBA), which provides the closest approximation to the response of the human ear *(53)*. Conversion from Pascals to decibels is based on the following equation:

$$L = 20 \log \frac{P}{P_o} \tag{2}$$

Where:

L = sound pressure level in decibels

P = sound pressure level in Pascals

Po = reference sound pressure level in Pascals = 0.00002 (typical threshold of human hearing)

Roadside Noise Measurement

Transportation agencies are often confronted with noise issues related to traffic. The FHWA maintains guidelines for the assessment of roadside traffic noise levels *(34)*. These guidelines recommend collection of ambient roadside noise data during a typical 60-minute period using a calibrated A-weighted sound meter. The sound meter is to be positioned 5 ft above the roadway and at the specific point of interest along the roadside, typically less than 100 ft from the center of the nearest travel lane. Ambient roadside noise data is commonly summarized using:

- L_{eq}, which is the average sound pressure level and/or
- L_{10}, which is the sound pressure level that is exceeded 10 percent of the time (90th percentile sound pressure level).

In order to assess the impact of ambient traffic sound levels on the surrounding environment, the FHWA has established threshold levels for L_{eq} and L_{10} for various land-use categories *(53)*. These categories and the respective sound thresholds include the following:

- Category A: Lands where serenity and quiet are of extraordinary significance and serve an important public need: L_{eq}=57 dBA, L_{10}=60 dBA
- Category B: Picnic areas, recreation areas, playgrounds, sports areas, parks, residences, motels/hotels, schools, churches, libraries, and hospitals: L_{eq}=67 dBA, L_{10}=70 dBA
- Category C: Developed lands, properties, or activities not included in Categories A or B:

  L_{eq}=72 dBA, L_{10}=75 dBA
- Category D: Undeveloped lands. No maximum sound pressure level.

The roadside noise produced by rumble strips has been investigated in past research. Higgins and Barbel *(52)* determined that transverse in-lane rumble strips produce a low frequency noise that increased the noise produced by a vehicle traveling through the site by 7 dB. The noise levels produced by an automobile traveling over the rumble strips were slightly less than those produced by the pass of a large truck. Gupta *(49)* measured external noise at a distance of 10 ft from the edge of pavement. The measured roadside noise for vehicles traveling over the rumble strips was 74-80 dB for passenger cars and 82-90 dB for trucks, representing up to a 7 dB increase over baseline conditions when no contact with the rumble strips was made. Chen *(54)* found that SRS increased exterior noise by 11 dB for vehicles traveling at 65 mph. Sutton and Way *(55)* found that the rumble strips increased noise by 10 to 12 dB at the edge of pavement, compared to noise increases of 8 dB and 7 dB when measured at 25 ft and 50 ft, respectively. Rumble strip noise levels were approximately at baseline traffic noise levels at a distance of approximately 200 ft from the edge of pavement.

Finley and Miles *(17)* measured roadside noise produced by a car and commercial vehicle traveling over five types of rumble strips at 55 and 70 mph, at an offset of 50 ft from the edge of the rumble strips. The car traveling over a hot-mix asphalt (HMA) pavement surface at 55 mph produced an average baseline noise level of 71 dB and the commercial vehicle yielded a baseline noise of 82 dB. Milled rumble strip noise over the same pavement type was 84 dB for the car and 93 dB for the commercial vehicle. The chipseal pavement yielded a smaller increase in noise due to rumble strips with a baseline of 77 dB for the car, and 85 dB for the commercial vehicle with an average rumble strip noise of 81 dB and 87 dB, respectively.

Karkle, et.al *(56,18)* conducted a study in Kansas on the roadside noise generated by a car and a van passing over rumble strips at 40 mph and 60 mph. Sound meters were placed at lateral offsets of 50 ft, 100 ft, and 150 ft from the centerline of the highway. The highest sound level measured was at 50 ft from centerline and was 82.36dB, while the lowest was recorded at 150 ft and was 55.77 dB. It was also shown that commercial vehicles produced a higher level of noise when compared to the rumble strip noise produced by the van and car.

Field Study

A controlled field study was performed to evaluate increases in roadside noise produced by rumble strips on rural two-lane highways in Michigan as a function of rumble strip depth, location (centerline vs. edgeline), and pavement surface type.

Twelve study sites were selected from the statewide list of MDOT-maintained two-lane rural highways where rumble strips were installed in 2010. The study locations were selected to provide a representative balance between various roadway and rumble strip characteristics. All study locations had posted speed limits of 55 mph. The characteristics of the study sites are shown in Table 17.

Table 17. Site Characteristics

HIGHWAY	PAVEMENT TYPE	RUMBLE STRIP	DEPTH (IN) (CLRS,SRS)	LANE WIDTH (FT)	PAVED SHOULDER WIDTH (FT)
M-57 (A)	Chipseal	CLRS	0.25	12	4
M-57 (B)	Chipseal	CLRS	0.44	12	4
M-19	HMA	CLRS	0.44	11	3
M-179	Chipseal	CLRS	0.69	12	5
M-43	HMA	CLRS & SRS	0.56, 0.56	11	8
M-25	HMA	CLRS & SRS	0.44, 0.44	12	8
M-136	HMA	CLRS	0.38	11	3
M-72 (A)	Chipseal	CLRS	0.50	11	3
M-72 (B)	Chipseal	CLRS	0.56	11	3
M-55	Chipseal	CLRS & SRS	0.38, 0.5	12	7.5
M-28	Chipseal	CLRS	0.31	12	4.5
US-41	HMA	CLRS & SRS	0.44, 0.50	12	8

Note: All rumble strips were a milled application installed during 2010.

Equipment Setup and Preparation

A Tenma digital sound meter with a foam windscreen was utilized for the noise measurements. The sound meter was placed at a suitable roadside location that was 50 ft away from the roadway centerline at a height of 5 ft above the pavement surface, as recommended by the FHWA for roadside noise measurement *(34)*. The 50 ft lateral offset is also consistent with MDOT's procedure for roadside noise measurement on rural roadways. To ensure that the peak noise measurement was recorded during each pass of the test vehicle, the sound meter was programmed to measure at the fastest possible rate of one measurement per 125 milliseconds. A typical sound meter setup and test vehicle pass is shown in Figure 13.

