FHWA-NJ-2018-004

Evaluation of Raised Pavement Markers

FINAL REPORT
July 2018

Submitted by

Xiang Liu, Ph.D.
Assistant Professor of Civil & Environmental Engineering
Rutgers, The State University of New Jersey

John Bullough, Ph.D.
Director of Transportation & Safety Lighting Programs
Rensselaer Polytechnic Institute

Liwen Tian
Graduate Research Assistant of Civil & Environmental Engineering
Rutgers, The State University of New Jersey

Shan Jiang
Graduate Research Assistant of Industrial & Systems Engineering
Rutgers, The State University of New Jersey

Mohsen Jafari, Ph.D.
Professor of Industrial & Systems Engineering
Rutgers, The State University of New Jersey

NJDOT Research Project Manager
Pragna Shah

In cooperation with

New Jersey
Department of Transportation
Bureau of Research
And
U.S. Department of Transportation
Federal Highway Administration

DISCLAIMER

TECHNICAL REPORT
STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA NJ-2018-004		

4. Title and Subtitle	5. Report Date
Evaluation of Raised Pavement Markers	July 2018
	6. Performing Organization Code
7. Author(s) Xiang Liu, John Bullough, Liwen Tian, Shan Jiang, Mohsen Jafari	8. Performing Organization Report No.
9. Performing Organization Name and Address Rutgers, The State University of New Jersey Piscataway, NJ 08854 & Rensselaer Polytechnic Institute Troy, NY 12180	10. Work Unit No. 11. Contract or Grant No. Task Order 328
12. Sponsoring Agency Name and Address New Jersey Department of Transportation PO 600 Trenton, NJ 08625 Federal Highway Administration U.S. Department of Transportation Washington, D.C.	13. Type of Report and Period Covered FINAL September 1, 2015 to February 28, 2018 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In the State of New Jersey, raised pavement markers (RPMs) are used along all centerlines and skip lines, regardless of traffic volume, roadway geometry, or roadway classification. The extensive use of RPMs has raised interest in understanding 1) whether this significant investment generates variant safety benefits at different locations; 2) whether there are alternatives or modifications to the existing RPMs; and 3) how to optimize the installation, monitoring, and maintenance of RPMs and their promising alternatives in order to attain a more cost-effective safety improvement.

This study reviewed the relevant literature and provided a methodological framework for quantifying the safety effectiveness and implementation costs of RPMs and their alternatives given specified road and traffic characteristics. A luminance measurement method was developed to allow researchers to estimate the luminance of these devices and to compare different reflective pavement markers and their alternatives regarding the ability to provide visual delineation. The study also analyzed the installation practices in various states and proposed guidelines for the use of RPMs and relevant alternatives accounting for various road classification, geometry, and traffic factors. Finally, the study developed a computer-aided decision support tool that can be used to calculate the life cycle cost of RPMs and other alternatives, thereby supporting decisions with respect to the optimal use of safety investment.

17. Key Words	18. Distribution Statement
Raised pavement markers, Transportation safety	

19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	167	

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

This research was supported by New Jersey Department of Transportation. We thank Eileen Sheehy, Angelo Mendola, Chris Barretts, Vasudevan Ganarajan, Gary Leach, Andrew Zeleznock, Mamun Rashid, Amanda Gendek, Pragna Shah, and Camille Crichton-Sumners for providing helpful support in this research.

We thank all the collaborators from 3M (Juan Carlos Ojeda Alcala, Leah Picone, Steven Rhyner, Cristina Thomas, Matt Wilding), Ennis Flint (Stephen Bennett, Jerry Britt, Stephen Gainer, Klyne McCarty, Arati Patel, David Villani) and Nightline for their assistance with luminance testing.

We also thank all the students involved in this project from Rutgers University and Rensselaer Polytechnic Institute, for their diligent and efficient work.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER 1: LITERATURE REVIEW

Executive Summary

Raised pavement markers (RPMs) have been used throughout the world since the 1930s. In the State of New Jersey, RPMs are used along all centerlines and skip lines, regardless of traffic volume, roadway geometry, or roadway classification. The extensive use of RPMs has increased interest in understanding the safety benefits, promising cost-effective alternatives or modifications, and the best practices for RPMs. Under the auspices of the New Jersey Department of Transportation (NJDOT), Rutgers University is conducting a study evaluating RPMs. This chapter presents the results of a comprehensive literature review on this subject.

The review of previous studies has led to the following observations:

- There is no consensus regarding whether and how RPMs affect the crash rate. Depending on scope and data, different studies report different magnitudes of safety changes (positive or negative) after RPMs are implemented.
- There are various alternatives and modifications possible for RPMs, such as rumble strips and traffic tape. The use of these alternatives varies by state.

In the next step, this project will develop a methodological framework for quantifying the cost-effectiveness of RPMs and their alternatives according to specified road and traffic characteristics.

Introduction

In the United States, more than one-third of fatal crashes on two-lane undivided highways and 27 percent of fatal crashes on four-lane divided highways occur in dark, unlighted conditions. (1) Raised pavement markers (RPMs) are widely used along centerlines and edgelines to improve preview distance and provide guidance for drivers in inclement weather and low light conditions. There are two main types of RPMs: snowplowable and non-snowplowable RPMs. Non-snowplowable RPMs, widely used in the southern and western parts of the United States, have a rounded or square reflector epoxied to the pavement surface. By contrast, snowplowable RPMs have a metal housing designed to protect the reflector from snowplow hits. [(2)] The State of New Jersey and other states with frequent winter snows commonly use snowplowable RPMs.

A previous study published by the National Cooperative Highway Research Program (NCHRP) evaluated the safety effectiveness of RPMs in several states. [(3)] According to this study, there was no consensus regarding whether and how RPMs affect roadway safety. For example, positive effects were found in New York for total nighttime crashes where RPMs were installed at locations selected according to their wet-weather nighttime crash history. However, similar safety effects were not found in Pennsylvania, where RPMs were implemented at locations selected on the basis of total nighttime crash history. Using a disaggregated statistical approach, Bahar et al. [(3)] found that at AADTs (Annual Average Daily Traffic) ranging between 15,000 and 20,000 vehicles/day on a roadway with a degree of curvature less than 3.5, RPM implementation resulted in an estimated 24.3% reduction in nighttime crashes. At lower AADTs and sharper curvatures, however, the locations with RPMs had increased crash risk. Finally, the NCHRP study stated that “in general, there have been few comprehensive and conclusive studies performed that quantify the safety effects of RPMs.” The use of different data and analytical methodologies may partly explain the discrepancy in prior RPM safety evaluation research. This problem motivates the development of new research to evaluate the use of RPMs in New Jersey based on suitable data and methods.

As part of this research effort, a comprehensive review of the prior research effort was conducted to accomplish the following objectives:

- Evaluate methodologies for estimating the safety effectiveness of RPMs
- Identify data needs for normative safety evaluation studies
- Identify potential alternatives or modifications of RPMs
- Discuss the "best practices" of RPM installation, monitoring, and replacement
- Suggest possible research directions

This chapter is structured as follows: First, we discuss the sources of the literature that were reviewed. Second, we review, categorize, and evaluate the useful information and findings for each study. Third, we develop a taxonomy of the current data collection and analysis methods for evaluating RPMs. Fourth, we identify and discuss potential alternatives or modifications of RPMs. Fifth, we analyze the current and emerging asset-management strategies for maximizing the utility of RPMs or alternatives/modifications. Finally, we propose several research directions in the next phase of the study. As the project progresses, we will endeavor to continuously enhance the existing understanding of the use and impact of RPMs and their asset management practices.

Literature Source

We used various databases within the Rutgers University Library, Google Searches, and Google Scholar to identify a number of relevant studies. Furthermore, we retrieved several previous reports from the website of the New Jersey Department of Transportation Research Bureau. Below is a list of the sources of the articles or reports we have collected so far.

<u>Academic Journals</u>

- Journal of Institute of Transportation Engineers
- Transportation Research Record: Journal of the Transportation Research Board, Vol. 975, 1784, 1897 and 2258
- Journal of Traffic Engineering, 1966
- Journal of Traffic Engineering & Control, Vol. 33 1992, and Vol. 40, 1999

Research Reports

Texas Transportation Institute, College Station, Texas

- Evaluation of Wet Weather and Contrast Pavement Marking Applications
- Evaluation of Wet Weather Pavement Markings: First Year Report
- Using the Before-and-After Design with Yoked Comparisons to Estimate the Effectiveness of Accident Countermeasures Implemented at Multiple Treatment Locations
- An Evaluation of the Accident Reduction Effectiveness of Raised Pavement Markers
- Evaluation of the Safety Effects of Raised Pavement Markers
- Evaluation of Accident Methodology

Center for Transportation Research, University of Texas at Austin

- Before-After Comparison of Edgeline Effects on Rural Two-Lane Highways

Federal Highway Administration

- Alternatives to Raised Pavement Markers (RPMs)
- Pavement Marking Demonstration Projects: State of Alaska and State of Tennessee
- Safety Evaluation of Centerline Plus Shoulder Rumble Strips
- Synthesis of Benefits and Costs of Alternative Lane Marking Strategies
- Guidelines for the Use of Raised Pavement Markers
- Technical Advisory for Shoulder and Edgeline Strips and Center Line Rumble Strips
- Roadway Delineation Practices Handbook
- Safety Comparison of Roadway Design Elements on Urban Collectors with Access

New York State Department of Transportation (NYSDOT)

- Long-Term Performance of Grooved Stripe-reflective Markers
- Highway Safety Improvement Program – Annual Evaluation Report
- Raised Reflectorized Snowplowable Pavement Markers: A Report to the Governor
- Special Specification 688.10XX-18 Preformed, Wet-Reflective Tape (Grooved Pavement Method
- Centerline Rumble Strips on Secondary Highways: A Systematic Crash Analysis

Purdue University

- Crash Reduction Factors for Indiana
- Retroreflectivity Durability Comparison of Rumble Stripes vs. Painted Line

Virginia Transportation Research Council

- Evaluation of Pavement Markings for Improved Visibility during Wet Night Conditions
- Wet Night Visibility of Pavement Markings

Florida Department of Transportation

- Update of Florida Crash Reduction Factors and Countermeasures to improve the Development of District Safety Improvement Projects

Kentucky Transportation Center

- Evaluation of the Use of Snowplowable Raised Pavement Markers

University of North Carolina

- Accident Research Manual

North Dakota Department of Transportation

- Evaluation of Snowplowable Reflective Pavement Markers for Effective Delineation

Vermont Agency of Transportation

- Evaluation and Comparison of Snowplowable Raised Pavement Markings (SRPMs)

Arizona State University

- Spacing of Raised Reflective Pavement Markers

Maryland State Highway Administration

- Evaluation of Snowplowable, Retroreflective Raised Pavement Markers

Center for Transportation Research and Education, Iowa State University

- Pavement Markings and Safety

University of Connecticut

- Estimating Benefits from Specific Highway Safety Improvements

State of Georgia

- Effect of pavement markers on nighttime crashes in Georgia

Alberta Transportation

- Study of Snowplowable Raised Pavement Markers

Engineering Manuals

- Manual on Uniform Traffic Control Devices, Federal Highway Administration, Washington, D.C., 2009
- Traffic Control Devices Handbook. Institute of Transportation Engineers, 2001

Safety Evaluation of RPMs

Wright et al. [4] studied the effects of RPMs on nighttime crashes at horizontal curves on two-lane highways with more than six degrees of curvature in Georgia. In this study, the change in nighttime crashes (from 6:00 p.m. to 5:59 a.m.) was examined and daytime crashes at the same sites were used as a comparison group. RPMs were installed between 1977 and 1979 on centerlines. A log-linear model was used to analyze the accident data stratified by the year of installation, daytime-versus-nighttime crashes, and before-versus-after the installation period. The study found a 22 percent reduction in the number of nighttime crashes. Single-vehicle crashes were reduced by a larger amount compared to other types of nighttime crashes. Also, the reduction in nighttime crashes is independent of traffic volume or horizontal curvature for curves with the degree of curvature greater than 6. [5] The findings indicate that RPMs can improve highway safety on horizontal curves on two-lane highways with more than six degrees of curvature during nighttime. This reduction may be due to the better preview that RPMs provide during nighttime. However, the use of daytime crashes as a control group assumed that RPMs have no effect on roadway safety in the daytime, which may not always be true. [6]

Kugle et al. [7] analyzed nighttime crash risk by crash severity. The analysis was based on crash data for a two-year period before RPM installation and crash data for a two-year period after RPM installation at 469 Texas locations ranging in length from 0.2 to 24.5 miles (0.32 to 39.4 km). Total daytime crashes served as the comparison group, under the assumption that RPMs have no or little effect on daytime crashes. The AADT, the number of lanes, and the number of wet weather days were collected in this study. Two-, three-, four-, five-, and six-lane roadways were studied. The analysis used three statistical methods. In the first method, the cross-product ratio was calculated as an overall measure of effectiveness using daytime crashes as the comparison group. In this method**,** data from all sites were aggregated. Site-specific differences in certain factors (e.g., AADT) were not explicitly accounted for. In the second method, the cross-product ratio at each individual location was calculated and each estimate was weighted by the total number of crashes at that site. The third method was a logistic regression model. The probability of a nighttime accident occurring was modeled as a function of time (before/after), AADT, and the number of lanes. The authors found a 15 percent increase in nighttime crashes and a nonsignificant 1.4 percent decrease in wet-weather crashes using the first method; a 31 percent increase in nighttime crashes and a nonsignificant 1 percent decrease in wet-weather crashes using the second method; and a significant increase in nighttime crashes and a nonsignificant decrease in wet-weather crashes were shown in the logistic regression model. A reduction in both nighttime and wet weather crashes was observed in roughly half of the sites; however, roughly 10 percent of the sites indicated very large increases in total crashes, which probably skewed the overall result. The number of nighttime crashes increased from 15 percent to 31 percent (depending on the type of crash). No significant effect of RPMs on wet-weather crashes was found.

Mak et al. [(8)] used a subset of the data from Kugle et al. [(7)] The subset was obtained by screening the original database of 469 locations, and those locations that underwent major modifications other than the RPM installation during the evaluation period were eliminated. They also eliminated several other locations from the original database of 469 locations, because they experienced no crashes in either the 2-year period prior or the 2-year period after the implementation of RPMs. After this screening process, only 87 of the original 469 locations were included in the analysis. The data for intersection type, within/outside city, horizontal curvature, grade, structures, the number of lanes, and divided/undivided were collected. A before-and-after study employing the comparison group method was used to analyze the data. Total daytime crashes were used as a comparison group to account for any factors that may have influenced crash frequency between the before and after periods which were not caused by the RPM installation. However, crashes occurring during dusk or dawn were not included in the daytime crashes; they reported that dusk and dawn crashes that were not included in the analysis accounted for between 1 percent and 3 percent of the total crashes. 4.6 percent of locations showed significant crash reductions, 10.3 percent showed significant increases, and 85.1 percent showed nonsignificant effects. This study's findings differed considerably from those found by Kugle et al., (7) although Mak et al. (8) used a subset of the same data.

Griffin (9) used the same data as Mak et al. (8) In this study, they did not include one of the locations used in the previous analysis because it could not be located. This analysis also utilized a before-and-after study employing a comparison group. Total daytime crashes were used as a comparison group. The before-and-after periods were two years in length. Eighty-six locations were considered as treatment locations and were analyzed. Average or overall effect of RPM installation on nighttime crashes was estimated by calculating a weighted log odds ratio. The expected change in nighttime crashes after the installation of RPMs was a 16.8 percent increase, estimated with 95 percent confidence according to this methodology.

Pendleton (10) researched the effects of raised pavement marks on total nighttime crashes on divided and undivided arterials in Michigan. Before-and-after methods for evaluating the effect of RPM nighttime crashes were used. RPMs were installed at 17 locations totaling 56 miles (90 km). The RPMs were installed along centerlines on undivided arterials and lane lines on divided arterials. There were 42 control sites without RPMs totaling 146 miles (235 km). Divided/undivided roadways and vehicle miles traveled (VMT) were used as independent variables in an empirical Bayes analysis. The analysis showed an increase in nighttime crashes on undivided roadways and a decrease in nighttime crashes on divided roadways after RPM implementation. “Whether a highway was divided was concluded to be the most significant road characteristic affecting the effectiveness of RPMs”. (5) Larger reductions in crashes were seen when the comparison group was comprised of daytime crashes at treated sites than when the comparison group was comprised of nighttime crashes at untreated sites. “The issue of which comparison group to use stayed unresolved”. (5)

The New York State DOT (11,12) studied the effects of raised pavement markers on total crashes and total nighttime crashes on suburban and rural roadways. Two analyses were conducted using a simple before-and-after method. In the first analysis, unlit suburban and rural roadways with proportionately high numbers of nighttime crashes and nighttime wet-weather crashes at 20 sites were studied. A nonsignificant decrease of 7 percent for total crashes, a highly significant decrease of 26 percent for nighttime crashes, and a significant decrease of 33 percent for nighttime wet weather crashes were found overall. RPMs installed non-selectively over 50 long sections of highway were analyzed in the second analysis. The result of this analysis showed nighttime crashes were reduced by a nonsignificant 8.6 percent, that total crashes were reduced by a statistically significant 7.4 percent, and that nighttime wet-weather crashes increased by a nonsignificant 7.4 percent. Thereafter, the New York State DOT recommended that RPMs be installed selectively. They recommend that the RPMs be installed “when their use is likely to reduce crash frequency cost effectively by improving delineation during nighttime wet weather conditions”. (12) “It further stated that RPMs should be installed only at locations having high frequencies of wet weather, nighttime, guidance-related crashes”. (5)

In Pennsylvania, Orth-Rodgers and Associates, Inc. [13] investigated the effect of RPMs on Interstate highways in rural non-illuminated areas on total nighttime crashes, nighttime wet road crashes, and nighttime wet road sideswipe fixed-object crashes. Both raised and recessed reflective markers were examined in their study. They eliminated sites that had no crashes in the daytime or nighttime periods before or after RPM installation, because in the "odds ratio" methodology that they used, a zero value would make the odd ratio meaningless. They did not include several crash types in their analysis because they considered them to be unrelated to the RPMs. Crashes that happened during dusk, dawn, unknown lighting conditions, no adverse weather conditions, a time when the road surface condition was other than dry or wet, and a time when the crashes for which the impact type was unknown were excluded. They made the following observations: an 18.1 percent overall increase in nighttime crashes; large increases ranging from 30 to 47 percent (confidence limits not reported), depending on the comparison group of crashes used (daytime wet condition, nighttime other than wet condition, or all daytime crashes). Their findings indicate that the raised and recessed pavement markers had negative effects on road safety.

Hammond & Wegmann [6] studied the effects of raised pavement markers (RPMs) on horizontal curves in daytime conditions in Knoxville, Tennessee. Encroachment distances were measured before and after the installation of raised pavement markers at 40-ft (12-m) spacing. Additional raised pavement markers were added to the roadway to change the spacing from 40 feet (12 m) to 20 feet (6 m). The encroachment distances were measured after the installation of additional raised pavement markers. At the same time, the encroachment measurements were being made, the average operating speeds throughout the length of the curve before and after RPM installation were measured. The markers were placed in pairs on two sides of the painted centerline. The Tennessee study produced the following results: vehicle speed was not affected significantly by the raised pavement markers. A statistically significant reduction in encroachment from the control condition to the 40-ft spacing condition was observed. However, the reduction from 40-ft spacing to 20-ft spacing was not statistically significant. The study concluded that the RPMs had a positive effect on highway safety on horizontal roadway curves in the daytime. [(5)]

In 2004, the NCHRP Report 518 [(3)] selected six states for the safety evaluation of raised pavement markers. The study collected highway safety data and analyzed the impacts of raised pavement markers on the safety of two-lane and four-lane roadways. Accident and traffic data were collected from all six states. Two types of safety data analyses were performed: (1) a composite analysis that determined the overall effect of RPMs by state for a number of different crash types (e.g., nighttime, wet weather, and guidance); and (2) a disaggregate analysis that investigated the relationship between the safety effect of RPMs on nighttime crashes and roadway and traffic characteristics. The estimated impacts of RPMs on two-lane roadways were found to be as follows:

- Nighttime head-on crashes decreased, and the benefit of RPMs increased with traffic volume. This is probably because improved delineation of the centerline by RPMs at night and the consequent movement away from the centerline reduced head-on crashes at night. [(5)]
- As the degree of curvature increased, the safety benefit of RPMs decreased. Based on the regression model developed, roadways with a degree of curvature exceeding 3.5 had more crashes after the installation of RPMs. One possible reason might be that as the vehicle moves closer to the edgeline, the risk of run-off-road crashes on two-lane roadways should be higher on roadways with higher degrees of curvature or narrower pavement widths.
- Daytime wet weather crashes decreased slightly with RPMs. Snowplowable RPMs may improve daytime visibility under wet-weather conditions because of “the profile of the RPM housing above the film of water covering the painted markings”. [(5)]

- The effects of RPMs were less significant on well-illuminated roads.

The estimated impacts of RPMs on four-lane roadways are as follows :

- Nighttime crashes decreased after the installation of RPMs
- The safety benefits of RPMs were dependent on traffic volumes. According to Jiang [(5)], "RPMs may only be effective in reducing nighttime crashes on four-lane freeways with AADTs exceeding 20,000 vehicles per day". [(5)] After RPM installation, both guidance-related crashes and wet-weather crashes decreased.

The NCHRP study also provided criteria for selecting appropriate roadway sections for the use of raised pavement markers. An index called the crash modification factor (CMF) was used to evaluate the effect of RPMs. [(3)] The CMF is defined as the ratio of the expected number of crashes after the installation of RPM to the number of crashes had RPMs not been installed. When CMF < 1.0, RPMs are expected to improve transportation safety and when CMF > 1, RPMs are expected to reduce transportation safety. When CMF = 1, it means that RPMs do not affect the safety.

Tsyganov et al. [(14)] analyzed data from rural two-lane highways in Texas to understand the effect of edgeline markers. In this study, a highway network was divided into segments of three miles or greater. Crash data from 1998 to 2001 were used to evaluate the safety benefit of edgeline markers. It was found that accident frequency may be reduced by the addition of edgeline markers on rural two-lane highways. Edgeline markers were found to have the greatest safety benefits on curved segments with narrow lane widths (9 to 10 feet).

Smadi et al. [(15)] conducted a study on the relationship between crash occurrence probability and the retroreflectivity of longitudinal pavement markers in the state of Iowa. A spatial-temporal database was developed that combined representative retroreflectivity values and crash data under dark conditions. A series of logistic regressions were used. The analysis found that crash occurrence probability is inversely associated with the retroreflectivity of longitudinal pavement markers.

In 2013, Das et al. (16) analyzed the safety impact of RPMs on rural and urban roads in Louisiana. On Louisiana freeways, the quality of RPMs along with pavement striping (centerline and edgeline) are inspected annually by one designated engineer. Subjective ratings in three categories (good, fair, or poor) are assigned to describe the condition of RPMs and striping. Rating data were gathered for nine years (2002-2010) for nearly 900 miles of freeway in 533 segments. "The nine years' worth of crashes were populated into each segment based on the longitudinal and latitudinal information". (16) Due to differences in segment length and AADT, the crash rate was used instead of crash frequency. Three analysis methods were used. In the first method, average crash rates in each category were calculated for rural and urban roadways separately. As the combined ratings went from good to poor, the overall crash rate increased. In the second method, the differences between crash rates for different ratings were investigated by t-tests at three AADT levels. The results showed a slight variation in the safety effect of RPMs by AADT. In the third method, a with-and-without crash analysis was used. This analysis showed a significant reduction in crash rates at night by RPMs. All three analyses show that RPMs have a positive impact on rural safety. Regarding urban freeways, the test (t-test) showed no significant difference (either positive or negative) in crash rates under all scenarios. The author believes that the statistical test is the most reliable analysis method. In the remaining two methods, segment averages over the nine years for AADT and crashes were used, possibly making the results less accurate. Furthermore, ratings of RPMs and striping conditions were subjective and susceptible to evaluation errors; however, to account for this potential error, the RPMs in fair condition were not included in the analysis. This study indicated that RPMs have a positive safety impact on rural freeways, but no safety benefit on urban freeways (probably due to the difference in ambient lighting conditions).

Table 1 presents a summary of previous studies regarding the safety evaluation of RPMs.

Table 1 - Selected studies regarding the safety effectiveness of RPMs (3)

Author	Location	Methodology	Conclusions
Wright et al. (1982) (4) Georgia	Horizontal curves on two-lane highways over 6 degrees of curvature	Before-and-after study with comparison group	A 22% reduction in the number of nighttime crashes; single-vehicle crashes were reduced by a larger amount compared to other types of nighttime crashes. Also, the reduction in nighttime crash frequency is independent of traffic volume or horizontal curvature for degrees of curvature greater than 6
Kugle et al. (1984) (7) Texas	Two-, three-, four-, five -, and six-lane roadways	Cross product ratio, Gart's procedure, and logistic regression	15% to 31% increase in nighttime crashes; no significant effect on wet weather crashes
Mak et al. (1987) (8) Texas	Two-, three-, four-, five-, and six-lane roadways	Before-and-after study with comparison group	4.6% of locations showed significant reductions, 10.3% showed significant increases, 85.1% showed nonsignificant effects
Griffin (1990) (9) Texas	Two-, three-, four-, five-, and six-lane roadways	Before-and-after study with comparison group	16.8% increase in nighttime crashes
Pendleton (1996) (10) Michigan	Divided and undivided arterials	Before-and-after study with comparison group	No significant effect; direction of effect positive or negative depending on method used and access control
New York State DOT (1989), (11) (1997) (12)	Suburban and rural roadways	Naive before-and-after study	26% decrease in nighttime crashes when placed selectively, no significant effect when installed nonselectively

Orth-Rodgers and Associates Inc. (1998) [13] Pennsylvania	Interstate highways in rural non-illuminated areas	Before-and-after study with comparison group	18.1% overall increase in nighttime crashes, nighttime wet condition crashes increased from 30 to 47%, nighttime wet road sideswipe or fixed-object collisions increased by 56.2%
NCHRP study (2004) [3]	Two-lane and four-lane roadways	EB before-and-after study	Based on the traffic volume and degree of curvature, RPMs can have a positive or negative effect
Das et al. (2013) [16] Louisiana	Rural and urban roads	With-and-without test	Positive safety impact on rural freeways, but probably due to the difference in lighting conditions, there was no safety benefit on urban freeways.
Smadi et al. (2010) [15] Iowa	Spring/fall database consisting of retroreflectivity measurements collected by the Iowa DOT on state primary roads from 2004 through 2008	Series of logistic regressions	Crash occurrence probability was found to increase as values of longitudinal pavement marker retroreflectivity decreases
Hammond and Wagmann (2001) [6] Tennessee	horizontal curves during daytime	Before-and-after study by comparison group	Pavement markers had a positive effect on highway safety on horizontal roadway curves during daytime.
Tsyganov et al. (2006) [14] Texas	rural two-lane highways where edgeline makers were added	Before-and-after study by comparison group	accident frequency may be reduced by the addition of edgelines on rural two-lane highways

Alternatives to RPMs

NCHRP Report 518 [3] states that, in Colorado and Iowa, RPMs were removed due to high maintenance costs, and that plans for future installations have been halted. Moreover, “The tort liability exposure associated with dislodged RPMs has caused several states, including Iowa, Missouri, and Nebraska, to initiate the removal of Snowplowable Raised Pavement Markers (SRPMs)”. (17) The cost of the installation and maintenance of RPMs has been investigated in several studies. Washington State DOT replaces more than two million RPMs annually at a price of $2.40 per unit. (18) The price for each installed raised pavement marker ranges from $13 to $20. Each lens replacement costs about $3.3 to $8. (5) The Virginia Department of Transportation (VDOT) bid data shows that installing an RPM costs over $23.

A Virginia Tech Transportation Institute Study (19) investigated the visibility distance of RPMs, paint with standard beads, paint with large beads, profiled thermoplastic, wet retroreflective tape, and semi-wet retroreflective tape. They concluded that “The RPMs were visible from a greater distance than any other type of marking under both wet and dry conditions”. (19) Semi-wet retroreflective tape under wet conditions had the next best visibility distance. The luminance of each marker under wet conditions was also examined. Utilizing various methods, it was concluded that RPMs had the highest luminance.

The Texas Transportation Institute (TTI) conducted a series of evaluations of the wet-weather nighttime visibility of different pavement markers, including waterborne paint, thermoplastic, tapes, exotics, and non-snowplowable RPMs. (8) Similar to the study conducted by the Virginia Tech Transportation Institute, TTI’s study also showed that RPMs had the highest visibility distance among the alternatives. They found that RPMs provided the longest detection distance, followed by the 3M A760ES and 380WR tapes. Among non-tape markers, thermoplastic with large beads performed the best. During wet conditions, the study recommended that the Texas Department of Transportation (TxDOT) continue to use a thermoplastic marker with supplemental RPMs.

The University of Iowa conducted several driver studies to assess the detection distance and retroreflectivity of several marking systems. Although RPMs were not included in the analysis, some alternative products were examined. Flat, patterned, and wet-weather tape under dry, wet-recovery (after rainfall), and rain (1 in/hr) conditions were evaluated. [20] Wet reflective tape was found to have the longest detection distances and the highest retroreflectivity under all conditions. Patterned tape was found to perform better than flat tape under wet-recovery conditions, but during a simulated rain event, the two materials had the same level of performance. Paint markers with large beads, patterned tape with high-index beads, and patterned tape with mixed high-index beads were assessed in another study by the University of Iowa. [21]

The Virginia Transportation Research Council (VTRC) examined latex paint with large beads and waffle tape. [22] The visibility of both materials was found to be approximately the same during wet-weather nighttime conditions based on a subjective evaluation.

Many states attempt to increase preview distance by providing more effective painted lane delineation. [3] Snowplowable RPMs are one of the technologies used with painted lines to improve nighttime visibility. Nevertheless, it is expensive to install and maintain RPMs, which may dislodge as the roadway degrades. [3,23,24] When dislodged, the RPMs can result in tire punctures, increased degradation of the pavement, and even become an airborne projectile that could penetrate windshields. [25] Also, as mentioned previously, the tort liability exposure associated with dislodged SRPMs has caused several states, including Iowa, Missouri, and Nebraska, to initiate the removal of all SRPMs. [17] Some agencies also use painted rumble strips [2] to improve visibility in nighttime conditions and to provide vibratory feedback for drivers who depart from the marked lane. [25] An NCHRP project studied the safety effect of the retroreflectivity of pavement markings and markers on state maintained multilane freeways, multilane highways, and two-lane highways in California. [3] In this study, they evaluated the relationship between retroreflectivity and safety over time. They found that the safety benefit associated with greater sight detection distances from retroreflective markings or markers may be diminished when drivers adapt to road conditions. A Federal Highway Administration study examined the safety impacts of the combined application of centerline and shoulder rumble strips on two-lane rural roads in Kentucky, Missouri, and Pennsylvania. (26) The researchers measured the safety effectiveness of the combined application of centerline and shoulder rumble strips by measuring the changes in the frequency of crashes (excluding intersection-related and animal-vehicle crashes). Target crash types included total crashes, injury crashes, run-off-road crashes, head-on crashes, and sideswipe-opposite-direction crashes. They used the empirical Bayes before-after study method for evaluation. They found a statistically significant decrease at the 95 percent confidence level in all crash types. A 36.8 percent reduction in head-on crashes was observed. Run-off-road and sideswipe-opposite-direction crashes decreased by 25.8 percent and 23.2 percent, respectively. For all crash types combined, a 20 percent reduction was observed. (26) According to Mitkey et al., (25) “a collateral benefit of painting edgelines along the rumble strips is the potential to increase the retroreflective durability of the lines, particularly in areas that have substantial winter plowing operations.”

Figure 1. Rumble strips

Source: https://www.fhwa.dot.gov/publications/publicroads/08july/02.cfm

Mitkey et al. [25] state that “under dry conditions, the median coefficient of retroreflectivity for a rumble stripe with glass beads surpassed the standard painted line by approximately 95 percent for white and 80 percent for yellow. A possible mechanism for the improvement in retroreflectivity of the rumble strip is the upward-sloping painted surface located at the back of the rumble.” In summary, the literature has identified the following pavement marking products:

- Waterborne paint [27]
- Paint with standard beads [19]
- Paint with large beads [20]
- Latex paint [22]
- Conventional solvent paint [28]
- Polyurea with bead clusters [29]
- Thermoplastic [29]
- Preformed tape, flat [28]
- Preformed tape, profiled [28]
- Wet retroreflective tape [19]
- Semi-wet retroreflective tape [19]
- Patterned tape [20]
- Epoxy [18]
- Epoxy with Visionglow and standard beads [30]
- Methyl methacrylate [31]
- Thermoplastic, profiled [31]
- Polyester [31]
- Polyurea [29]

Rumble strips with thermoplastic [30]

a) Rumble strips

b) Thermoplastic road marking paint

c) Tape

d) Retroreflective tape

Figure 2. Example pavement marking products

a) Rumble Strips; b) Thermoplastic road marking paint; c) Tape; d) Retroreflective Tape.

Image sources:

Rumble strips

https://www.fhwa.dot.gov/publications/publicroads/08july/02.cfm

Thermoplastic road marking paint

http://www.devplastics.com/

Tape

http://www.dyroadmark.com/faqs/products-faqs.html?start=10

Retroreflective tape

http://www.rbi-inc.com/technology.htm

Asset Management of RPMs and Alternatives

Installation of RPMs

Guidance for standard spacing between RPMs is provided in The Manual on Uniform Traffic Control Devices (MUTCD). [32] Table 2 shows that spacing requirements vary depending on the geometry of the road and the manner in which RPMs are used to supplement continuous markings. [2]

Table 2 - MUTCD guidance on spacing for raised pavement markers [2]

Location	Spacing
Typical spacing, skip lines	80 feet
Solid lines, curves, transitions, or lateral shifts	40 feet or less
Straight, level freeway sections skip lines	Up to 120 feet
Left edgelines	20 feet or less

In 2004, NCHRP Report 518 reviewed installation practices for RPMs in several states. [3] In that study, 29 states with known RPM installations were surveyed. Of these 29 states, 14 were using snowplowable RPMs, and the rest of the states used non-snowplowable RPMs. NCHRP Report 518 classified the usage of RPMs in two categories: non-selective or selective. In Ohio, Texas, and California, RPMs were installed on all state-maintained roads (non-selective installation). In several other states, RPMs were installed selectively on certain types of roads based on certain characteristics, such as AADT, speed limit, or geometric considerations. [2] Table 3 summarizes statewide installation guidelines for RPMs.