Figure 13. Example Sound Meter Setup and Test Vehicle Pass

Relevant characteristics of the roadway and rumble strips were collected at each study location. These data included the lane width, shoulder width, length and width of the corrugations, spacing, and rumble strip depth. Depth measurements were taken for five randomly selected rumble strip corrugations that were in close proximity of the sound meter. A custom depth gauge was used to measure the depth to the bottom of the corrugation to the nearest 0.0625 (1/16th) of an inch. The reported depth was then taken from the average of the five readings. The depth measurements did not vary by more than ± 0.0625 of an inch within a given study site.

Controlled Roadside Noise Measurement with Test Vehicle

A 2010 Chrysler Town and Country minivan was used as the test vehicle for all controlled noise measurements. The test vehicle made 40 passes through each study site at the prescribed speed of 55 mph. Twenty (20) passes were performed while making continuous contact with the centerline rumble strips. The remaining 20 passes were performed while driving as close to the centerline rumble strips as possible, without making contact, which was considered the "baseline" noise produced by the test vehicle. An additional 20 passes were also performed while driving on the shoulder rumble strips at the four locations. The groups of vehicle passes were also equally subdivided between the vehicle traveling in the near side lane (closest to meter set-up) and the far side lane.

In order to maintain maximum safety and measurement accuracy, a team of three personnel were used during the field study. One person was stationed at the roadside to watch for approaching traffic. Another person was stationed at the sound meter and recorded the peak noise measurement for each pass of the test vehicle. The third individual drove the test vehicle. They communicated using a two-way radio during each pass. To ensure safety of the data collectors, data were only collected on tangent sections with ample sight distance.

The peak decibel level was measured during each pass of the test vehicle, which occurred when the vehicle was approximately tangent to the meter. A typical vehicle pass over a centerline rumble strip is shown in Figure 13 (page 53). The data collectors ensured that no other vehicles were present in the study area during each pass of the test vehicle. In addition to measurement of the test vehicle passes, the peak decibel readings of random passerby tractor trailer trucks were also taken as they passed by the sound meter, although no speed assessment could be made. Truck noise was only recorded if no additional traffic was present. Note that none of the trucks were traveling over the rumble strips during the noise measurement. To account for noise due to uncontrolled factors at study sites, background noise measurements were also recorded periodically when no vehicles were present in the area.

Ambient Roadside Noise Measurement

A 60-minute ambient noise measurement was recorded immediately after the controlled evaluation using the identical sound meter setup. The meter was programmed to record one measurement per second to the internal memory. Thus, a total of 3600 sound measurements were recorded per 60-minute data collection period. A pole mounted video camera was also set up nearby to observe vehicles passing by the meter which allowed for the determination of the traffic volume, composition, and the occurrence of vehicles in contact with the rumble strips. The videos were later reviewed to extract relevant information for vehicles passing by the sound meter during the ambient noise recording period that included:

- Vehicle type
- Lane
- Whether vehicle contacted the rumble strips (visual or audible confirmation)

Results

Descriptive Statistics

The noise data collection using the test vehicle yielded a total of 240 peak noise measurements recorded while the test vehicle was traveling over CLRS, 240 baseline peak noise measurements were also recorded while the test vehicle was traveling off the rumble strips. The noise measurements were equally split between the 12 study locations and between the near side and far side of the travel lanes. An additional 80 peak noise measurements were recorded while the test vehicle was traveling over the SRS at the four locations. Peak noise measurements were obtained for a total of 93 random passerby tractor trailer trucks. Table 18 presents the site-by-site summary statistics for the noise evaluation using a test vehicle along with the overall aggregated values for all sites.

Table 18. Results of Noise Measurements Using Test Vehicle
[Mean Peak Noise Measurements by Site (dBA)]

HIGHWAY	TEST VEHICLE – IN LANE (OFF RS)	TEST VEHICLE – ON CLRS	TEST VEHICLE – ON SRS	TRUCKS – IN LANE (OFF RS)
M-57 (A)	73.3	77.5	-	83.6
M-57 (B)	71.1	79.7	-	80.9
M-19	73.1	77.7	-	84.0
M-179	72.5	85.4	-	82.9
M-43	69.9	84.4	87.9	84.8
M-25	71.0	78.6	80.4	83.5
M-136	69.0	76.4	-	-
M-72 (A)	74.5	83.3	-	84.2
M-72 (B)	71.0	85.1	-	82.8
M-55	76.0	77.6	78.1	81.6
M-28	73.1	76.4	-	81.9
US-41	73.8	77.8	80.2	82.6
OVERALL	**72.6**	**80.7**	**82.5**	**83.0**

Impact of Rumble Strip Location

It can be observed from Table 18 (page 55) that the overall baseline mean peak noise produced by the test vehicle traveling at 55 mph without contacting the rumble strip was 72.61 dBA. Contact with the CLRS during the test vehicle passes produced an increase in overall mean peak noise by 8.11 dBA to 80.72 dBA. Contact with the SRS produced an even greater mean noise level of 82.57 dBA. The sample of random tractor trailers produced mean peak noise levels of 83.08 dBA. The aggregated mean peak noise results are displayed graphically in Figure 14 along with the 95 percent confidence intervals.