Table 3 - RPM installation guidelines [2,3]

State	Guideline
Delaware	Not used on right edgeline except in special cases where additional delineation needed
Illinois	Install on: • Rural two-lane roads with ADT > 2,500 vpd • Multilane roads with ADT > 10,000 vpd • Horizontal curves where advisory speed more than 10 mph below posted speed limit • Lane reduction transitions, rural left turn lanes, and two-way left-turn lanes (TWLTLs)
Indiana	Install on: • Rural two-lane roads with ADT > 2,500 vpd • Multilane roads with ADT > 6,000 vpd
Kansas	Install on roads with AADT > 3,000 vpd and truck AADT > 450 vpd
Kentucky	SRPMs not used on bridge decks or local roads
Maryland	Installed on: • All two-lane roads with speed limit > 45 mph • Horizontal curves where advisory speed more than 10 mph below posted speed limit • one-lane bridges, TWLTLs, lane transitions
Massachusetts	Installed on all undivided highways with speed limit > 50 mph
Michigan	Installed on all freeways without illumination
Mississippi	Installed on interstates and other multilane divided highways
New Jersey	RPMs are installed along all centerlines and skip lines, regardless of traffic volume, roadway geometry, and roadway classification
South Carolina	Installed only on interstates and multilane primaries with AADT > 10,000 vpd
Utah	Installed on all unlit exit ramps with AADT > 100 vpd

West Virginia	Installed on roads with AADT > 10,000 vpd
Wisconsin	Installed on all roads with speed limit > 65 mph

Notes: AADT = annual average daily traffic, vpd = vehicles per day.

Maintenance of RPMs

Some commonly used maintenance strategies that state DOTs routinely use to examine RPMs have been summarized in the Roadway Delineation Practices Handbook (hereafter referred to as the Handbook). (18) In some cases, an expected service life is used by states to schedule the replacement of all RPMs on a highway. (18) The Handbook notes that this is often not cost-effective, as some well-functioning markers will be replaced even if they are still providing adequate visibility. (2) Alternatively, the agencies may conduct regular inspections of RPMs and replace castings and lenses as needed.

A summary of maintenance practices for RPMs in some states has been provided in NCHRP Report 518. (3) In Ohio and Pennsylvania, RPM reflectors are replaced in two- to three-year cycles. In Indiana, RPM lens replacement cycles are defined as a function of the average daily traffic (ADT) on the road and the number of lanes present, while on higher volume roads they replace lenses more frequently. (3) In Colorado and Iowa, all RPMs were removed and plans for future installations have been halted due to high maintenance costs. (2)

In 2005, the Missouri DOT conducted a survey on the use of RPMs. (33) 20 American states and two Canadian provinces responded to the survey. Of these, 12 agencies reported using snowplowable RPMs, while three of them mentioned that their use was experimental. When asked about the problem of RPMs coming loose from the pavement, five of the nine agencies who are using RPMs non-experimentally answered that they have been aware of a single or occasional occurrence. When asked about the reason for failure, the commonly cited reasons were: “hits from snowplow blades, pavement failures, or improper installation”

Because of heavy snowplow operation which may dislodge even snowplowable RPMs, three northern states (Alaska, Montana, and Colorado) do not install RPMs. All-weather paint, Alaska Department of Transportation (AKDOT) paint, Methyl methacrylate, Tape, Low-temperature acrylic paint, High-build acrylic paint, Polyurea, Preformed thermoplastic and Modified urethane are some pavement marking types installed in Alaska. (34) The New York State DOT indicated that they use wet night reflective tape as an alternative to RPMs, and RPMs are used infrequently. (35)

Table 4 - Maintenance practices for RPMs (See references 3, 19, 28, and 35)

State	Replacement cycles and criteria
California	RPMs are replaced when two successive retroreflective RPMs are missing.
Colorado	Due to high maintenance costs, all RPMs have been removed and plans for future installations have been halted
Florida	RPMs are replaced when eight or more successive RPMs are missing
Indiana	RPM lens replacement cycles are defined as a function of the average daily traffic (ADT) on a road and the number of lanes present, while on higher volume roads they replace lenses more frequently.
Iowa	Due to high maintenance costs, all RPMs have been removed and plans for future installations have been halted
Massachusetts	RPMs are replaced if 30% or more of existing RPMs are missing in an inspected section.
New Jersey	Through a visual inspection process, lenses are replaced only if the casting is intact.
Ohio	RPM reflectors are replaced on fixed two- to three-year cycles.
Pennsylvania	RPMs are visually inspected when work crews are performing other work in the area. RPMs are thereafter replaced as needed.
Texas	RPMs are replaced when 50% or more of existing RPMs are missing in one mile of highway.

Durability of SRPMs

The service life of RPM castings and lenses has been estimated in several studies (Table 5 and Table 6). (22,27,36) Casting service life ranges from four years to ten years. (27,36) Lens service life ranges from three years to four years. (22,36) Those estimates were based on field tests, opinions of knowledgeable practitioners, or predictive retroreflective performance models. (35)

The durability of RPMs has been reviewed by several other studies over a relatively short period on isolated test segments. The North Dakota DOT conducted a durability study of RPMs in 2005. (37) The experiment was conducted at two locations over four years. They found an average life of 8.2 service years for RPMs. (37) The Alberta DOT evaluated low-profile RPMs which provided by two manufacturers in 2006. (38) The study did not find casting failures within the study period but found many failures in lenses, especially on shoulder installations. The average lens failure rate was 5.9 percent on centerlines and 59.2 percent on shoulders. (35)

The durability of four types of RPMs from three manufacturers was examined by the Vermont Agency of Transportation in 2007. (24) Lens damage was more prevalent, but castings were undamaged. Furthermore, between 37 percent and 65 percent of all snowplowable RPM lenses were missing or damaged at the end of the test period (30 months). (35)

Table 5 - Service life of RPMs according to different studies

Service Life Estimate of RPMs	Bryden 1979 (36)	Markow 2007 (27)	Cottrell 1996 (22)	Doerr et al. 2005 (37)
Casting service life	4 years	10 years	NA	8.2 years
Lens service life	3 years	NA	4 years	8.2 years

Table 6 - Results of durability tests of RPMs conducted by different agencies

Study	Results of durability test
Alberta DOT (38)	At the end of the five-year period, the average lens failure rates were 5.9% for centerlines and 59.2% for shoulder installations
Vermont Agency of Transportation (24)	Lens damage was prevalent, but castings were undamaged. Between 37% and 65% of all SRPM lenses were missing or damaged at the end of the test period (30 months)

Durability of Other Marking Materials

The durability of different marking materials has also been studied. Some studies used surveys of transportation professionals or historical data from DOTs, (See references 18, 27, 29, and 39) while others used models. (31,40) Published findings are summarized in Table 7.

Table 7 - Service life (in years) of different pavement marking materials (2)

Material	Color	Migletz et al., 1994 (18)	Markow, 2007 (27)	Migletz et al., 2001 (31)	Andrady, 1997 (40)		Cottrell, 2001 (39)	Carlson et al., 2007 (29)
					PA	AL		
Waterborne paint	Unspecified	0.25-1.0	1.1				1	0.6-1.0
	White			0.87	2.31	3.17		
	Yellow				2.18	1.46		
Epoxy paint	Unspecified	1-2	3.3		1.57		3	
	White			1.07-3.28				
	Yellow			1.93-3.68				
Thermoplastic	Unspecified	3-5	4.2				3	1.9-4.5
	White			1.88-3.05	1.16	3.38		
	Yellow			2.06-2.82	0.65	1.54		
Profiled thermoplastic	Unspecified							1.5-4.0
	White			1.53-4.64				

	Yellow			1.96-4.23				
Profiled tape	Unspecified		6.3				6	1.6-6.0
	White			1.63-3.11	1.18	2.60		
	Yellow			1.63-3.24	1.03	2.53		
Polyester	White			1.73-2.28	3.31	13.83		
	Yellow			3.31-3.99	0.33	3.93		
Methyl methacrylate	Unspecified				0.9	1.53		1.2-5.0
	White			0.99-2.44				
	Yellow			1.30-1.71				
Profiled methyl methacrylate	White			1.17-3.83				
	Yellow			1.76-3.30				

Notes: PA = Pennsylvania results, AL = Alabama results. Materials that have cells with no value were not reviewed in the particular study.

<u>Cost of Markings</u>

The average costs to install markers have been investigated in several studies (Table 8). (See references 18, 28, 29, 39, and 40) Unit costs summarized in Table 8 are in dollars per linear foot for markers and per unit for RPMs.

Table 8 - Unit costs of markers (in dollars) [2]

Marking Material	Migletz et al., 1994 [18]	Andrady, 1997 [40]	Cottrell, 2001 [39]	Migletz and Graham, 2002 [28]	Carlson et al., 2007 [29]
Waterborne paint	0.04-0.06	0.06	0.04-0.15	0.06	0.08
Thermoplastic	0.32-0.60	0.30	0.35	0.32	0.27-0.32
Preformed tape, flat	1.25			1.41	
Preformed tape, profiled		1.75	1.80	2.33	2.75-3.75

Epoxy	0.40-0.45	0.25	0.40	0.26	
Conventional solvent paint				0.07	
Methyl methacrylate		0.75		1.22	1.50-2.10
Thermoplastic, profiled				0.87	0.75
Polyester		0.10		0.13	
Polyurea			0.70	0.90	0.85
Rumble stripe with thermoplastic					0.50
Snowplowable RPM (casting)	16.50-23.98			35.98	
SRPM (lens)	3.75				

Conclusions

This chapter reviews current research and practice regarding RPMs. Potential alternatives or modifications to RPMs investigated by several studies were discussed. The safety effect of RPMs evaluated by many studies was reviewed. The literature review shows that there is no consensus regarding whether and how RPMs affect the crash rate. Depending on scope and data, different studies report different magnitudes of safety changes (positive or negative) after RPMs are implemented. There are various alternatives and modifications possible for RPMs, such as rumble strips and traffic tape. The use of these alternatives varies by state.

CHAPTER 2: SURVEY ANALYSIS

Purpose of the Survey

Raised pavement markers (RPMs) are delineation devices used to improve preview distances and provide guidance for drivers in inclement weather and low-light conditions. There are various types of RPMs, which can be used in different areas with assorted roadway and environment characteristics. RPMs can be viewed as safety assets under the control, operation, and management of Departments of Transportation (DOTs) and other safety agencies. An effective plan for installation, monitoring, inspection, and maintenance of RPMs will lead to make cost-effective decisions.

FHWA published "Guidelines for the Use of Raised Pavement Markers" [41] to provide general recommendations for the implementation of RPMs. In accordance with the FHWA guidelines, different states develop their respective practices on the installation, monitoring, and maintenance of RPMs based on road characteristics. Also, there are various RPM alternatives such as rumble strips and wet reflective tape, that add reflective elements to roadside features such as utility poles, trees, etc.

In order to identify state-wide use of RPMs and alternatives or modifications, a survey is developed to obtain the information about RPM installation, maintenance, and replacement. The purpose of this survey is to acquire the answers to following inquiries:

- What types of RPMs are currently in use?
- What are the locations, installation and maintenance policies of RPMs?
- What alternatives or modifications are used in lieu of RPMs?
- What are the engineering and operational challenges observed regarding the use of RPM and alternatives?

Development of Survey Questions

Different states may have particular asset management strategies in terms of installation, monitoring, inspection, and maintenance of RPMs. In general, the survey consists of two main sections, which are I) RPM Installation and II) RPM Inspection and Maintenance. Some of the questions in these sections are adapted from a previous report developed by Purdue University in cooperation with the Indiana Department of Transportation and the U.S. Department of Transportation Federal Highway Administration. Each section of the survey is detailed as follows:

RPM Installation

Some states install RPMs selectively based on certain locational characteristics of the roadways. Some key features of RPM installation, such as spacing between RPMs, are determined according to traffic volume, degree of curvature, and other factors. The following questions are asked to solicit information regarding the location, spacing and influencing factors of RPM installation:

- Which state do you represent when responding to this survey?
- In your state, are raised pavement markers (RPMs) installed selectively at certain locations or non-selectively on all the roads?
- If RPMs are installed selectively, what locational characteristics are used in the selection? (e.g., The number of lanes, Traffic volume, Accident history, Presence of street lighting, etc.)
- What types of RPMs are installed in your state?
- Where are RPMs installed in your state? (e.g., Centerlines, Edgelines, Gore areas, etc.)
- What is the typical spacing between RPMs for each location (in feet)?
- What factors determine the spacing used?
- Please provide any engineering problems that were observed in RPM installation.

RPM Inspection and Maintenance

The inspection and maintenance of RPM could also be affected by roadway and operating characteristics such as traffic volume, curvature, usage, reflectivity, inspection records and other factors. The following questions are asked to understand state-specific asset management strategies for RPMs:

- What specialized equipment has been used for RPM monitoring and inspection?
- After how many years do the RPMs usually need replacement or repair?
- What are the replacement criteria?
- Which part of the RPMs usually needs replacement? (e.g., Entire RPM, Reflecting lens, Casting, etc.)
- Please provide any procedure/equipment problems reported during the inspection and replacement of RPMs.

Development of A Web-Based Survey Tool

In order to collect and integrate information in a time-efficient manner, a Web-based survey tool was developed using a third-party survey generation software called "Survey Gizmo" (https://www.surveygizmo.com). The responses provided will remain confidential. Contact information will not be used for any purpose beyond the survey. Only aggregate information, which cannot be tied back to an individual or organization, will be reported. Additionally, survey responses will not be recorded or saved until the respondent selects the "submit" button at the end of the survey. At the end of the survey, participants are asked if they want their name to be acknowledged in the report and if they are interested in receiving the survey results summary.

Below is the link for the developed online survey:
http://www.surveygizmo.com/s3/2452123/Raised-Pavement-Markers-Safety-Evaluation

Analysis of Survey Results

Contact points from 45 state DOTs were sent invitations to answer the RPM survey. Figure 3 shows a map of the 22 states that completed the survey.

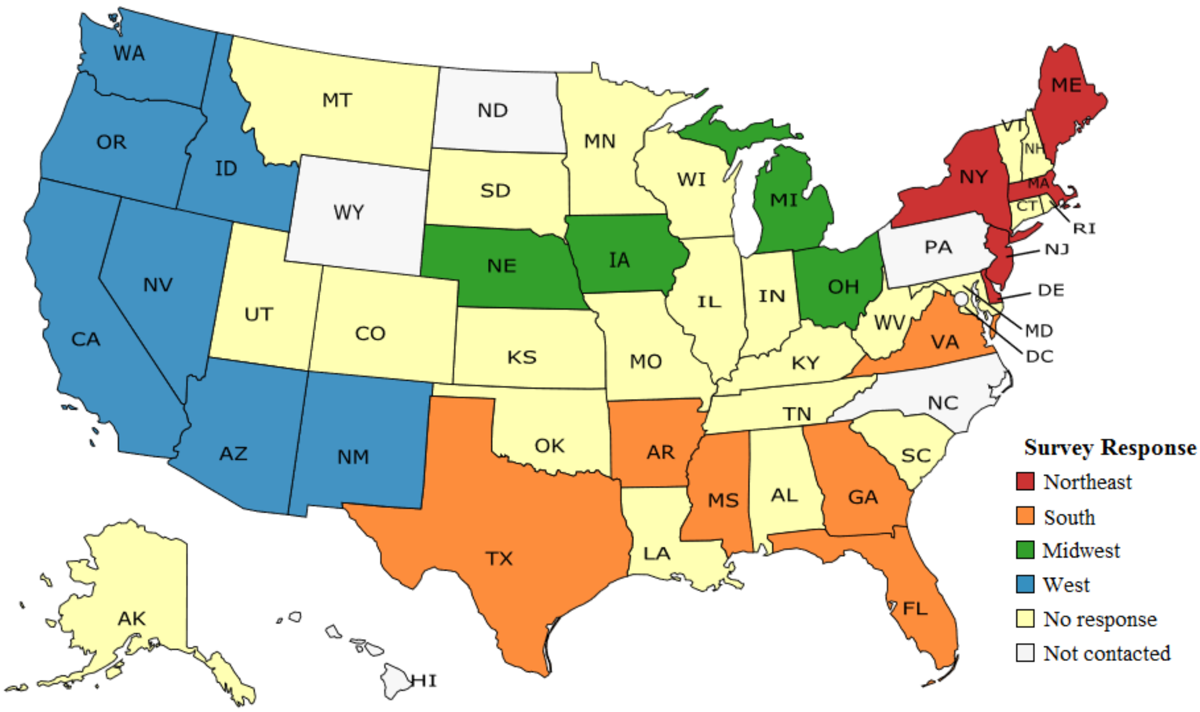


Figure 3. Survey response

The results of the survey are discussed in two sections: RPM Installation and RPM Inspection and Maintenance.

<u>RPM Installation</u>

From the answers obtained, 59 percent of the states have their RPMs installed selectively, 32 percent install non-selectively and nine percent do not have RPMs installed. Maine and Iowa represent the nine percent of participating States that do not have RPMs installed. This breakdown of results can be seen in Figure 4.