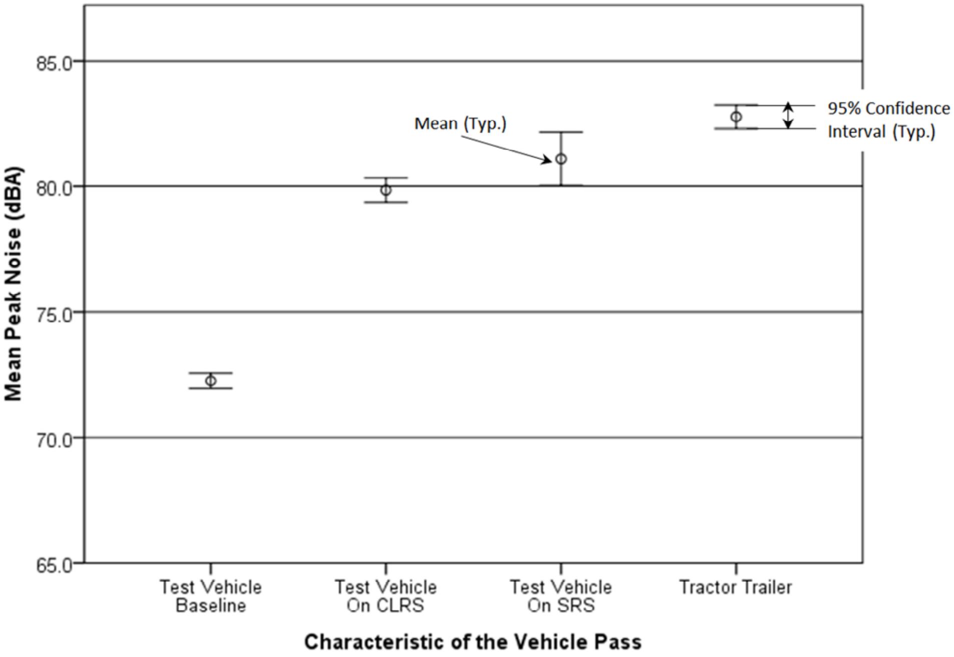


Figure 14. Test Vehicle Noise Data Summary

The one-way ANOVA found these differences in noise levels with respect to the characteristics of the passing vehicle to be statistically significant at a 95 percent level of confidence. A post-hoc analysis using Tukey HSD showed that the mean noise produced by the test vehicle traveling over the SRS was not significantly different from that of either the CLRS or tractor trailers. While the mean noise produced by the test vehicle in contact with the CLRS was not significantly different from the SRS, it was significantly lower than what was produced by the tractor trailers.

The multi-factor ANOVA for CLRS noise indicated that several of the main factor effects and factor interactions were statistically significant at a 95 percent confidence level. The detailed ANOVA results are summarized as follows:

- Statistically significant variables
    - Rumble strip depth
    - Pavement surface type
    - Travel lane during the vehicle pass
    - Pavement surface type x travel lane during the vehicle pass (Interaction)
- Statistically insignificant variables
    - Average background noise at the study site when no vehicles were present
    - Baseline test vehicle noise

The depth of the CLRS had the greatest effect on noise produced by the test vehicle when it made contact, as indicated by the relative magnitude of the F-statistic. Figure 15 provides a graphical representation of peak CLRS noise measurement versus depth. As expected, CLRS noise levels were positively correlated with the depth of the corrugations, although this correlation was non-linear, as evidenced by the sharp increase in peak noise at depths of 0.5 inches. For CLRS with depths of less than 0.5 inches, the mean peak noise was 77.82 dBA. For CLRS with depths of 0.5 inches and greater, the mean peak noise increased by 6.8 dBA to 84.62.

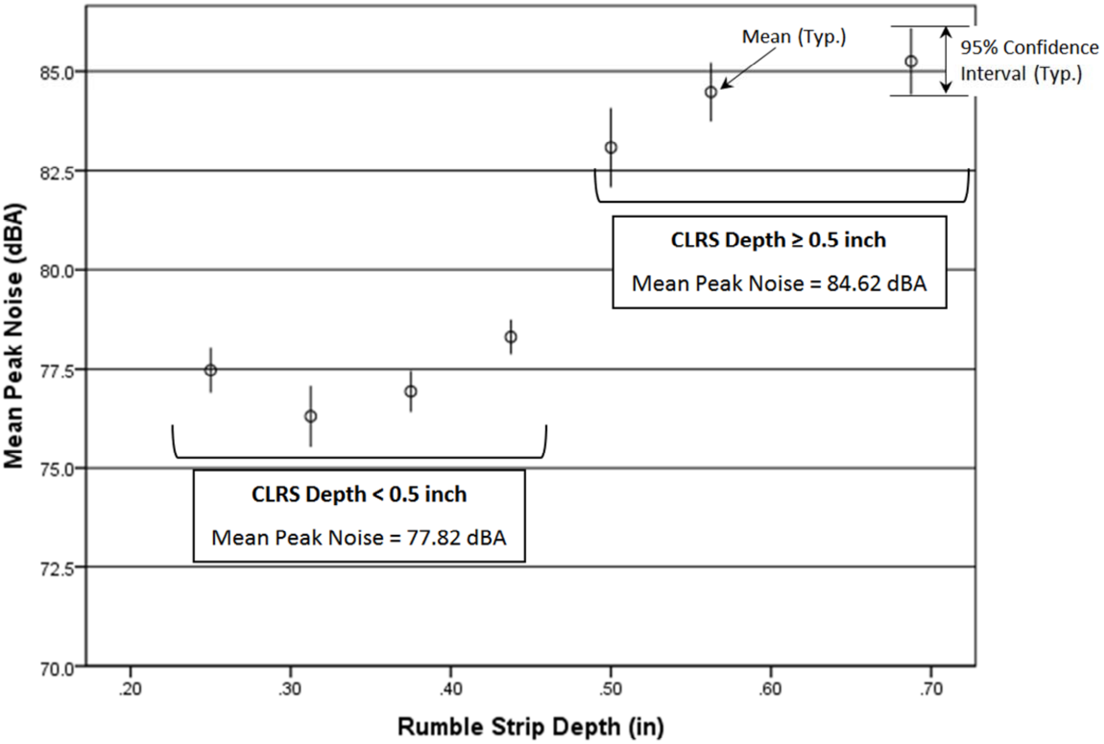


Figure 15. Impacts of CLRS Depth Using Test Vehicle

Ambient Noise

The 60-minute ambient noise measurement summary statistics are shown for each study site in Table 19. Three of the study locations had L_{10} levels that exceeded the noise threshold for land-use Category B, while none of the locations exceeded the L_{eq} threshold. It is unlikely that the rumble strips had an influence in the threshold levels being exceeded due to the small number of vehicles in contact with the rumble strips, during the 60-minute measurement periods at the locations. Overall, a total of 23 vehicles (1.2 percent of all vehicles) were visibly and/or audibly observed to contact the rumble strips in the vicinity of the noise meter during the measurement periods. This equated to one rumble strip contact for every 85.4 vehicles or one contact every 28.7 minutes.

Table 19. Ambient Noise Results
(Represents 60-minute Daytime Ambient Noise Measurement Per Site,
1 measurement recorded per second)

HIGHWAY	NO. OF NOISE MEAS.	TOTAL VEHICLE COUNT	TOTAL TRUCK COUNT	VEHICLES CONTACTING RUMBLE STRIPS		AMBIENT NOISE STATISTICS	
				TOTAL COUNT	PERCENT OF ALL VEHICLES	L_{10} (DBA)	L_{EQ} (DBA)
M-57 (A)	3,600	180	24	0	0.0%	70.2	62.0
M-57 (B)	3,600	204	22	1	0.5%	70.0	62.4
M-19	3,600	175	20	0	0.0%	69.0	59.8
M-179	3,600	205	19	0	0.0%	67.8	58.9
M-43	3,600	228	8	3	1.3%	68.3	59.8
M-25	3,600	224	21	5	2.2%	69.0	62.1
M-136	3,600	209	3	7	3.3%	66.3	57.8
M-72 (A)	3,600	77	9	3	3.9%	64.0	57.5
M-72 (B)	3,600	262	21	3	1.1%	70.6*	65.1
M-28	3,600	83	7	0	0.0%	63.7	55.8
US-41	3,600	117	6	1	0.9%	69.7	63.3
OVERALL	**39,600**	**1,964**	**160**	**23**	**1.2%**	**68.9**	**60.8**

Conclusions

When driven over by a test vehicle, both centerline and shoulder rumble strips produced an increased level of roadside noise, as compared to passes where no contact is made. At 55 mph, contact with the centerline rumble strips produced a mean peak noise level of 80.72 dBA when measured 50 ft from the roadway centerline. This represented an 8.11 dBA above the test vehicle's baseline peak noise level of 72.61 dBA. Contact with the shoulder rumble strips produced an even greater mean peak noise level of 82.57 dBA. The noise levels produced by CLRS and SRS were not significantly different from each other and SRS noise levels were similar to that produced by tractor trailers trucks, although CLRS were marginally lower. Pavement surface type impacted the noise produced by the test vehicle when in contact with the CLRS. Chipsealed pavement surfaces provided a mean peak CLRS noise measurement that was

1.92 dBA greater than that measured on HMA pavements. Ambient noise measurements at the study sites showed a relatively low rate of vehicular contact with rumble strips, which consequently did not impact ambient roadside noise levels. These findings were consistent with those found in previous research.

The milled depth of the rumble strip corrugation had, by far, the greatest effect on the noise produced by the test vehicle when contact was made with the rumble strips, although the impact of depth was not linear, as evidenced by the sharp increase in peak noise at depths of 0.5 inches and above. The mean peak noise produced by CLRS with depths of at least 0.5 inches was 84.62 dBA compared to 77.82 dBA for CLRS depths that were less than 0.5 inches, representing a 6.8 dBA difference. CLRS with depths of at least 0.5 inches exceeded the noise levels produced by tractor trailers by 1.54 dBA. Within the range of observed depth values (0.25 inch to 0.69 inch), noise levels were found to increase by an average of 1.25 dBA per 0.0625 inch increase in rumble strip depth. To prevent unnecessarily high levels of unwanted roadside noise, it is recommended that rumble strips be milled at depths between 0.25 and 0.50 inches.

VIII. SAMPLE SPEED STUDY

Vehicular speeds were measured for sample free-flow (off-peak) vehicles before-and-after installation of the rumble strips by the Transportation Research Group research team using a radar gun at five locations. A sample of 450 vehicular speed measurements was obtained from the five passing zone locations. The speed data were analyzed using a Student's t-test both for the individual sites and overall with the results shown in Table 20.

Table 20. Before-and-After Speed Results by Site (Radar Gun)

LOCATION	NO. OF VEHICLES		MEAN SPEED (MPH)			85TH PERCENTILE SPEED (MPH)		
	BEFORE	AFTER	BEFORE	AFTER	DIFFERENCE	BEFORE	AFTER	DIFFERENCE
M-19 - Site 2	100	100	55.9	57.4	1.5	61.0	61.0	0.0
M-19 - Site 1 (A)	100	100	58.2	56.3	-1.9*	62.0	60.0	-2.0
M-19 - Site 1 (B)	100	100	56.8	58.6	1.8	60.2	63.0	2.9
M-136 - Site 1	50	50	56.0	57.2	1.1	60.8	61.0	0.2
M-25	100	100	56.2	55.1	-1.2	61.0	59.0	-2.0
OVERALL	**450**	**450**	**56.7**	**56.9**	**0.2**	**61.0**	**61.0**	**0.0**

* Statistically significant difference in the mean speeds at 95 percent confidence level based on a Bonferroni corrected critical t-score of ± 2.77

Table 20 shows that the overall average vehicular speed was not significantly impacted by the presence of rumble strips. The site-by-site analysis found statistically insignificant differences in average speeds between the before and after periods at four of the five locations. The presence of rumble strips also did not impact the overall, as well as at individual sites', 85th percentile speed.

MDOT staff also provided before-and-after 24-hour speed data for an additional seven locations collected utilizing automated data collection equipment. These data were aggregated into hourly mean and 85th percentile speed values by the data collection equipment. Weighted average values for the mean and 85th percentile speeds were then computed for each time-of-day for all study locations. These data are presented in Table 21 (all hours).

Table 21. Aggregated Before-and-After Speed Results by Time of Day (Automated Counters)