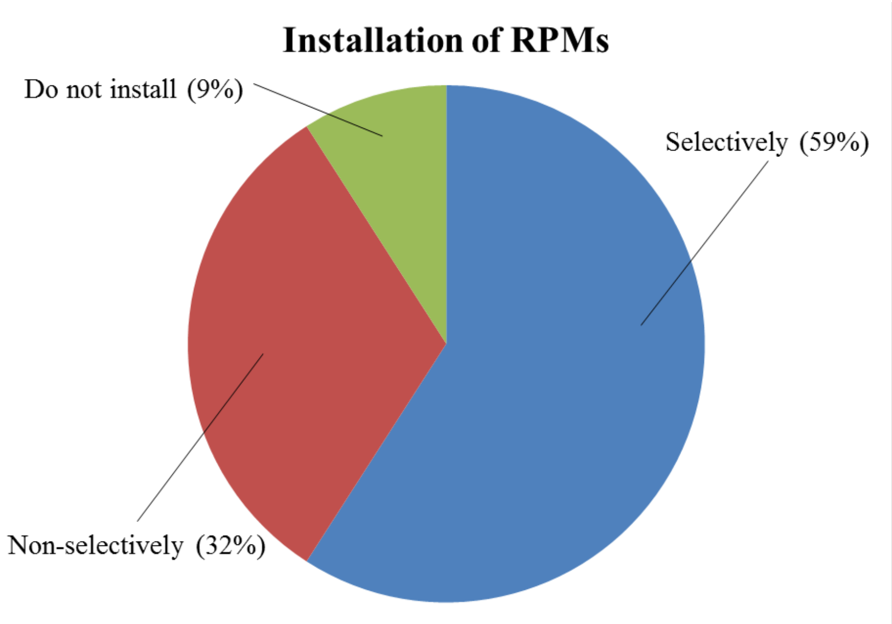


Figure 4. Installation of RPMs

When installed selectively, the states use different locational characteristics to determine the RPM installation location. For instance, New Jersey installs RPMs on all state and interstate highways while in Oregon the RPM installation strategy varies according to its regions which can include considerations such as traffic volume, accident history, and wet weather performance. Table 9 shows the summary of the answers regarding the locational characteristics that determine the RPM installation, per state.

Table 9 - Locational characteristics to determine RPM installation selection

State	Locational characteristics to select RPM installation
New Jersey	Installed on all state highways and interstate highways.
Ohio	RPMs are installed 100% all over the Interstates, US Routes, and State Routes.
Virginia	Interstates and primaries.
New Mexico	Used on multi-lane highways, high speed, with high accident highways. Also used in areas with dust storms.
Washington	Specific state region policy on select state routes, other areas at the discretion of the region traffic engineer as augmentation of lines.

Nevada	Raised pavement markers are used in areas where it doesn't snow.
Texas	Surface course thickness < 2", Shoulder width, Bicyclist accommodation, Road Classification.
Oregon	Traffic volume, accident history, wet weather performance, winter maintenance activities, complaints, and areas without illumination are the main reasons we use markers. The actual strategy varies depending on the Region.
Massachusetts	RPMs are used on all higher speed roadways (with a posted speed of 40 mph or greater).
Delaware	Raised pavement markers should be installed along interstates, freeways, expressways, and principal arterials. RPMs should be considered for use along conventional roads under the following conditions: A. Roadways with posted speed limits of 45 miles per hour or greater, with horizontal and/or vertical curves, and areas of low lighting B. Locations with a history of roadway departure crashes C. Locations with advisory speed postings D. Locations where a barrier or parapet is less than 6 feet from the edge of the travel lane.

A single state can have one or more types of RPMs installed, such as a Raised Snowplowable Marker, a Raised Pavement Marker, and a Raised Temporary Marker. As seen in Figure 5, Raised Temporary Marker is the most common RPM type used followed by Raised and Recessed Snowplowable Markers. Table 10 shows which type of RPM is used by each state.

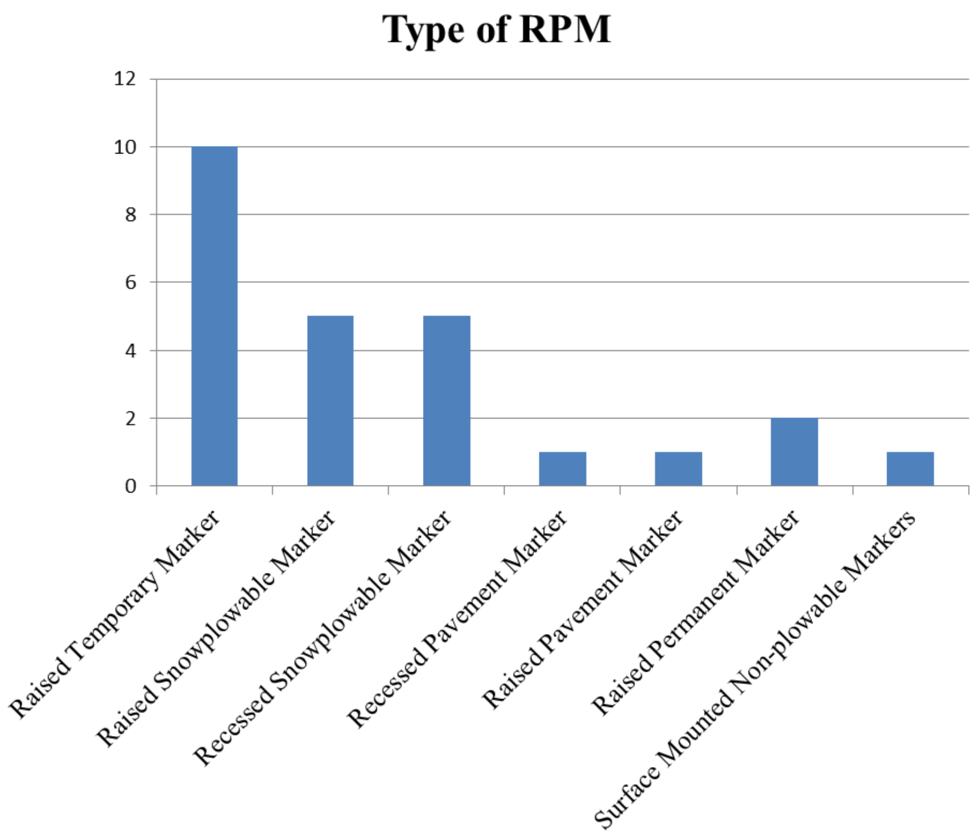


Figure 5. Type of RPM installed

Table 10 - Type of RPM by state(s)

Type of RPM	State(s)
Raised temporary marker	Ohio, Nebraska, Michigan, Mississippi, Virginia, California, Arizona, Washington, Idaho, Nevada
Raised snowplowable marker	New Jersey, Ohio, Virginia, Washington, Delaware
Recessed snowplowable marker	New York, California, New Mexico, Washington, Massachusetts
Recessed pavement marker	Oregon
Raised pavement marker	Oregon
Raised permanent marker	Florida, Georgia
Surface Mounted Non-plowable Marker	Arkansas

The most common physical installation locations of RPMs are in the centerlines, gore areas, edgelines and lane lines, respectively, as seen in Figure 6. Centerlines, for example, are present in 17 out of the 20 surveyed states that have RPMs installed.

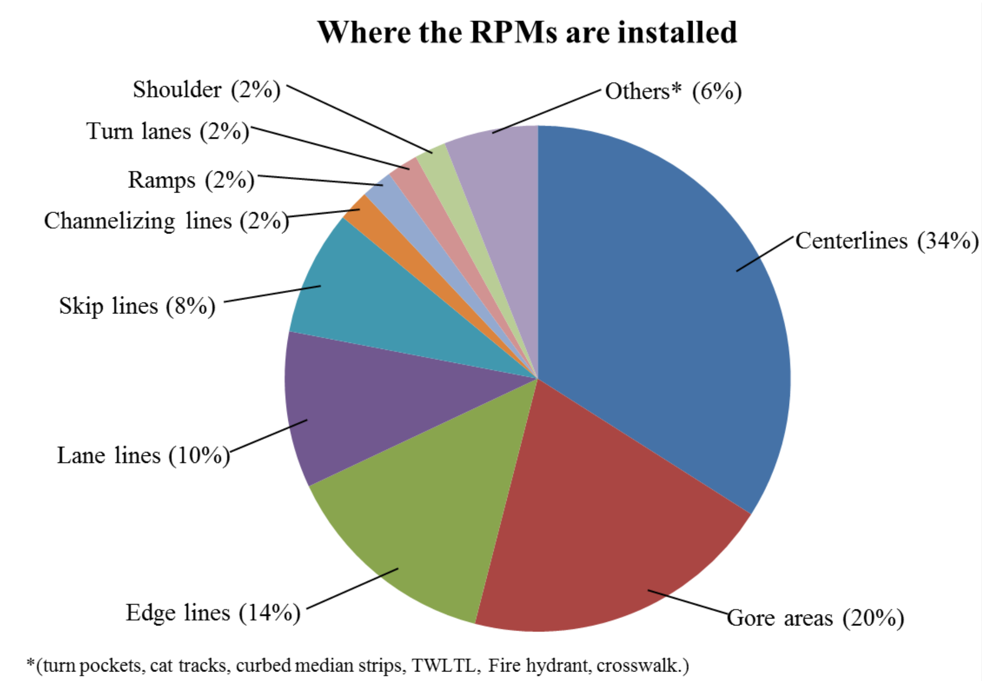


Figure 6. Location of RPM installation

RPM Inspection and Maintenance

According to the survey response, the RPMs are usually replaced every 2-4 years, but it varies due to different criteria used per state. Shown in Table 11, Arkansas typically replaces the RPMs every two years if not plowed off in the winter, Delaware has a three-year replacement cycle policy, and in Arizona the replacement occurs usually every four years.

Table 11 - Replacement cycle by state

State	Replacement Cycle
New Jersey	When the pavement is repaved (10 - 25 years). Lens are looked at every 3 years to determine if they need to be replaced
Ohio	RPMs have two parts 1. RPM Casting: last for the life of asphalt or concrete pavement, 2. RPM Reflective Lens: replaced after every three years (1/3 each year)
Florida	Interstate facilities: 2 years. Others longer depending on AADT and % trucks
Georgia	Typically, 2 years or less on interstate >15,000 ADT on four lanes
Michigan	Replacement of temporary RPMs is as-needed
Mississippi	Roughly 5, but is based on missing markers
Virginia	Visual evaluations are done approximately 2-4 years
California	Determined by maintenance during routine inspections
New Mexico	3 years for AADT > 8,000 on two-lane one-direction lanes
Arizona	Replacement cycle is approximately 4 years, based on visual inspection
Washington	2 years for surface/4 years for grooved but that varies much (AADT, weather, plow ops, lane changes, truck percent, installation care etc.)
Texas	7- or 8-year cycle
Oregon	Other than Region 1 (Portland metro area 3 years) there is no replacement cycle. Public complaints and political pressure are the main factors for replacement of pavement markers
Massachusetts	Generally, do not replace/repair RPMs
Arkansas	Typically, 2 years if not plowed off in the winter
Delaware	3 years

As mentioned, the replacement criteria vary between the states, but missing/broken casting and reflectivity represent 48 percent and 30 percent of causes between all the criteria listed by the states, respectively (Figure 7). Figure 8 illustrates a raised snowplowable pavement marker (RSPM) with broken casting and reflector.

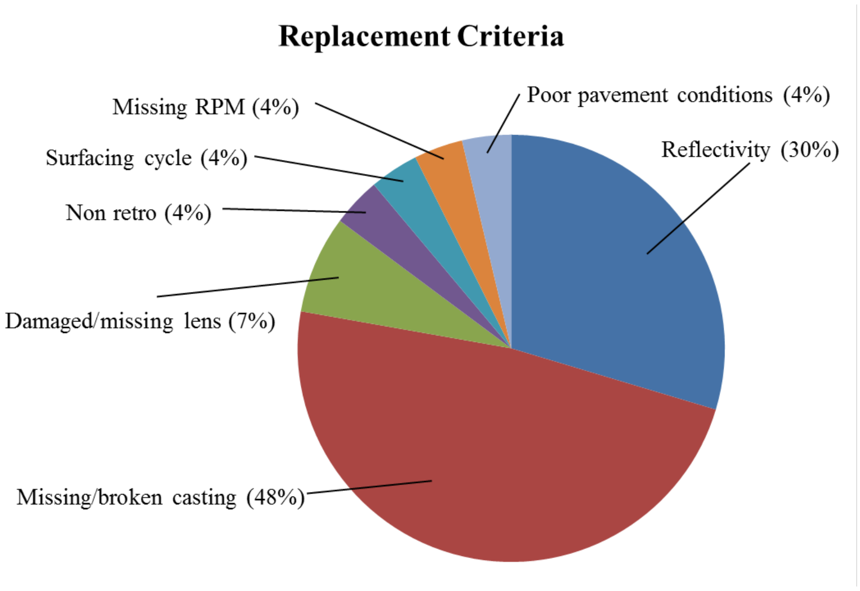


Figure 7. Replacement criteria

Figure 8. RSPM with broken casting and lens

According to the survey, the part of the RPM that needs replacement the most is the entire RPM followed by the reflecting lens and the casting as seen in Figure 9.

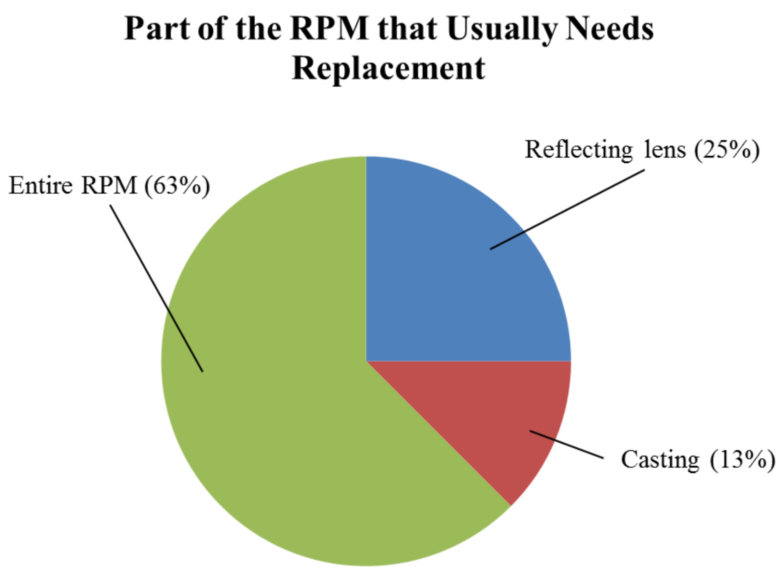


Figure 9. Part of the RPM that usually needs replacement

Table 12 shows some alternative safety devices that states are using to improve preview distances and guidance for drivers. For instance, states such as Georgia, Michigan, and Massachusetts have been using wet reflective striping (Figure 10), and Ohio, Arizona and Washington have been using delineators (Figure 11).

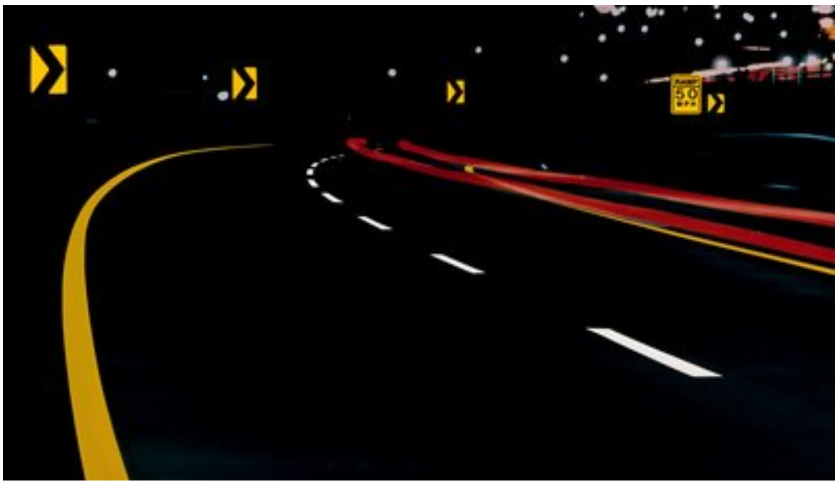


Figure 10. Wet reflective stripe

Figure 11. Traffic delineator

Table 12 - Alternative safety devices

State	Safety Device
Ohio	Delineators; Barrier Reflectors; 3M - Linear Delineation System
Georgia	Reflective materials on guard rails, wet reflective striping materials
Michigan	Some wet reflective pavement markings
California	Other pavement marking materials such as tape, thermo etc.
New Mexico	Rumble strip being striped and adding double drop elements
Arizona	Delineators
Washington	Striping, RPMS, signing, markings, guideposts, LDS panels, and lighting
Texas	Buttons, reflective striping
Oregon	Previously used non-reflective markers; now utilize pavement markers that augment durable markings and perform well in wet weather conditions
Massachusetts	We are exploring the use of wet reflective tape instead of recessed pavement markers
Arkansas	Rumble Strips

CHAPTER 3: METHODOLOGY AND DATA COLLECTION

Executive Summary

This chapter provides an overview of an analytical framework for evaluating the safety effectiveness and implementation cost of raised pavement markers (RPMs). We also introduce the data needed to implement the methodology as well as the sources for acquiring the data. Detailed data analysis based on this methodology will be presented in chapter 4: "Cost Effectiveness of Raised Pavement Markers".

In addition to statistical data analysis, this chapter also summarizes a simple luminance measurement method for pavement markers and other forms of pavement marking and delineation systems. The objective of the method is to allow researchers to estimate the luminance of these devices under varying vehicle and driver-eye geometric conditions.

Statistical Methodology

The purpose of this analysis is to present an analytical methodological framework that is able to calculate and compare roadway crash rates (the number of crashes per traffic exposure) by roadway characteristics and traffic volumes with either the presence or absence of raised pavement markers (RPMs). Each step of the framework is detailed in the proceeding sections. Figure 12 provides an overview of the methodology in the form of a flow chart.

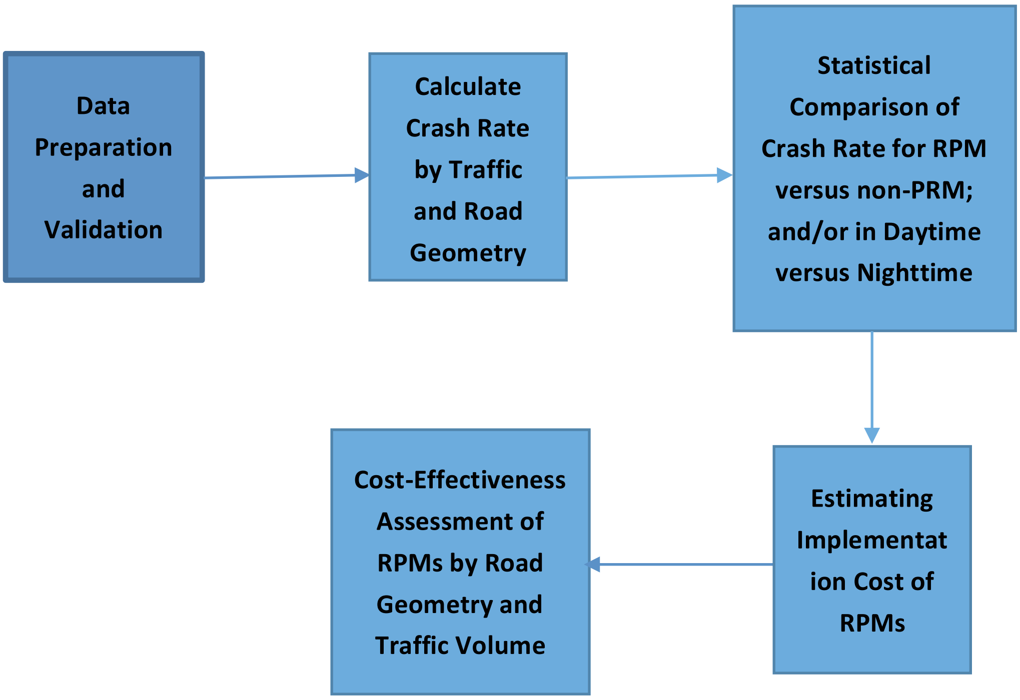


Figure 12. Overview of the methodological framework

Data Preparation and Validation

Data Preparation

The RPM project utilizes two primary data sources provided by NJ DOT. One is the NJ Crash data. The up-to-date crash information is obtained from a weekly data feed established between NJ OIT (Office of Information Technology) and Rutgers CAIT. The full data description is available online at http://www.nj.gov/transportation/refdata/accident/. We also used the NJDOT SLD (Straight Line Diagram) database. The information is publicly available in PDF format at http://www.state.nj.us/transportation/refdata/sldiag/.

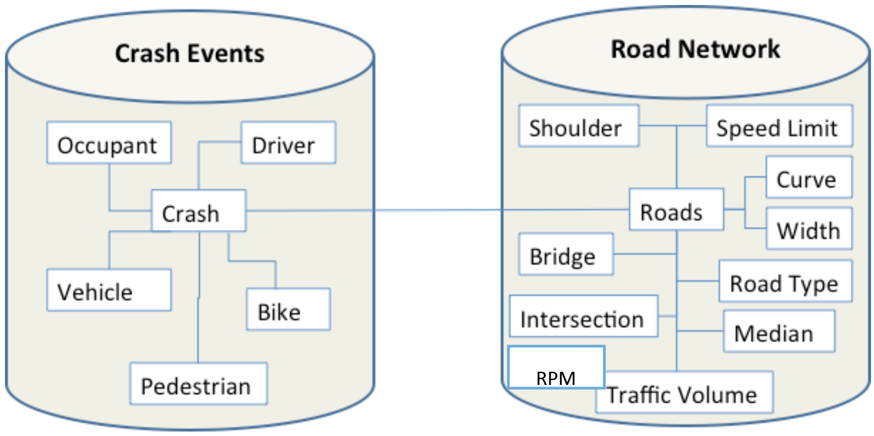


Figure 13. Data elements supporting RPM analysis

As shown in Figure 13, we integrate the two databases in an SQL Server via their spatial component. This gives us the ability to see what crashes are occurring on what road sections. In addition, we utilize the crash month and crash time parameters to determine if a crash occurred at night or during the day. The definition we are using for this characteristic is standard: "Daytime means from a half hour before sunrise to a half hour after sunset. Nighttime means at any other hour." (42) The approximate sunrise/sunset times per month were taken according to the US Navy reference provided online at http://aa.usno.navy.mil/data/docs/RS_OneYear.php. We extract the severity of the crash from the crash data, which is rated according to the most severe injury to any participant in the crash on a scale from 1 to 5 (1=property damage only, 2=complaints of pain, 3=minor injury, 4=incapacitating injury, 5=fatality). We will use all crashes in 2014 for our preliminary analysis.

Naturally, we also had to consider RPM presence when creating this model. The RPM data recorded in the NJDOT SLD did not exactly meet our needs. In this table, sections of RPM are recorded by "number of rows." Because of this fact, overlap exists between segments on the same roadway where the number or rows changes. We could not support overlapping segments in our model, as it would lead to duplication of crash counts. Therefore, we developed a process to scan the

LN_RPM table in the SLD to identify and merge overlapping segments, regardless of the number of rows.

The study was interested in comparing road segments with RPM to those without. Because of this need, we were required to develop one final data table: LN_NO_RPM. This table stored road segments where no RPM was present. Two sources of data completed this table. The first source was the segments in the LN_RPM roads where no RPM was present. These gaps were recorded in the NO_RPM table. A second source was any NJ State Jurisdiction road which did not have any RPM. These segments were also added to the NO_RPM table for analysis. Note that all state roadways have RPMs. We consider county roadways without RPMs as an alternative reference group.

The last step was to create homogenous roadway segments based upon roadway characteristics of interest in RPM studies. A homogeneous roadway segment is a continuous stretch of road where none of the defined characteristics change. A simple example is shown in Figure 14 to illustrate how the individual road characteristics are combined into our final homogenous roadway model. From the literature review and the availability of data on NJ roads, the following parameters were determined to be useful: the number of lanes, pavement width, shoulder width, and traffic volume (AADT).

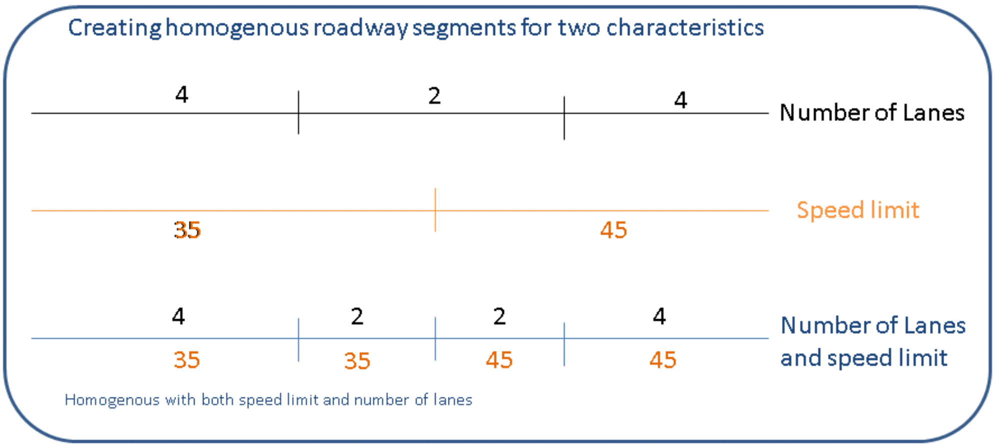


Figure 14. Homogeneous road segment visualization

Data Validation

Validation of our model is a two-step process. The first step is to ascertain the accuracy of the roadway network. The second is to ensure that the crash data is properly integrated. To validate the homogeneous network, we select several road segments at random from our model. We then check the associated parameters (the number of lanes, AADT, etc.) via the SQL Query against the NJ SLD. If the correct value for the parameter matches, then that characteristic is validated.

We check the crash data in a similar fashion. By using an SQL Query, we can identify the number of crashes that occur on a certain roadway at specific times of the day. For the randomly selected segments in our model, we validate the appropriate number of each night/day severity crash occurs.

Calculate Crash Rate by Traffic Volume and Road Geometry

Based on the collected data, we are able to calculate crash rates for the network with segments that already have RPMs and the network that do not have RPMs. This will contribute to learning how the installation of RPMs makes a difference in crash rates, holding all other factors constant. Specifically, we will analyze the crash rate variation for each roadway network (with RPM and without RPM) based on the traffic volume and the number of lanes. We will consider at least two categories of traffic volume (delineated as above or below the average) and at least two categories of the number of lanes (e.g., one or two lanes versus three and more lanes).

In recognition that RPM and non-RPM networks may have various heterogeneous features that may not be fully incorporated in data analysis, we also use the daytime crashes as a reference group and assume that RPMs have limited effect on safety in the daytime. In this way, we can calculate crash rate in the daytime versus in nighttime for both RPM and non-RPM networks. Hourly traffic count data by location is acquired from NJDOT.

Statistical Comparison of Crash Rate

After calculating the crash rate for each class of AADT of Lanes in each network (with RPM and without RPM), we statistically compare crash rates given specific traffic and road characteristics, with or without RPM. Similarly, we also compare daytime crash rate versus nighttime crash rate on networks both with and without RPMs. By these comparisons, we can infer the possible effect of RPMs on roadway safety in New Jersey.

Implementation Cost of RPMs

The cost of RPM consists of its initial installation cost as well as the inspection and maintenance cost in its life cycle. The cost information will be collected based on the literature review, survey, and communication with NJDOT. Total annualized RPM implementation cost will be calculated and used for cost-effectiveness analysis in the next step.

Pavement Marker Luminance/Reflectivity Measurement

The objective of the method is to allow researchers to estimate the luminance of these devices under varying vehicle and driver-eye geometric conditions. Because the geometry among vehicle headlights, a driver's eyes, and a pavement marker can vary widely for different roadway situations, the proposed method uses a sample of measurements for several geometric conditions. This method is not intended to replace or supplant consensus-based standard measurement methods for measuring retroreflective materials such as those published by the American Society of Testing and Materials (ASTM).

Rationale

The proposed measurement method provides a way to compare different reflective pavement markers and alternatives regarding their ability to reflect light from drivers' headlights back toward their eyes to provide visual delineation, for a range of angles corresponding to those representatives of driving conditions. A series of retroreflection coefficients are determined for each of ten angular geometries; these coefficients can be used in conjunction with headlight intensity data to estimate the luminance of the devices they would exhibit in roadway conditions.

Method

The measurement should occur in a black-painted room to minimize reflections from stray light. A calibrated luminance meter should be used with a spot size large enough to completely encompass the marker or delineation element (e.g., 1°). A light source producing a fixed intensity within a 10° radius from the center of the source should be mounted on a tripod or mounting bracket, with the marker mounted to another tripod or mounting bracket directly in front of the light source at one of two specified heights, corresponding to 0° or 1° below the horizontal line extended from the light source toward the marker. The luminance meter should be mounted at a height corresponding to 1° above the light source, relative to the marker height (see Figure 15).

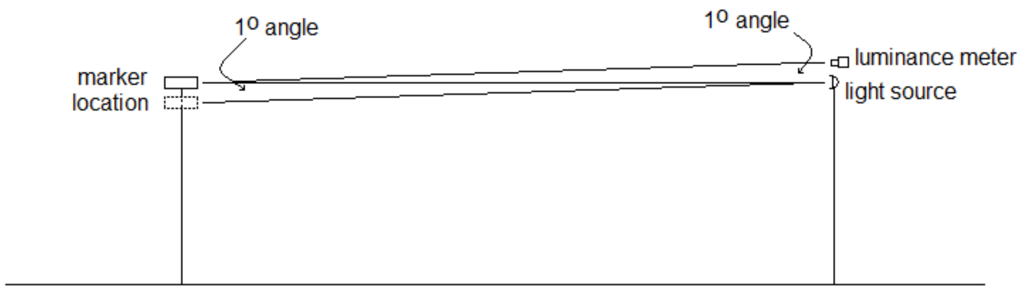


Figure 15. Diagram showing the light source, marker, and luminance meter heights

The marker should also be able to be mounted 5° and 10° to each side of the centerline between the light source and the original marker location (see Figure 16).

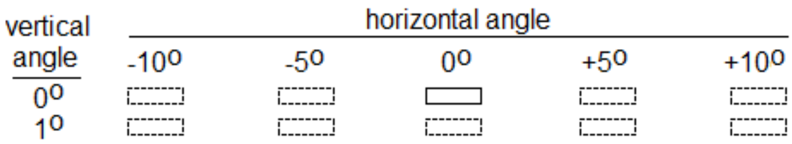


Figure 16. Horizontal and vertical locations of the marker being measured, viewed from the location of the light source.

Notes: *Negative horizontal angles correspond to those to the left of center (toward the driver side); positive horizontal angles correspond to those to the right of center (toward the passenger side).*

The 1° range of vertical angles and 20° range of horizontal angles corresponds to the representative ranges for pavement-mounted reflectors that could be encountered on roadway curves.

With the light source energized, the luminance meter should be used to capture the luminance of the 1° aperture centered around the marker (L_a, in cd/m²). The projected angular area of a 1° luminance spot is 0.7854 degrees². The projected angular area of the marker (A_p, in degrees²) should be calculated for the marker or device being measured. Assuming a uniform marker luminance, its luminance (L_m, in cd/m²) can be calculated from the luminance spot measurement using the following equation:

$$L_m = L_a (0.7854/A_p)$$

The vertical illuminance (E, in lux) from the light source at each location in Figure 16 should also be measured. From these data, it is possible to calculate the coefficient of retroreflectivity (R_c, in cd/m²/lux) for each angle, using the following equation:

$$R_c = L_m/E$$

This quantity is independent of the amount of illumination falling on the reflector at any particular location because the coefficient of retroreflectivity is defined as the ratio of its luminance for a given illuminance. If the illuminance were doubled, the luminance of the reflector would also be doubled, but the ratio between these quantities would remain the same.

Finally, to estimate what the luminance of the marker would be in an actual roadway scenario (L_{rs}, in cd/m²) under low beam headlamps at a given distance d (in meters), headlamp intensity data (I, in cd; see Table 13) from the University of Michigan [(43)] can be applied to the corresponding angular location's coefficient of retroflectivity using the following equation:

$$L_{rs} = R_c I/d^2$$

The data in Table 13 are for a pair of headlights.

As a comparative Figure of merit, the ten luminance values calculated for a given distance (d) or set of distances can be used to compare alternative systems for their relative brightness when viewed under representative low beam headlamp illumination on the road.

Table 13 - Luminous intensities from a representative pair of low beam headlamps toward several angular locations

Vertical Angle	Horizontal Angle				
	-10°	-5°	0°	+5°	+10°
0°	1346 cd	2186 cd	17,660 cd	9434 cd	2240 cd
1° down	6124 cd	10,612 cd	37,804 cd	19,796 cd	5602 cd

It can be seen in Table 13 that low beam headlights tend to produce more light at 1° down than they do at a vertical angle of 0°. The amount of light at the horizontal angle of +5°, which corresponds to one lane toward the passenger side of the vehicle 50 m ahead, is also larger than the amount of light at the horizontal angle of -5°, one lane toward the driver side.

Utility of the Calculated Luminance Values

The proposed measurement and calculation method is designed to provide the user with an approximate range of luminance that pavement markers will exhibit under low beam headlamp illumination, due to retroreflectivity. It is also possible to estimate the additional luminance that can be produced by roadway illumination, even though this latter quantity will be much lower than the retroreflective luminance. If the roadway is illuminated to an average illuminance E (in lux), the luminance (L, in cd/m²) of a diffuse element will be calculated by the following equation:

$$L = \rho E/\pi$$

In the equation above, ρ is the diffuse reflectance of the marker, and can be estimated based on its color as follows:

- White: 0.7
- Yellow: 0.45
- Green: 0.12
- Red: 0.15
- Blue: 0.12

It is, therefore, possible to compare different reflective markers with respect to the luminance they are likely to produce for a range of different lighting conditions.

Planned Request for Samples

The project team plans to conduct measurements using the present methodology to compare markers and delineators of several types. Three samples of raised pavement markers will be requested from the major manufacturers, of the following types:

- Raised reflective pavement markers
- Snowplowable raised pavement markers
- Overlay markers
- Post-mounted delineator sheeting
- Wet reflective pavement marking tape

The initial focus will be on markers and delineators having yellow and white color.

Samples from Manufacturers

From two manufacturers, the project team requested raised pavement markers (markers from one manufacturer were mounted in steel casters and were white and yellow in color; markers from the other manufacturer were not and were white, yellow, red and blue). The project team has received the following alternative devices from one manufacturer: wet reflective pavement marking tape (white and yellow) and barrier-mounted reflective delineators (white, yellow, orange and red). The latter delineator materials will only be measured at the 0° vertical angle and the -10°, -5° and 0° horizontal angles because it would be mounted above ground level and on the side of a centerline barrier toward oncoming traffic

CHAPTER 4: COST EFFECTIVENESS OF RAISED PAVEMENT MARKERS

Statistical Data Analysis of RPMs

This chapter provides a preliminary statistical analysis of the cost and potential safety benefit of the implementation of raised pavement markers (RPMs). The analysis of safety benefit of RPMs is based upon the calculation of certain types of crash rates that RPMs may prevent. These crash types include same direction-side swipe, opposite direction-head on/angular, opposite direction-side swipe, encroachment, and fixed object. The crash rate is calculated by traffic volume, day or night, and the number of lanes. The costs of RPM implementation include installation cost, inspection cost, replacement cost and others. Based on the cost-effectiveness assessment, we estimate the benefit to cost ratio of RPMs installation under various circumstances.