TIME	MEAN SPEEDS (MPH)			85TH PERCENTILE SPEEDS (MPH)		
	BEFORE	AFTER	DIFFERENCE	BEFORE	AFTER	DIFFERENCE
12:00 AM	57.9	57.4	-0.5	62.4	62.0	-0.4
1:00 AM	58.8	57.4	-1.4	63.5	61.6	-1.9
2:00 AM	59.9	58.6	-1.3	61.1	62.7	1.6
3:00 AM	54.1	57.7	3.6	60.5	61.0	0.5
4:00 AM	56.4	56.4	0.0	61.4	61.7	0.3
5:00 AM	58.2	58.2	0.0	62.3	62.7	0.5
6:00 AM	58.1	58.3	0.2	62.3	62.5	0.2
7:00 AM	58.1	58.9	0.7	62.2	62.9	0.8
8:00 AM	58.2	59.0	0.8	62.2	63.0	0.7
9:00 AM	58.3	58.4	0.1	62.3	62.6	0.3
10:00 AM	57.8	57.8	0.1	62.2	62.2	0.0
11:00 AM	57.5	57.7	0.2	62.3	62.0	-0.3
12:00 PM	57.8	57.8	0.0	61.9	62.1	0.2
1:00 PM	57.0	58.0	1.0	61.5	62.2	0.7
2:00 PM	57.6	57.7	0.1	61.5	62.1	0.6
3:00 PM	57.4	57.5	0.1	61.6	61.9	0.3
4:00 PM	57.9	57.6	-0.3	62.3	62.1	-0.2
5:00 PM	57.9	57.8	-0.2	62.3	62.0	-0.2
6:00 PM	58.2	57.9	-0.3	62.2	62.3	0.1
7:00 PM	58.1	58.1	0.0	62.5	62.6	0.1
8:00 PM	58.3	58.4	0.0	62.8	62.7	-0.1
9:00 PM	58.3	58.0	-0.3	63.0	62.7	-0.3
10:00 PM	57.9	57.3	-0.6	62.5	61.9	-0.6
11:00 PM	57.7	57.3	-0.5	62.8	61.9	-0.8
OVERALL	**57.9**	**58.0**	**0.1**	**62.4**	**62.4**	**0.0**

Note: The data shown in the table represent the weighted average values for data collected at the following seven locations: M-179 near 4th St., M-79 near Devine Rd, M-66 near Lake City, M-66 near Butler, M-44 west of M-91, M-44 near M-66, and M-50 near Lewis.

The aggregated hourly speed data shown in Table 21 demonstrated only nominal differences in before-and-after mean and 85th percentile speeds for each hour of the day. As expected, the greatest before-and-after differences were observed during the nighttime hours when volumes are typically very low and free flow speeds prevail. During daytime hours, neither the mean nor 85th percentile speeds varied by greater than 1.0 mph between the before-and-after periods. The impact of installation of rumble strips on the overall mean and 85th percentile speeds was negligible and was not statistically significant.

IX. ANALYSIS OF “BEFORE” CRASH DATA

As a part of analyzing impacts of MDOT’s 2008-2010 centerline rumble strip installation program, it will be necessary to determine the safety consequences on lane departure crashes. A “Before” and “After” study should be performed to properly investigate these effects. This report presents the results of a detailed analysis of police-reported crash data, for the three-year period before rumble strip installation on state maintained high speed, two-lane highways.

Data Collection

The Michigan Department of Transportation provided details of where centerline rumble strips were installed as part of this program in each of the three years (2008-2010). MDOT compiled these data from the annual restriping and construction contracts that were provided. Duplicate or overlapping road segments in the database and other issues were corrected, resulting in a final sample of 4,540 miles of highway as the candidate segments for analysis. It is important to note this differs from the 5,326 total miles of highways that MDOT reports have received CLRS in the three-year installation program. This is due to some MDOT offices not providing contract completion data.

From this installation database, each of the highway segments were identified and crash data for the “Before” period were queried via the Michigan State Police crash database. This dataset included all crashes that occurred during the three years preceding installation of rumble strips for each segment provided by MDOT and included a total of 54,767 crashes (Table 22). As centerline rumble strips are designed to improve safety along mid-block road segments, all crashes that were coded as having occurred at an intersection, interchange, or non-traffic area were removed, resulting in a crash database totaling 41,979 crashes. The UD-10 crash report forms for these crashes were acquired via the Traffic Crash Reporting System (TCRS).

Table 22. Summary of “Before” Crash Data

YEAR OF CLRS INSTALLATIONS	NO. OF ROADWAY MILES	3 YEARS OF “BEFORE” CRASHES		
		INTERSECTION AND OTHER CRASHES IRRELEVANT TO CLRS	CRASHES FOR MANUAL REVIEW	TOTAL
2008	1,494	4,489	14,537	19,026
2009	1,310	4,116	12,527	16,643
2010	1,736	4,183	14,915	19,098
TOTAL	**4,540**	**12,788**	**41,979**	**54,767**

The “MTCF Data Query Tool” was used to identify candidate crashes for the study segments. The part of the Query Builder gives the following options:

- Intersections
- Interchange
- Mid-Block, and
- Non-Traffic Area

The crashes were then separated according to the noted locations. The entire three-year “Before” crash data for each of the noted categories of locations are as follows:

- Intersections - 12,433
- Interchange - 354
- Mid-Block, and - 41,979
- Non-Traffic Area - 1

Total - 54,767

Manual Review

From this database of 41,979 crashes, it was necessary to determine the number of target crashes that are potentially correctable by installation of rumble strips. Crashes were classified as target if it was determined that the presence of centerline rumble strips may have potentially prevented the crash, or otherwise influenced the severity of the crashes and the outcome. In addition to these crashes, other crashes that may be correctable, but involved other specific contributing circumstances, were also included in the target group of crashes. All 41,979 UD-10 forms were individually analyzed and categorized as target or non-target based on the written description and diagram provided on the form. The crashes were categorized into one of four categories:

- **Typical Target Crash -** This includes crashes where the driver crossed the centerline due to inattention, tiredness, an aggressive passing maneuver, or some other cause which may be potentially correctable by the presence of a centerline rumble strip. It is important to note that this category does not include crashes that may have had another contributing circumstance or a prior event that may have forced the driver to cross or touch the center line.

- **Alcohol/Drugs/Other Involved Crash -** This includes crashes where the crash report noted that the driver was impaired. However, a critical review of the diagram and the crash report (UD-10) indicated that the vehicle encroached into the centerline and the drift-off action could be alleviated by the installation of CLRS. This qualified category produced a very small number of target crashes.

- **Adverse Pavement Condition -** This category includes crashes where the crash report noted that the wet/icy/snowy road conditions may have partially contributed to the driver crossing the centerline. Drift-off crashes under adverse weather/pavement condition often occur due to drivers' selection of inappropriate speed for the condition. The portion of crashes that was included in this target crash group was a small percentage (approximately 10% of all non-intersection adverse pavement condition-related crashes) of all adverse weather-related crashes. The UD-10 reports in this group of crashes noted adverse pavement conditions and also the driver crossed the centerline without being forced by contact with another vehicle or object. It is expected that the presence of CLRS may impact the outcome in terms of reduction in speed and/or path of the errant vehicle, thus impacting the outcome. In most cases, the UD-10 narrative does not indicate if the driver is sleepy, inattentive or distracted.