First of all, the whole dataset was divided into three exclusive networks in order to make it possible to investigate the effect of the installation of RPMs. These three networks are State Roadway (a network with RPMs installed throughout its entirety), County Roadway with RPMs, and County Roadway without RPMs. This classification enables us to identify the potential effects of RPM installation based on the difference in the crash rates in these networks. The meaning of crash rate and the way to estimate it are explained in this report. The crash rates under different circumstances are presented.

Crash Rate Calculation

The crash rate for a network is calculated by dividing the number of accidents by traffic exposure, which is typically measured by the total vehicle miles given the study period. Therefore, the accident rate is measured in terms of "accidents per million vehicle miles". Given the data available to us, this analysis considers three networks, which are first, State roadways; second, county roadways that have RPMs; and third, county roadways that do not have RPMs. All the data used is for the year 2014. Moreover, all of the daytime and nighttime crash rates were calculated based on the assumption that daytime traffic accounts for 73.5 percent of AADT and nighttime traffic equals to 26.5 percent of AADT as per the sample hourly traffic data at 54 locations provided by NJDOT. In this study, daytime means from a half hour before the sunrise to a half hour after sunset. Nighttime indicates any other hour. [42] Daytime and nighttime crash rates were calculated by dividing daytime crashes and nighttime crashes normalized by their respective traffic exposure.

$$Crash\ rate\ for\ roadway\ segment = \frac{Number\ of\ crashes(N)}{Million\ vehicle - \text{miles}\ (MVM)}$$

Where,

$$MVM = \frac{AADT * Length\ of\ section\ segment(L) * Number\ of\ Years * 365}{1{,}000{,}000}$$

First, we analyzed crash rates on State roadways by traffic volume and the number of lanes. The number of lanes is a surrogate for road width on a segment. Table 14 shows that the crash rates for one-lane or two-lane segments are close to those on the segments with more than two lanes in both daytime and nighttime, including total.

Table 14 - State roadway crash rate per million vehicle-miles by the number of lanes

		One lane or two lanes	**More than two lanes**
State roadway	Daytime	2.48	2.47
	Nighttime	2.47	2.44
	Total	2.48	2.47

Next, we analyzed crash rates by traffic volume, which is delineated by 30,000 and is the average AADT for State roadway in the dataset used in our analysis. It was found that a higher traffic volume is associated with a lower crash rate (Table 15). This might be because when a roadway has a lower traffic volume, drivers may more frequently change lanes, thereby incurring the possibility for accidents. Also, higher traffic volume segments may have more stringent safety standards, which may partly explain the lower crash rates. Given the data available to us, the exact reasons for the observed crash rate comparison results are unclear. In the following tables, we will consider additional factors besides the number of lanes and traffic volume.

Table 15 - State roadway crash rate per million vehicle-miles by traffic volume

		AADT <30,000	**AADT >30,000**
State roadway	Daytime	3.57	2.06
	Nighttime	3.36	2.11
	Total	3.52	2.07

In Table 16, we analyzed crash rates by both the number of lanes and traffic volume. When the AADT is lower than 30,000, a higher number of lanes have a higher crash rate in both daytime and nighttime. However, when the AADT is higher than 30,000, increasing the number of lanes does not necessarily have a significant increase in crash rate. This may be probably because some drivers may tend to change lanes when the traffic volumes are low on the roadways. This lane changing behavior may be a potential source of hazard for State roadway safety.

Table 16 - State roadway crash rate per million vehicle-miles by traffic volume and the number of lanes

		One lane or two lanes	More than two lanes	Percentage change of crash rate
AADT <30,000	Daytime	3.01	5.83	94%
	Nighttime	2.96	4.98	68%
	Total	3.00	5.60	87%
AADT >30,000	Daytime	2.03	2.08	2%
	Nighttime	2.05	2.14	4%
	Total	2.04	2.09	2%

Similarly, Table 17 shows that given the number of lanes, a higher traffic volume (AADT > 30,000) is associated with a lower crash rate.

Table 17 - State roadway crash rate per million vehicle-miles by traffic volume and the number of lanes

		AADT <30,000	AADT >30,000	Percentage change of crash rate
One lane or two lanes	Daytime	3.01	2.03	-32%
	Nighttime	2.96	2.05	-31%
	Total	3.00	2.04	-32%
More than two lanes	Daytime	5.83	2.08	-64%
	Nighttime	4.98	2.14	-57%
	Total	5.60	2.09	-63%

After studying the crash rate in State roadways under different traffic volumes and numbers of lanes, we developed similar analyses for county roadways because some have RPMs while some do not. Since almost all the county roadways have no more than two lanes, we only considered the effect of traffic volume on crash rate, on both RPM equipped roadways and the county roadways without RPMs. The average traffic volume for county roadways is 10,000.

Table 18 - Crash rates for county roadways by traffic volume with and without RPMs

		AADT <10,000	**AADT >10,000**
County roadway with RPM	Daytime	3.00	3.83
	Nighttime	3.34	3.90
	Total	3.09	3.85
County roadway without RPM	Daytime	3.32	4.87
	Nighttime	4.39	4.55
	Total	3.60	4.78

Based on Table 18, on county roadways with and without RPMs, the higher the traffic volume, the higher the crash rate. On State roadways, the speed limits are higher. The lane changing behavior might be dominated by the amount of traffic. When there is more traffic, drivers may be less inclined to change lanes. While, on county roadways, the speed limits are lower. There might be closer spacing between vehicles. Lane changing and unexpected stopping may be hazard sources for crashes that occur. Noteworthy is that the average traffic volume on State roadways differs from that on county roadways. Also, the safety standards and geometric design for State roadways and county roadways may differ. Caveats should be kept in mind when comparing and interpreting crash rate statistics on different roadway networks. Keeping this in mind, we compared crash rates on county roadways and State roadways in daytime and nighttime.

Table 19 - Crash rates for state roadways and county roadways in daytime and nighttime

	Daytime	Nighttime	Total
State roadway	2.48	2.46	2.47
County roadway with RPM	3.50	3.68	3.55
County roadway without RPM	4.41	4.50	4.43

According to Table 19, the crash rate for State roadway is lower than that for county roadway. In the literature, the effectiveness of RPMs has been studied in different weather conditions and for different types of crashes and apparently, RPM's performance might vary in different weather conditions and it might help to prevent certain type of crashes more effectively than some other type of crashes in a certain period of the day. [(1)]

Because almost all the county roadways (with RPMs or without RPMs) have two lanes, in Table 20, crash rates for the segments of State roadway that have two lanes (one lane in each direction) were calculated to compare crash rates for county roadways with RPMs and county roadways without RPMs.

Table 20 - Crash rates per million vehicle-miles for state roadway with two lanes and county roadways

	Daytime	Nighttime	Total
State roadway (two Lanes)	2.46	2.45	2.46
County roadway with RPM	3.50	3.68	3.55
County roadway without RPM	4.41	4.50	4.43

Overall, the crash rate on State roadway (two lanes) is lower than that on county roadways. With respect to county roadways, the segments with RPMs have lower crash rates than those county roadways without RPMs, for both daytime and nighttime.

In Table 21, crash rates are shown for different crash types. All the crash types have been divided into two general categories, related to RPMs and not related to RPMs. Crash types that are apparently related to RPM include same direction-side swipe, opposite direction-head on/angular, opposite direction-side swipe, encroachment, and fixed object. All the other crash types are categorized into class not related to RPMs.

Table 21 - Crash rates per million vehicle-miles by accident type

		Related to RPM	Not Related to RPM
State roadway	Daytime	0.72	1.76
	Nighttime	0.86	1.60
	Total	0.75	1.72
County roadway with RPM	Daytime	0.90	2.58
	Nighttime	1.06	2.69
	Total	0.95	2.61
County roadway without RPM	Daytime	1.13	3.27
	Nighttime	1.20	3.29
	Total	1.15	3.28

According to Table 21, the number of not RPM related crashes is two or three times more than RPM related crashes in daytime and nighttime. For each type, the crash rate on State roadway is the lowest, and the county roadway without RPMs has the highest rate.

Table 22 is a more comprehensive analysis comparing crash rate by crash type (RPM related, or not RPM related), weather (dry and wet), traffic volume and time period of the day (daytime versus nighttime), on county roadways with or without RPMs.

Table 22 - Crash rate comparison between county roadways with RPMs and county roadways without RPMs

	Crash Type		Weather		Traffic Volume		Overall
	Related to RPM	Not Related to RPM	Wet	Dry	AADT <10,000	AADT >10,000	
(Day RPM - Day non-RPM)/ (Day non-RPM)	-19%	-21%	-15%	-21%	-9%	-21%	-20%
(Night RPM - Night non-RPM)/ (Night non-RPM)	-12%	-18%	-24%	-14%	-24%	-14%	-18%
(Total RPM - Total non-RPM)/ (Total non-RPM)	-17%	-20%	-18%	-19%	-14%	-19%	-19%

Overall, the crash rate decreases 19 percent when the RPMs exist. If we assume that RPM installation could have the same effect on the State roadway, it could be interpreted as 19 percent decrease in crash rate of State roadway network might be possible by installation of RPMs.

We can see that the most significant decrease in crash rate happened in nighttime wet weather conditions. This seems to indicate that RPMs may have more safety effects under wet weather condition and in the nighttime. However, due to the sensitivity of daytime and nighttime crash rates to the assumptions made for hourly traffic distribution, the conclusion might be subject to uncertainty.

Cost of RPMs

Different States report different prices for RPM. Also, the replacement cycle and maintenance practices for RPMs varies among the States. For example, Washington State DOT replaces more than two million RPMs annually at a price of $2.40 per unit. [(18)] Based on the results of a survey in the State of Indiana, each installed raised pavement marker's price ranges from $13 to $20. Each lens replacement costs about $3.3 to $8. [(44)] The Virginia Department of Transportation (VDOT) bid data shows that installing an RPM costs over $23. New Jersey Department of Transportation (NJDOT) bid data shows the average price for each RPM installed is $26.35 for 2015 fiscal year, including materials and installation. According to the Rutgers survey, Lenses of the RPMs are typically inspected every three years to determine if they need to be replaced.

Crash Severity

A crash accident can result in different severities, each of which has a different monetary measure (Table 23).

Table 23 - Crash cost with different severity types

Severity	Cost
Fatality	$9,200,000
Incapacitated Injury	$5,455,600
Moderate Injury	$432,400
Pain	$27,600
Property Damage Only (PDO)	$3,927

Next, we are interested in seeing if the average crash cost (including property damage and monetarized casualty cost) would be different between county roadways with RPMs, without RPMs and State roadways.

Table 24 - Mean value of crash cost by road type

Road type	Number of crashes	Mean crash cost
County roadways with RPMs	6,033	$83,413
County roadways without RPMs	5,592	$85,217
State roadways	58,430	$71,981

If crash severity cost is used for cost-benefit analysis, the average cost might be around $80,000.

Lab Testing of RPMs

The present document summarizes photometric measurements that were made of several RPMs from three different manufacturers. Samples of RPMs were provided new from the manufacturers; in addition, two used products of one type of RPM matching those provided by manufacturers were provided by the New Jersey Department of Transportation (NJDOT).

The objective of the measurements was to estimate the luminance of the markers and devices as they would be experienced under nighttime conditions while driving with low beam headlights, and to use these luminance values to estimate a driver's visual performance in terms of the speed and accuracy of detecting/identifying each of the markers and devices. Measurement of the used markers allows an estimation of the degradation in performance over time when used in the field.

Method

RPM samples were mounted onto a platform fastened to a tripod (Figure 17), and adjusted for height and orientation to be either 0° or 1° below the measurement aperture of a handheld luminance meter (Minolta, LS-100), which was mounted onto another tripod 20 ft. away (Figure 18). Also attached to the luminance meter was a 40-W incandescent appliance lamp bulb, positioned 4 in. below the luminance meter's aperture (and located 1° below from a distance of 20 ft.).

Figure 17. RPM measurement sample mounted on tripod platform

The measurement sample tripod could be moved to different lateral positions to be located directly ahead of the luminance meter (0° horizontal angle), 5° or 10° to either side of the luminance meter. The height of the tripod could be set to match the height of the luminance meter aperture or 4 in. below (1° below the luminance meter aperture for the measurement distance of 20 ft.).

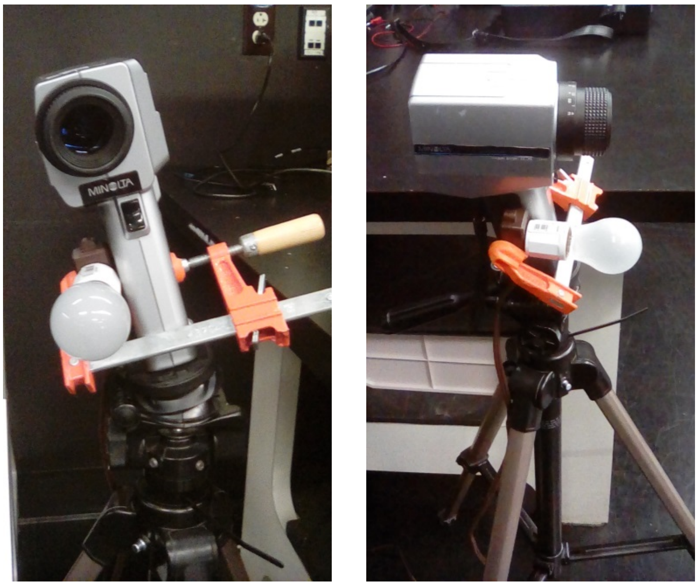


Figure 18. Luminance meter and light source
Left: front view. Right: side view

Figure 19 shows several of the sample RPMs that were measured. Some of them were mounted in steel casters and others were unmounted. Portions of the RPM housings that were constructed of yellow plastic were colored with a black permanent magic marker to reduce measurement noise.

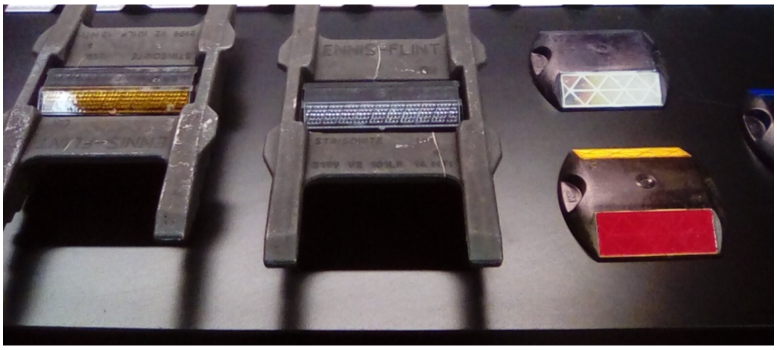


Figure 19. RPM samples used for measurements

Figure 20. Used RPM samples corresponding to one of the types measured in new condition

The measurements took place in a black painted room to minimize reflections from stray light. The calibrated luminance meter (Figure 20) was used with a spot size large enough to completely encompass the marker or delineation element (e.g., 1°). The marker and device locations used are described graphically in Figure 21.

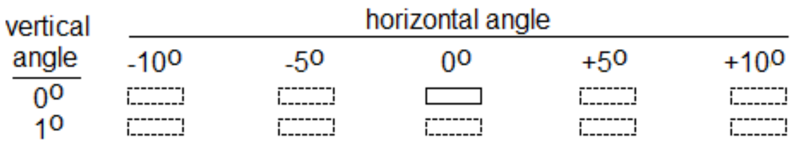


Figure 21. Horizontal and vertical locations of the marker being measured, viewed from the location of the light source.

Notes: *Negative horizontal angles correspond to those to the left of center (toward the driver side); positive horizontal angles correspond to those to the right of center (toward the passenger side)*

The 1° range of vertical angles and 20° range of horizontal angles corresponds to the representative ranges for pavement mounted reflectors that could be encountered on roadway curves.

With the light source energized, the luminance meter was used to capture the luminance of the 1° aperture centered around the marker (L_a, in cd/m²). The projected angular area of a 1° luminance spot is 0.7854 degrees². The projected angular area of the marker (A_p, in degrees²) was calculated for the marker or device being measured. Assuming a uniform marker luminance, its luminance (L_m, in cd/m²) could be calculated from the luminance spot measurement using the following equation:

$$L_m = L_a (0.7854/A_p)$$

The vertical illuminance (E, in lux) from the light source at each location in Figure 18 was also measured. From this data, it was possible to calculate the coefficient of retroreflectivity (R_c, in cd/m²/lux) for each angle, using the following equation:

$$R_c = L_m/E$$

This quantity is independent of the amount of illumination falling on the reflector at any particular location because the coefficient of retroreflectivity is defined as the ratio of its luminance for a given illuminance. If the illuminance were doubled, the luminance of the reflector would also be doubled, but the ratio between these quantities would remain the same.