The presence of CLRS even on a wet/icy/snowy pavement often creates one or more of the following consequences:

1. Creates somewhat slightly bumpy ride, thus assists the driver regaining improved control.
2. Allows speed reduction.
3. If there is hydroplaning, probably nothing can mitigate such crashes. True hydroplaning crashes are extremely rare.
4. There are anecdotal stories from the Michigan Department of Transportation (MDOT) and other local agency engineering and enforcement officials in the Upper Peninsula that rumble strips provide the necessary tactile guidance during white-out conditions and/or when the road surface is covered with snow.

The noted observations necessitate the inclusion of crashes in adverse weather and Alcohol/Drug/Other categories in the target group. However, maintaining these crash type categories allows the Phase 2 researcher the option to use or not use these as target crashes.

- **Deer/Animal/Fixed Object -** This includes crashes where the crash report noted that the driver claimed a deer, animal, or other object caused them to take evasive action that resulted in crossing the centerline and was involved in the crash. It should be noted that crashes where the driver did have contact with an animal or object, it was considered as a non-target crash. Target crashes in this category were a very small portion [268 out of a total of 31,068 Deer/Animal/Fixed Object (coded) of total crashes in this category]. This small group was included in the CLRS target group, since review of the diagram led to the conclusions that the presence of CLRS may have impacted the outcome.

- **Other Target Crashes –** There were some crashes labeled as "Angle" crashes, which involved vehicles from opposite directions. In such circumstances one vehicle crossed the centerline and collided with the vehicles from the opposite direction. In spite of the collision occurring at other than true head-to-head collision, they were grouped in the "Head On" category, as included in Table 23.

As a result of the manual review of the UD-10 forms, a total of 4,576 crashes out of 41,979 were identified as target crashes that required further analysis. Summary statistics for these crashes are presented in Tables 23 and 24. The target crash data are aggregated by crash type, as well as the year the centerline rumble strips were installed.

The following is the overall breakdown of the three-year "Before" target crashes:

Target Crashes by Category	
Type	**Crashes**
Typical	2,971
Alcohol/Drug/Other	146
Weather	1,191
Deer/Object	268
Total	**4,576**

Table 23. Type of Target "Before" Crashes (3 Year Period) and Rates

CRASH TYPE	2008 INSTALLATION SAMPLE 1,494 MILES		2009 INSTALLATION SAMPLE 1,310 MILES		2010 INSTALLATION SAMPLE 1,736 MILES		TOTAL SAMPLE 4,540 MILES	
	Crashes	Rate*	Crashes	Rate*	Crashes	Rate*	Crashes	Rate*
Head On	230	0.051	174	0.044	191	0.037	595	0.044
Sideswipe Opposite	195	0.044	146	0.037	139	0.027	480	0.035
Sideswipe Same	96	0.021	77	0.020	103	0.020	276	0.020
Run Off Road Left	1,102	0.246	842	0.214	971	0.186	2,915	0.214
Run Off Road Right	97	0.022	54	0.014	68	0.013	219	0.016
Rear End	2	0.000	2	0.001	2	0.000	6	0.000
Other	30	0.007	24	0.006	31	0.006	85	0.006
TOTAL CRASHES/RATES	1,752	0.391	1,319	0.336	1,505	0.289	4,576	0.336

* Rate - Crashes/Installation Sample Miles/Year

Table 24. Summary of "Before" Period Crash Data – By Year

YEAR OF INSTALLATION	2008		2009		2010		TOTAL	
INSTALLATION MILES OF CENTERLINE RUMBLE STRIPS	1,494		1,310		1,736		4,540	
PERIOD	CRASHES		CRASHES		CRASHES		CRASHES	
	TARGET	TOTAL	TARGET	TOTAL	TARGET	TOTAL	TARGET	TOTAL
1 YEAR PRIOR	656	6,471	393	5,457	494	6,270	1,543	18,198
2 YEAR PRIOR	528	6,205	440	5,687	553	6,440	1,521	18,332
3 YEAR PRIOR	568	6,350	486	5,499	458	6,388	1,512	18,237
TOTAL (3 YR. PERIOD)	1,752	19,026	1,319	16,643	1,505	19,098	4,576	54,767
ANNUAL AVERAGE	584	6,342	440	5,548	502	6,366	1,525	18,256
CRASH/MILE/ YEAR	0.391	4.245	0.336	4.235	0.289	3.667	0.336	4.021

The definition used in classifying the target crashes into various crash types, as included in Table 23 (page 67), are:

> Head On – Vehicles approaching from opposite directions and one vehicle crosses the centerline and collides with another vehicle.
>
> Sideswipe Opposite – Vehicles approaching from opposite directions when one vehicle crosses the centerline and sideswipes the vehicle coming from the opposite direction.
>
> Sideswipe Same – Both vehicles travelling in the same direction. One vehicle crosses the centerline for passing or turning, and misestimates the other vehicle's speed and/or path, causing a sideswipe in the same direction. Such crash type was identified after reviewing the crash descriptions and diagrams in the UD-10 reports.
>
> Run Off Road Left – Vehicle crosses the centerline and leaves the roadway on the left.
>
> Run Off Road Right – Vehicles encroach the centerline before travelling to the right. Vehicles drifting off to the right without touching or crossing the centerline are not included in this category since existence of CLRS will not impact such crashes.
>
> Rear End – Both vehicles travel in the same direction. One vehicle crosses the centerline and then collides into the back of the other vehicle.
>
> Other – Crashes that involve a vehicle that crosses the centerline, but does not fall in the crash categories described above.

Samples of UD-10s for each of these types of crashes are included in Appendix IV.

The details of the traffic crashes by each highway segment are included in Appendix V. This data is separated by study segment for each of the three installation years (2008, 2009 and 2010).