Finally, to estimate what the luminance of the marker would be in an actual roadway scenario (L_{rs}, in cd/m²) under low beam headlamps at a given distance d (in meters), headlamp intensity data (I, in cd; see Table 25) from the University of Michigan [(43)] were applied to the corresponding angular location's coefficient of retroreflectivity using the following equation:

$$L_{rs} = R_c I/d^2$$

The data in Table 25 are for a pair of low beam headlights, assumed for this purpose to be co-located.

Table 25 - Luminous intensities from a representative pair of low beam headlamps toward several angular locations

Vertical Angle	Horizontal Angle				
	-10°	-5°	0°	+5°	+10°
0°	1346 cd	2186 cd	17,660 cd	9434 cd	2240 cd
1° down	6124 cd	10,612 cd	37,804 cd	19,796 cd	5602 cd

It can be seen in Table 25, that low beam headlights tend to produce more light at 1° down than they do at a vertical angle of 0°. The amount of light at the horizontal angle of +5°, which corresponds to one lane toward the passenger side of the vehicle 50 m ahead, is also larger than the amount of light at the horizontal angle of -5°, one lane toward the driver side.

Result

RPM Measurements

Four types of RPMs from Manufacturer A were measured, having retroreflective elements that were white, yellow, red and blue in color (Table 26 to Table 29). Two types of RPMs from Manufacturer B were measured, having retroreflective elements that were white and yellow (Table 30 and 31). One type of RPM from Manufacturer C was measured, having retroreflective elements that were white (Table 32). Two used RPMs from Manufacturer B (yellow in color) were also measured (Table 33 and 34). Table 26 to Table 34 summarize the measurements and the relative visual performance (RVP) model calculations that were made. Ten combinations of vertical angles (0° and 1° down) and horizontal angles (0°, and 5° and 10° to the left and right) were set up for each RPM.

Each table shows the following characteristics:

- Vertical illuminance at the front face of the marker (lx)
- Average measured luminance of the 1° luminance meter aperture (cd/m²)
- Actual marker luminance, correcting for the aperture size (cd/m²)
- Coefficient of retroreflectivity for the measured illuminance and luminance (cd/lx/m²)
- Low beam headlight set intensity toward the marker for each geometric condition (cd)
- Low beam headlight illuminance at a distance of 100 m ahead (lx)
- Predicted RPM luminance under low beam headlights (cd/m²)
- Relative visual performance (RVP) for the predicted luminance

Relative visual performance (RVP) is a quantity without units representing the relative speed and accuracy of visual processing. RVP depends on the light level, the contrast between an object and its background, the size of the object, and the age of the observer (an age of 60 years is assumed for all RVP calculations). RVP values can range from zero at the threshold of identification for an object, to values of one or greater. A value of one corresponds to the level of visibility under a reference visual task similar to reading black laser printed text under office light levels; higher values are possible, but once an object achieves a high (>0.9) RVP level, further increases in light level, contrast or size will not make substantial improvements in visual performance.

It can be seen from inspection of the following tables that RVP values for all of the markers and geometric conditions are quite high (>>0.9) indicating that the markers would be highly visible to drivers under all of the geometric conditions included in the present measurements (e.g., horizontal angles between 10° to the left and 10° to the right, and vertical angles between 0° and 1° down). This indicates that RPMs do indeed provide high levels of visibility to drivers.

Discussion

Most of the data in Table 26 through 34 are for brand new products of each type in very good condition. Obviously, RPMs are subject to wear and tear. Based on feedback from NJDOT safety engineers, the project team requested and received samples of RPMs from field installations in New Jersey for photometric measurement in order to assess the amount of luminance degradation that can occur following installation. The results in Table 33 and 34 show that used RPMs have lower retroreflectivity characteristics (Sample #1 was about 30 percent to 35 percent lower and Sample #2 was about 15 percent to 20 percent lower than the new sample). Nonetheless, these used devices still resulted in high (>0.9) levels of visual performance for the scenarios investigated.

Table 26 - Photometric/Visual Performance Summary: White RPM (Manufacturer A)

RPM A (white)		*Proj. Area (deg ^{2}):*	0.068567		
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.8	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	6.389	6.525	7.215	6.680	6.497
-1 V	6.477	6.212	7.193	6.284	6.729
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	73.18292	74.74074	82.64435	76.51619	74.42001
-1 V	74.19092	71.15547	82.39235	71.9802	77.07746
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	121.9715	106.7725	103.3054	109.3088	124.0333
-1 V	123.6515	101.6507	102.9904	102.8289	128.4624
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**16.42**	**23.34**	**182.44**	**103.12**	**27.78**
-1 V	**75.72**	**107.87**	**389.35**	**203.56**	**71.96**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.995**	**1.000**	**1.022**	**1.016**	**1.002**
-1 V	**1.013**	**1.017**	**1.029**	**1.023**	**1.013**

Table 27 - Photometric/Visual Performance Summary: Yellow RPM (Manufacturer A)

RPM A (yellow)		*Proj. Area (deg²):*		0.068567	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.8	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	3.577	3.632	4.329	3.574	3.689
-1 V	3.477	3.533	3.847	3.464	3.471
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	40.97281	41.60281	49.58661	40.93845	42.25572
-1 V	39.82736	40.46882	44.06553	39.67845	39.75863
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	68.28802	59.43259	61.98327	58.4835	70.4262
-1 V	66.37894	57.81259	55.08192	56.6835	66.26439
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**9.19**	**12.99**	**109.46**	**55.17**	**15.78**
-1 V	**40.65**	**61.35**	**208.23**	**112.21**	**37.12**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.984**	**0.991**	**1.017**	**1.010**	**0.994**
-1 V	**1.006**	**1.011**	**1.023**	**1.017**	**1.005**

Table 28 - Photometric/Visual Performance Summary: Red RPM (Manufacturer A)

RPM A (red)		*Proj. Area (deg^2):*		0.068567	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.8	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m^2)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1.655	1.852	2.074	1.845	1.727
-1 V	1.758	1.822	1.901	1.824	1.744
Actual Luminance (cd/m^2)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	18.95723	21.21377	23.75667	21.13359	19.78195
-1 V	20.13704	20.87013	21.77504	20.89304	19.97668
Coefficient of Retro. ($cd/lx/m^2$)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	31.59538	30.30538	29.69584	30.19084	32.96992
-1 V	33.56174	29.81448	27.2188	29.8472	33.29447
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m^2)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**4.25**	**6.62**	**52.44**	**28.48**	**7.39**
-1 V	**20.55**	**31.64**	**102.90**	**59.09**	**18.65**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.958**	**0.975**	**1.009**	**1.002**	**0.978**
-1 V	**0.998**	**1.003**	**1.016**	**1.011**	**0.996**

Table 29 - Photometric/Visual Performance Summary: Blue RPM (Manufacturer A)

RPM A (blue)		*Proj. Area (deg^2):*		0.068567	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.8	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.361	0.366	0.403	0.379	0.366
-1 V	0.323	0.38	0.328	0.363	0.323
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	4.135081	4.192354	4.616171	4.341263	4.192354
-1 V	3.69981	4.352717	3.757082	4.15799	3.69981
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	6.891802	5.989077	5.770214	6.201804	6.987256
-1 V	6.166349	6.218167	4.696353	5.939986	6.166349
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.93**	**1.31**	**10.19**	**5.85**	**1.57**
-1 V	**3.78**	**6.60**	**17.75**	**11.76**	**3.45**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.956**	**0.957**	**0.962**	**0.959**	**0.957**
-1 V	**0.950**	**0.959**	**0.951**	**0.957**	**0.950**

Table 30 - Photometric/Visual Performance Summary: White RPM (Manufacturer B)

RPM B (white)		*Proj. Area (deg ^{2}):*		0.052536	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	2.621	2.372	3.051	2.391	2.612
-1 V	2.578	3.126	3.36	2.980	2.697
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	39.18298	35.46052	45.61132	35.74456	39.04843
-1 V	38.54014	46.73254	50.23075	44.54989	40.31915
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	65.30496	50.65788	65.15902	51.06366	65.08072
-1 V	64.23357	66.76077	62.78844	63.64271	67.19858
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**8.79**	**11.07**	**115.07**	**48.17**	**14.58**
-1 V	**39.34**	**70.85**	**237.37**	**125.99**	**37.64**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.980**	**0.985**	**1.017**	**1.008**	**0.991**
-1 V	**1.005**	**1.012**	**1.024**	**1.018**	**1.005**

Table 31 - Photometric/Visual Performance Summary: Yellow RPM (Manufacturer B)

RPM B (yellow)		*Proj. Area (deg^2):*		0.052536	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	3.095	3.411	4.283	3.412	3.061
-1 V	3.234	4.089	4.403	4.258	3.109
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	46.2691	50.99318	64.02926	51.00813	45.76081
-1 V	48.3471	61.12903	65.82322	63.65552	46.4784
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	77.11517	72.8474	91.47037	72.86876	76.26802
-1 V	80.5785	87.32719	82.27902	90.93646	77.46399
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**10.38**	**15.92**	**161.54**	**68.74**	**17.08**
-1 V	**49.35**	**92.67**	**311.05**	**180.02**	**43.40**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.984**	**0.993**	**1.021**	**1.012**	**0.994**
-1 V	**1.008**	**1.015**	**1.027**	**1.022**	**1.007**

Table 32 - Photometric/Visual Performance Summary: White RPM (Manufacturer C)

RPM C (white)		*Proj. Area (deg^2):*		0.052536	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	4.008	3.924	4.564	4.023	4.004
-1 V	3.977	4.149	4.669	4.049	4.182
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	59.92231	58.66816	68.22433	60.14062	59.86226
-1 V	59.44972	62.03058	69.80646	60.52612	62.51426
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	99.87052	83.81166	97.46334	85.91517	99.77043
-1 V	99.08286	88.61512	87.25807	86.46588	104.1904
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**13.44**	**18.32**	**172.12**	**81.05**	**22.35**
-1 V	**60.68**	**94.04**	**329.87**	**171.17**	**58.37**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.989**	**0.995**	**1.021**	**1.013**	**0.998**
-1 V	**1.011**	**1.015**	**1.027**	**1.021**	**1.010**

Table 33 - Photometric/Visual Performance Summary: Yellow RPM (Manufacturer B; Used Sample #1)

RPM B (yellow - used 1)		*Proj. Area (deg ^{2}):*		0.052536	
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	2.259	2.250	3.058	2.378	1.986
-1 V	2.274	2.736	3.140	2.395	1.727
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	33.77574	33.63402	45.71187	35.55622	29.69409
-1 V	33.99321	40.90309	46.93814	35.79921	25.81755
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	56.2929	48.04859	65.30267	50.79461	49.49016
-1 V	56.65535	58.43299	58.67267	51.14173	43.02924
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**7.58**	**10.50**	**115.32**	**47.92**	**11.09**
-1 V	**34.70**	**62.01**	**221.81**	**101.24**	**24.10**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.975**	**0.984**	**1.017**	**1.008**	**0.985**
-1 V	**1.004**	**1.011**	**1.024**	**1.016**	**0.999**

Table 34 - Photometric/Visual Performance Summary: Yellow RPM (Manufacturer B; Used Sample #2)

RPM B (yellow - used 2)		*Proj. Area (deg²):*	0.052536		
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.8	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	2.759	2.647	3.631	2.737	2.662
-1 V	2.508	3.538	3.599	3.582	2.713
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	41.24366	39.57659	54.2828	40.91531	39.79682
-1 V	37.49241	52.89827	53.80979	53.55542	40.56123
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	68.73944	56.53799	77.54686	58.45045	66.32803
-1 V	62.48734	75.56896	67.26224	76.50774	67.60205
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
RPM Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**9.25**	**12.36**	**136.95**	**55.14**	**14.86**
-1 V	**38.27**	**80.19**	**254.28**	**151.45**	**37.87**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.981**	**0.988**	**1.019**	**1.009**	**0.991**
-1 V	**1.005**	**1.013**	**1.025**	**1.020**	**1.005**

Visual Performance/Distance Analyses

For all RPMs, their visibility was estimated with a viewing distance of 100 m. Increasing the distance will have two primary impacts on visual performance: the size of the devices will decrease, and the headlight illuminance on the devices will decrease. Both factors will decrease with the square of the distance between the vehicle and the device.

Since the RVP values for all devices were close to 1.0, indicating very good visibility from 100 m, the distances were systematically decreased until the RVP value fell below zero, which is defined as the threshold for recognition visibility. Thus, the distances at which the RVP values reach zero is an estimate of the visibility distance for that device under low beam headlight illumination.

Figure 22 shows the resulting RVP values for the RPMs from manufacturer A (the gray curve is for the white RPM and the remaining colored curves are for the yellow, red and blue RPMs). Figure 23 shows the RVP values for the RPMs from manufacturer B (including two used yellow RPMs provided by NJDOT). Figure 24 shows the white RPM from manufacturer C.

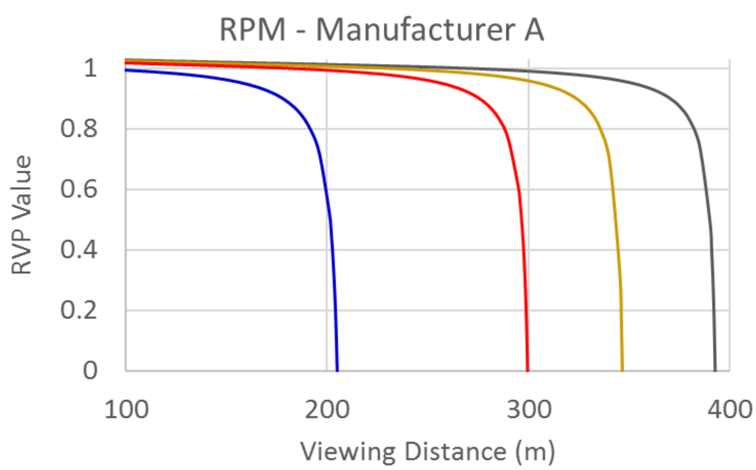


Figure 22. RVP values for the RPMs from manufacturer A

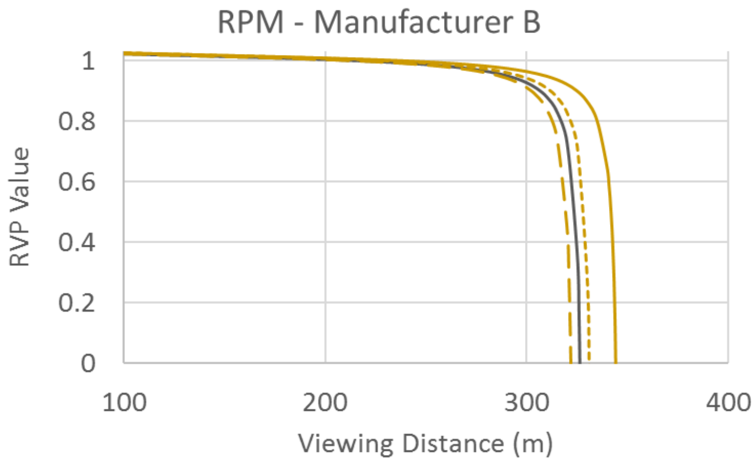


Figure 23. RVP values for the RPMs from manufacturer B.

The dotted/dashed curves in Figure 23 represent the used yellow RPM samples provided by NJDOT.

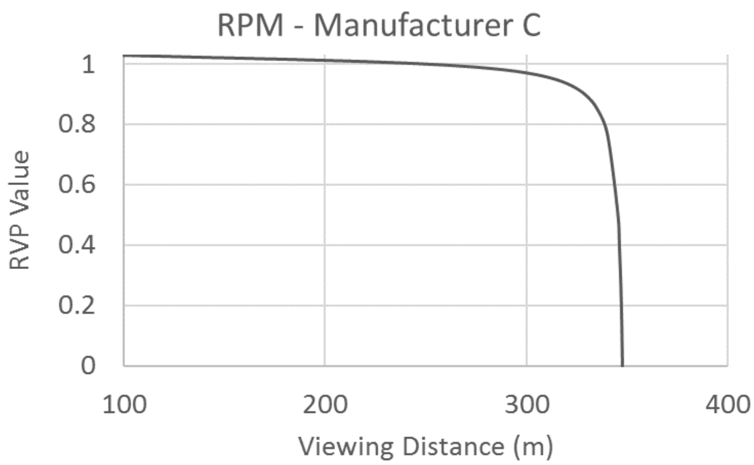


Figure 24. RVP values for the white RPM from manufacturer C

In general, RPMs tend to have visibility distances between 300 and 400 m before they reach the visibility threshold defined by an RVP value of zero.

CHAPTER 5: COST EFFECTIVENESS OF RPM ALTERNATIVES

Introduction

Delineation pavement markings are important for roadway safety. There are a variety of delineation marking products with various attributes and service qualities. This chapter will discuss widely used delineation pavement marking materials, regarding their design standards, cost-effectiveness, conditions of use, and performance for lane departure warning. These products, serving as potential alternatives to RPMs, will be analyzed for proper application under different conditions.

This chapter will firstly review the state of the art and practice documented in the literature regarding the safety benefits and costs of selected RPM alternatives in several States. Then, this chapter will present preliminary laboratory testing results regarding the visual performance comparison of RPM alternatives.

RPM Alternatives

Traffic Tapes

Traffic tape has several types and usually has a high initial cost. It tends to be used under safety-critical conditions. Traffic tape performance has two evaluation criteria: durability and visibility. Durability is measured by the number of materials remaining on pavement appearance or by the bond strength of the material to the surface. Visibility refers to the brightness of the material, measured by retroreflectivity. Traffic tapes have a wide range of estimated service lives given tape materials. Usually, they will be functional from 4 years to 8 years. The traffic tape that is pressed into pavement (inlaid tapes) outlast tapes adhered to pavement (overlaid tapes).