It is important to note that the "Deer/Animal" involved crashes are the most predominant type of crashes associated with high speed, non-freeway, highways in Michigan. This study is the Phase 1 of a larger effectiveness evaluation study that involves identification and analysis of the "Before" crash data at high speed, non-freeway roadways that received CLRS during the years 2008, 2009 and 2010. A nominal comparison of one year of "After" crash data was performed in order to establish a documented recommendation for the future Phase 2 study.

The highway segments where CLRS were installed in 2008 have experienced three years of "After" crash data. Table 25 presents three-year average of "Before" crashes by severity for the 1,494 miles of CRS installation locations. The "After" data is for the same highway segments, but for one year of crash data only.

Table 25. 2008 Installations - "Before" and "After" Crash Comparison - By Severity

CRASHES	"BEFORE" (ANNUAL AVERAGE*)				"AFTER" (ONE YEAR)			
	FATAL	INJURY	PDO	TOTAL	FATAL	INJURY	PDO	TOTAL
Target	13	214	357	584	8	127	257	392
Non-Target Coded as Non-Deer	22	647	1,587	2,256	23	589	1,491	2,103
Non-Target Coded as Deer	0	74	3,428	3,502	0	76	3,754	3,830
TOTAL	**35**	**935**	**5,372**	**6,342**	**31**	**792**	**5,502**	**6,325**

*Average of three year "Before" period

This comparison of "Before" and "After" crash data is included for providing a supportable recommendation only. It is not intended for any conclusive statistical inference of crash effectiveness.

A visual comparison shows the following:

- Total frequency of "After" crashes (all) for the 2008 CLRS installation group is virtually same as the annual average "Before" crashes (all).
- Total target crash and injury frequency decreased considerably during the "After" period.

- Injury crashes are substantively lower in the “After” period as compared to annual average “Before” crashes indicating potential positive impact.
- Deer crashes increased during the “After” period.

Table 26 presents the “Before” crashes by each of the three CLRS installation years. The “After” data presents one year of data. The data in the table also includes surrogate exposure based rate factors in addition to the crash frequency data. Crash frequencies were converted to “frequency per installation road miles.” It is not possible to obtain vehicle miles of travel data for each highway segment. Therefore, comparing various crash categories per unit installation miles, normalizes the data. The data clearly demonstrates a downward trend for the target crashes.

Table 26. "Before" and "After" Crash Data - Annual Averages - By CLRS Installation Year

INSTALLA-TION YEAR	MILES OF CLRS INSTALLED HIGHWAYS	“BEFORE” (ANNUAL AVERAGE*)						“AFTER” (ONE YEAR)					
		DEER CRASHES	DEER CRASHES PER MILE	TARGET CRASHES	TARGET CRASHES PER MILE	TOTAL CRASHES	TOTAL CRASHES PER MILE	DEER CRASHES	DEER CRASHES PER MILE	TARGET CRASHES	TARGET CRASHES PER MILE	TOTAL CRASHES	TOTAL CRASHES PER MILE
2008	1,494	3,516	2.354	584	0.391	6,342	4.245	3,841	2.571	392	0.262	6,325	4.234
2009	1,310	3,167	2.418	440	0.336	5,547	4.234	N/A	N/A	N/A	N/A	N/A	N/A
2010	1,736	3,853	2.219	502	0.289	6,366	3.667	N/A	N/A	N/A	N/A	N/A	N/A

*After values are based on one year (2009) of crash data for 2008 installation segments only.

X. CONCLUSIONS AND RECOMMENDATIONS

The goal of determining the impact associated with the installation of rumble strips on high-speed non-freeway highways in Michigan requires a comparison of “Before” and “After” data of various driver performance-related parameters, speed characteristics, roadside noise, pavement performance, and traffic crashes. This Phase 1 study goals included identification and analysis of three years’ of “Before” crash data on 2008, 2009 and 2010 rumble strip installation sites. The driver performance and other characteristics that may reveal quantitative impacts of rumble strip installations were compared.

The various studies performed as a part of this research have been described earlier in this report. These individual studies include detailed conclusions. The following presents the summary of all such conclusions related to driver behavior which are important in making an overall assessment of effectiveness of the CLRS installation program in Michigan.

A. Performance observations:

- Drivers tend to move away from centerline and place themselves more centrally in the lanes in the presence of rumble strips. This requires increased attention towards driving and results in improved operation, and may alleviate traffic crash and severity consequences.

- Lane positioning improved significantly for all types of vehicles in the presence of rumble strips.

- Improvement in lane positioning occurred both at horizontal (curve section) and tangent sections.

- Vehicle encroachment frequency or rate on centerline and/or edgelines is often considered as a surrogate measure of safety performances. Reduction of encroachment was observed in the study and they were statistically significant.

- High definition video camera-based technique provided a reliable and verifiable method of driver performance data collection.

- Data extraction from videos provided quality and reliable observational data ideal for application of modern quality assurance/quality control (QA/QC) methods.

B. Bicyclist observations

Sharing the road between all users is critical to efficient use of highway facilities and satisfying individual trip desires. While freeways are restricted to motorized transportation modes, non-freeway state trunklines are often used by road users of other modes, such as bicycles and pedestrians. The following represents conclusions related to the above:

- Use of post-mounted cameras provides a reliable method of tracking dynamic events that may demonstrate driver behavior in the presence of bicyclists.
- Study included a total of 1,197 events consisting of a motor vehicle passing a moving bicyclist in the study area.
- 47.7% (571 out of 1,197) of these events occurred on segments with rumble strips and 52.3% occurred on segments without rumble strips.
- Study indicated decrease in likelihood of motor vehicles riding onto or across the centerline in the presence of CLRS.
- Lateral position of bicyclists impacted position/placement of the motor vehicles in the travel lane.
- Presence of oncoming traffic reduced the likelihood of centerline contact/encroachment for the vehicular traffic.

C. Bicyclist opinion survey results

An online survey of the Michigan bicyclist community was performed. Two hundred thirteen (213) completed surveys were received and analyzed. Observations from this survey, related to the rumble strip program, include:

- Majority of bicyclists drive differently on highways where rumble strips are present.
- Half of the respondents believe roads should have a minimum paved shoulder width of 6 ft that can have rumble strips.

- About one-quarter consider that 12 ft gap length adequate for their maneuverability.
- Approximately one-quarter believe they are less safe on roadways with CLRS.
- Almost half felt less safe on roadways with both CLRS and SRS.
- Two-thirds believe that special signs or markings in advance of the rumble strip sections will be helpful.

D. Short-term pavement performance observations

A study of short-term pavement performance was conducted using MDOT's pavement imagery data for a random sample of 275 miles of highway with CLRS and 182 miles of highways where no CLRS was installed. Two sets of imagery data were available for the test and control group. The following represents the conclusions:

- The average number of transverse cracks per one-tenth of a mile segment before and after installation of CLRS in a two-year period produced an average increase of 3.45 cracks per tenth of a mile.
- The increase in the average frequency of cracks for the control group (no CLRS installed) in two years was observed to be 3.79 cracks per tenth of a mile.
- The historical crack propagation data demonstrated virtually the same rate of increase in the frequency of cracks per tenth of a mile. The increase can be attributal to pavement age rather than the influence of the installation.
- The installation of CLRS did not create any adverse impact on the short-term pavement performance.
- A comparison of pavement performance between upper, northern lower and southern lower peninsula did not demonstrate any discernable difference that can be attributable to the installation.

E. Roadside noise observations

A test vehicle study with a stationary roadside noise meter was performed at a number of rumble strip installation sites. This study was conducted on twelve Michigan routes where CLRS were installed. Only four of these highways included both CLRS and SRS. The following are the conclusions:

- The mean increase in noise level at these sites when test vehicles were on the CLRS was 8.1 dBA (72.6 dBA to 80.7 dBA), as compared to when the test vehicle was not on the CLRS or SRS.
- Depths of CLRS below 0.5 inches produced a mean peak noise of 77.82 dBA and rumble strips with depths of 0.5 inches or greater produced a mean peak noise of 84.62 dBA.
- The test sites with 0.375 CLRS depth produced a mean peak noise of 77.5 dBA.
- Rumble depth is the biggest factor that affects the amount of noise produced by a rumble crossing. Therefore, adherence to MDOT recommended standard depth of 0.5 inch at the center and 0.375 inch at the outer edges is desirable and should be continued in the future for all CLRS installations.
- The mean increase in noise with test vehicles on SRS, as compared to off all rumble strips, was recorded as 9.9 dBA.
- The noise levels of trucks not riding over the CLRS or SRS (83 dBA) was greater than the noise level generated by the test vehicles driving over either the CLRS or SRS.

F. Speed study

Sample speed studies were performed before and after installation of rumble strips. Off-peak hour speed studies were performed on six Michigan routes in the eastern part of the Lower Peninsula. MDOT also performed 24-hour speed studies using automatic counters at seven additional locations. In both studies, there were no discernable differences in the mean and 85th percentile speeds between before and after the installation of rumble strips. Therefore, it can be concluded that installation of CLRS did not impact the overall travel speed.

G. Analysis of "Before" crash data

A comprehensive study of the "Before" crash data for a three-year period was performed as a part of this Phase 1 study. The conclusions of this study are:

- 4,540 miles of high-speed non-freeway roads were identified as the candidates for this analysis. According to MDOT, there were approximately 5,400 miles of CLRS installed on high-speed non-freeway locations. However, the start date, starting point and ending point of several contracts were not received. Elimination of these segments, as well as intersection areas, resulted in the analysis of data for a total of 4,540 miles of highways where CLRS were installed.
- The three years of "Before" data analysis produced a total of 4,576 crashes that can be considered as target crashes. It is expected that such target crashes may be alleviated by installation of CLRS and are candidates for the "Before" and "After" study that will be performed in the Phase 2 effectiveness evaluation study.
- The annual average "Before" crash frequency for 4,540 miles of candidate highways are:

    Fatal - 13
    Injury - 214
    PDO - 357
    Total - 584
- The "Before" crash data has been organized to allow a direct comparison of "Before" and "After" crash and injury data in Phase 2 of the impact analysis.

A cursory review of one year of "After" crash data was analyzed for the highway segments (1,494 miles) that received CLRS treatment in the year 2008. This function was not part of the scope of the Phase 1 study. A comparison of annual average "Before" crash data and only one year of "After" crash data for the 2008 CLRS installation sample revealed the following:

- Total frequency of "After" crashes (all) for the 2008 CLRS installation group is virtually same as the annual average "Before" crashes (all).
- Total target crash and injury frequency decreased considerably during the "After" period.
- Injury crashes are substantively lower in the "After" period as compared to annual average "Before" crashes indicating potential positive impact.
- Deer crashes increased during the "After" period.

This result indicates that a properly performed Phase 2 study may reveal many objective safety-related findings that can be used to evaluate MDOT's statewide CLRS program. These findings would also provide a valuable resource for other states that are considering design and implementation of such areawide safety and operational improvement programs.

Recommendations

The following are the recommendations for future work related to CLRS impact analysis:

- Conduct further driver behavior-related video-based studies to allow for a temporal comparison of driver performances in the presence of CLRS. This study should be performed at the same locations of the Phase 1 study.
- The driver behavior in the presence of moving bicyclists should also be assessed in the Phase 2 study. Conducting a study at the same locations will provide valuable insight into the driver-bicyclist interaction characteristics over time.
- The "After" crash data should be collected for the same highway segments as was included in the Phase 1 study for a three-year "After" period.

- The “Before” and “After” effectiveness evaluation study of the entire 4,540 miles of highways should be included in the Phase 2 study.
- A well designed effectiveness evaluation study may also be included that utilizes the “Empirical Bayes (EB)” method.
- The Phase 2 study performance period should be two-years, allowing for the inclusion of three years of “After” crash data for the 2010 CLRS installation group. The following “After” periods should be included for in “After” crash database in the Phase 2 study:
    - 2008 CLRS installation group: 2009, 2010, and 2011
    - 2009 CLRS installation group: 2010, 2011, and 2012
    - 2010 CLRS installation group: 2011, 2012, and 2013
- Phase 2 study performance period should be from June 2013 to July 2015.
- MDOT may also consider having an interim report that includes the analysis of two out of three years of CLRS installations’ crash data analysis.
- MDOT may develop technical note document that demonstrates the rumble strip installation standards, expected consequences of CLRS and SRS, potential cost-benefit data that can assist further implementation of CLRS and SRS on high-speed county roadways.

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