Compared with other lane marking materials, traffic tapes are advantageous for their durability, especially regarding abrasion resistance. Traffic tapes are also recognized as an easy method of installation and removal procedures. Preformed tapes are generally fabricated as roll or sheet stocks in a factory, consisting of glass beads, resin binder, pigment, and fillers. Preformed tapes are ideal for locations of frequent replacement.

Safety Effectiveness of Traffic Tape

Carlson et al. (29) conducted research which compares various pavement marking products under wet-night conditions. Their results revealed that retroreflective raised pavement markers performed the best and rumble strips combined with bigger beads provided an improved result. Traffic tape is an option that should be considered where thermoplastic pavement markers and polyurea do not perform well. However, the cost of traffic tape may prohibit its use.

Although traffic tape products may have high initial costs, they have several advantages. Firstly, traffic tapes perform well on Portland Cement Concrete surface under high Annual Average Daily Traffic (AADT) conditions. Secondly, they provide higher visibility than other pavement markings under dry and wet conditions. Lastly, drivers may prefer a contrast marking to minimize driver confusion.

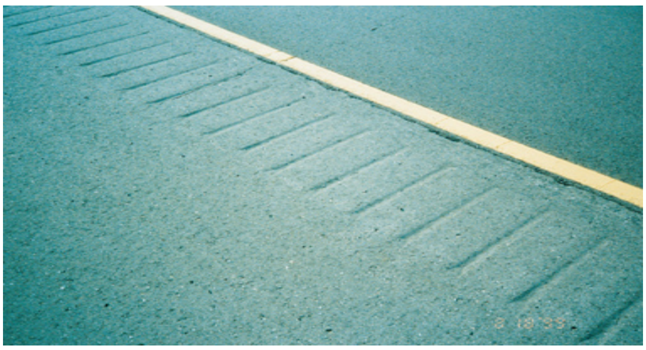
Cottrell and Hanson (39) from Virginia DOT investigated the safety, drivers' preference and cost effectiveness of various pavement marking materials. They used before-and-after accident analysis to explore their safety effects. However, their data and sites are insufficient to support any findings that the application of tape can reduce targeted crashes. They also investigated the most cost-effective alternatives under two-lane, four-lane, and six-lane roadways with either high or low levels of traffic volume. Under two-lane roadways with large traffic volumes and on four- and six- lane roadways with low volumes, paint was the most cost-effective method. For two- and four-lane roadways with high volume, polyuria combined with paint is the most cost-effective method. Their results also demonstrated that polyurea and waffle tape are the more cost-effective markings for six-lane roadways with high traffic volumes.

Rumble Strips

It has been found in many previous studies that centerline rumble strips combined with shoulder line rumble strips have safety benefits. Shoulder rumble strips are used to reduce single-vehicle-run-off-road (SVROR) crashes, and centerline rumble strips are used to reduce head-on (HO) crashes, opposite-direction sideswipe crashes, and SVROR-to-the-left crashes. There are various types of rumble strips: milled, rolled, formed, and raised. Milled rumble strips are the most widely used type most commonly on the centerline by transportation agencies.

Milled Rumble Strips

Raised Rumble Strips



Rolled Rumble Strips

Figure 25. Rumble strips (image sources: Morena, 2003)

Dimensions of Shoulder Line Rumble Strips

It is recommended that rumble strips should be designed to generate sound levels between 3 and 15 dBA above the ambient in-vehicle sound. One of the most common dimensions of milled shoulder rumble strips used throughout United States [45] are:

- Length: 16 in. (406 mm);
- Width: 7 in. (178 mm);
- Depth: 0.5 to 0.625 in. (13 to 16 mm);
- Spacing: 12 in. (305 mm).

Dimensions of Centerline Rumble Strips

Regarding the recommended design threshold values for centerline rumble strips, it is recommended that centerline rumble strip patterns be designed to generate approximately 10 to 15 dBA above the ambient in-vehicle sound level. The noise prediction models in Table 82 and 83 of the NCHRP 641 [45] report are applicable for designing centerline rumble strips. The most common dimensions of milled centerline rumble strips used [45] are as follows:

- Length: 12 or 16 in. (305 to 406 mm);
- Width: 7 in. (178 mm);
- Depth: 0.5 in. (13 mm);
- Spacing: 12 in. (305 mm).

Near residential or urban areas, consideration should be given to designing centerline rumble strip patterns that generate between 6 to 12 dBA above the ambient in-vehicle sound level to minimize the impacts on nearby residents.

Safety Effectiveness of Rumble Strips

The NCHRP 641 report [45] conducted safety evaluations of shoulder rumble strips, primarily on rural freeway facilities. The safety benefits of shoulder rumble strips vary by roadway type (e.g., lane width, shoulder width, roadside), traffic volume and distributions, operating speed, and the placement of rumble strips. That report also investigated the impact of shoulder rumble strips on specific target crashes (e.g. heavy vehicle crashes under low-lighting conditions). In this report, different road types were investigated for safety effectiveness of rumble strips, including urban freeway, urban multilane divided/undivided highways, urban two-lane roads, rural freeways, and rural roads. Shoulder rumble strips were found to reduce single-vehicle-run-off-road crashes by 22 percent and resulted in a 51 percent reduction of single-vehicle-run-off-road fatal and injury crashes. For urban two-lane roads, centerline rumble strips can reduce the total target crashes by 40 percent and fatal and injury crashes by 64 percent. For rural two-lane Roads, centerline rumble strips can reduce the total targeted crashes by 9 percent and fatal and injury crashes by 12 percent.

For urban freeways, shoulder rumble strips can reduce the total targeted crashes by 18 percent, and fatal and injury targeted crashes by 13 percent. For rural freeways, shoulder rumble strips can reduce SVROR crashes by 11 percent and SVROR fatal and injury crashes by 16 percent. For rural two-lane roads, shoulder rumble strips will reduce SVROR crashes by 15 percent and SVROR fatal and injury crashes by 29 percent.

An FHWA Report [26] conducted a before and after evaluation of the safety effectiveness of the combination of shoulder and centerline rumble strips measured by cash frequency. The targeted crash types included fatal and injury, run-off-road, head-on, and sideswipe-opposite-direction crashes. Their data came from Kentucky, Missouri, and Pennsylvania. The benefit of rumble strips is demonstrated by CMFs (crash modification factors) (Table 35). For head-on collision and sideswipe-opposite-direction collision, the CMF factor is 0.7. It indicates a 30 percent reduction with a 6.4 percent standard deviation. The benefit/cost ratios are estimated to range from 20.2 to 54.7, depending on product service life and the treatment cost used in the analysis.

Table 35 - Crash Modification Factors (CMFs) of rumble strips [26]

	Total	**Injury**	**Run-off-road (ROR)**	**Head-on (HO)**	**Sideswipe-opposite-direction (S-OD)**	**(HO) & (S-OD)**	**(ROR) & ROR+HO+S-OD**
CMF	0.8	0.771	0.742	0.632	0.767	0.7	0.733
Standard error	0.025	0.034	0.041	0.085	0.097	0.064	0.035

Massachusetts

Noyce and Elango [46] evaluated the safety effectiveness of centerline rumble strips by using before and after analysis considering crash frequency, head-on collisions, angle collisions, sideswipe in opposite directions, and run-off-the-road crashes with centerline encounters. Their data was obtained from segments of Massachusetts State Routes 2, 20, and 88. Their analysis didn't provide significant evidence of crash reduction but suggest the effectiveness of reducing the severity of crashes by installing centerline rumble strips. They also conducted a simulated experiment to study if centerline rumble strips can effectively correct lane position.

Minnesota

Patel et al. [(47)] conducted a before and after study to estimate safety benefits of shoulder rumble strips on two-lane rural highways in Minnesota. This study used crash data from 1992 to 2004, including 23 treatment sites totaling 183 miles. Their study indicates that shoulder rumble strips will reduce single-vehicle, run-off-road crashes (SVROR) by 13 percent. The injury-producing SVROR will be reduced by 18 percent on two-lane rural highways in Minnesota.

Connecticut

Connecticut Department of Transportation [(48)] collected data three years before and three years after the installation of rumble strips on 73 sections of roadway. The selected roadway sections range in length from less than one mile to over 18 miles. In their research, they used 11 rumble strip sections and 11 comparison sections. The expected number of accidents in comparison groups are defined as odds ratios, which are used to indicate safety benefits. The index of effectiveness is 0.71. It was found that there were 21 fewer fixed-object, single-vehicle, run-off-road accidents on the treatment roadways than on comparison roadways. The compiled accident data for the 11 rumble strip sections and their respective comparison sections resulted in an index of effectiveness of 0.68. The results also showed that there would have been 88 "rumble strip preventable" accidents if rumble strips were installed.

Maine

Garder and Davies [(49)] evaluated the effectiveness of the installation of rumble strips to prevent run-off-road (ROR) crashes using crash data from 1989 to 2002. An evaluation of safety effectiveness showed that continuous shoulder rumble strips reduced sleep-related ROR crashes by approximately 58 percent. A statistical analysis showed that there is 99.9 percent certainty that the typical reduction in sleep-related ROR crashes was at least 41 percent. Fatal crashes were reduced most significantly among all crashes. On a typical roadway segment in Maine, dry road ROR crashes were reduced by about 43percent, giving the cost-benefit ratio of installing CSRS at least 195:1. CSRS was less effective in eliminating crashes during inclement weather conditions. The overall safety effectiveness of CSRS was estimated to be 27 percent in terms of all ROR crashes.

Michigan

Michigan Department of Transportation (50) investigated the perceived differences among three types of experimental painted rumble strip patterns. The study involved residents living near the designed rumble strip area. Ten thousand households and seven focus group meetings with commercial truck drivers and law enforcement personnel were included in the survey. Results demonstrate that rumble strips are overwhelmingly accepted by a majority of local drivers and that they also prefer rumble strip markings that contain two painted (solid) stripes. Shoulder rumble strips are a proven roadside treatment in preventing run-off-the-road crashes on freeways, as an effective alarm for drowsy or distracted drivers who are leaving the roadway. By painting the shoulder rumble strips, the MDOT is trying to improve safety in areas where motorists lose visibility of the edgeline in fog and snow. Research has shown that painted rumble strips are visible at night in the rain, enhancing the effectiveness for drivers navigating Michigan’s freeways.

In 2008, the Michigan Department of Transportation began to install centerline rumble strips on more than 5,000 miles roadway and completed the project in 2010. They used a comprehensive crash dataset for a period of three years before installation of rumble strips and three years after the installation. They used the empirical Bayes method to assess the safety effectiveness of rumble strips. They found that cross-line crashes reduced by 27.3 percent when only centerline rumble strips were used. The crash rate reduced by 32.8 percent when both shoulder and centerline rumble strips were used.

Montana

Montana Department of Transportation [51] evaluates the effectiveness of shoulder rumble strips to prevent the single-vehicle off-road crashes on interstate and primary highways. They collected crash data for three years before and after the implementation of rumble strips. Their study demonstrated that shoulder rumble strips could reduce the crash rate by between 14 percent and 23.5 percent. While rollover crash rate was reduced by 5.5 percent, the rollover accident severity increased by 2.7 percent. The benefit/cost ratio was calculated to be approximately 20:1.

New York

Perrillo [52] conducted an analysis to determine the minimum benefit-cost ratio of continuous shoulder rumble strips for New York State Thruway. The cost of installation per roadway kilometer of rumble strips is $2,477. They collected the crash data before and after the installations of rumble strips. The total savings per year for three targeted accident types are $59 million. Based on six-year lifecycle length of rumble strips, the benefit-cost ratio was estimated to be 182:1.

Pennsylvania

Hickey [53] evaluated the safety effects of shoulder rumble strips installed in Pennsylvania Turnpike for 53 segments, totaling 348 miles of roadway. By using before-after analysis, the drift-off-road accidents per month decreased by 60 percent. The shoulder rumble strips reduced the accidents per million vehicle miles by 2.3. Porter et al. [54] investigated the effectiveness of centerline rumble strips on lateral vehicle placement and speed. Their findings suggest that the installation of centerline rumble strips affect the lateral vehicle placement.

Utah

Chen et al. [55] used two comparison groups to investigate the safety effectiveness of rumble strips measured in terms of accident rate reduction. The results showed that for both overall and run-off-the-road accidents, the accident rates were lower if rumble strips were installed. The accident rates with rumble strips were found to be 0.713 and 0.394 for overall and run-off-the-road accidents respectively. Highway sections without rumble strips were found to have accident rates of 33.4 percent higher and 26.9 percent higher for overall and run-off-the-road accidents, respectively. Furthermore, for segments with rumble strips, accident rates of serious accidents per mile were found to be 1.58 and 1.26 for overall and run-off-the-road accidents, respectively. The absence of rumble strips attributed to 27.2 percent higher and 8.7 percent higher of overall and run-off-the-road accidents, respectively. It was also found that rumble strips not only prevent accidents but also lower the severity of those accidents.

Texas

Carlson and Miles [56] presented a safety analysis of centerline and shoulder rumble strips in the case of Texas. Their results revealed that the cost-effectiveness of rumble strips vary with roadway type and traffic volume. The higher the traffic volume, the larger will the benefit-to-cost (B/C) ratio. When AADT is lower than 1500, the B/C ratio is less than one. However, when the AADT increases, B/C is greater and can be 26.42 when AADT is over 4500.

Kansas

Karkle [57] evaluated the safety effectiveness of centerline rumble strips. The results demonstrated that centerline rumble strips reduce total crashes by 29.21 percent. Fatal and injury crashes have been reduced by 34.05 percent. Crossover and run-off-road crashes have been reduced by 67.19 percent and 19.19 percent, respectively. In his research, both Naïve and Empirical Bayes methods were applied and showed statistically similar results.

Virginia

The Virginia DOT conducted a study in 2005. [58] The study included the development of guidelines that outline the application of CLRS, design dimensions, installation and maintenance, and other issues. The authors recommended that the Virginia Department of Transportation's Traffic Engineering Division implement the guidelines as a division memorandum. A sample estimated benefit-cost ratio per mile was over 7.6.

Kentucky

Kirk [59] did a crash analysis for 162 roadway segments with and without shoulder rumble strips using a three–year crash data on two-lane rural roads. Based on this analysis, their results show that two-lane rural roads with continuous shoulder rumble strips have lower total crash rates than roadways without rumble strips. Two-lane rural roads with continuous shoulder rumble strips have lower crash rates than roadways without them.

Florida

Spainhour and Mishra [60] used 579 fatal run-off-road crashes on State highways in Florida to examine the factors influencing overcorrection issues, which is highly related to run-off-road crashes. They used a logistic regression model to investigate the variables that may affect overcorrection behavior. They found that rumble strips can reduce more than 50 percent of overcorrection issues, and 20 percent of run-off-road crashes.

Canada

Sayed et al. [61] developed a crash prediction model using data from 2002 to 2005 in British Columbia. Their results indicated that severe collisions were reduced by 18 percent. Shoulder rumble strips reduced off-road-right collisions by 22.5 percent, and centerline rumble strips reduced 29.3 percent of off-road left and head-on collisions.

El-Basyouny and Sayed [62] did a safety assessment of the installation of shoulder rumble strips in British Columbia. They collected data on off-road-right collisions from 2001 to 2010 from 24 road segments with rumble strips. By using the Poisson–lognormal linear intervention model, they found that the crash rates reduced by 21.2 percent. Using an alternative non-linear Koyck model, they found that crash rates were reduced by 17.8 percent. Both estimations indicate significant safety effects after installation of rumble strips.

Table 36 summarizes Statewide safety evaluation of rumble stripes based on a review of the literature. Due to data limitations, there has been no study yet regarding the safety effectiveness of rumble strips in New Jersey, which could be one of the future research directions.

Table 36 - Safety benefits of rumble strips

Author	State	Analysis method	Type of treatment	Types of roadway	Types of targeted accidents	Percentage increase or decrease of targeted collisions
Patel et al. [47]	Minnesota	Before and after	Shoulder	Two-lane rural highway	SVROR	-13%
Garder and Davies [49]	Maine	Statistical Analysis	Centerline	Two-lane rural highway	ROR	-27%

Hickey [53]	Pennsylvania	Before and after	Shoulder	Two-lane rural highway	Drift-off-Road	-60%
Carlson and Miles [56]	Texas	Before and after	Centerline & Shoulder	Two-lane rural highway	ROR	Varies with Road Type and AADT
Chen and Cottrell [58]	Virginia	Data Analysis	Centerline	Two-lane rural highway	ROR	Varies with Road Site
Spainhour and Mishra [86]	Florida	Logistic Regression	Rumble Strips	Two-lane rural highway	Over-Correction	-50%
Spainhour and Mishra [60]	Florida	Logistic Regression	Rumble Strips	Two-lane rural highway	ROR	-20%
El-Basyouny and Sayed [62]	Canada	Poisson–lognormal linear intervention (PLLI) model	Shoulder	Two-lane rural highway	Off-road right collision	-21.20%
Sayed and Paul etc. [61]	Canada	Empirical Bayes	Shoulder	Two-lane rural highway	off-road collision	-22.50%
Sayed et al. [61]	Canada	Empirical Bayes	Centerline	Two-lane rural highway	Head-On and off-road left	-29.30%
Marvin and Clark [51]	Montana	Before-after with comparison sites	Shoulder	Interstate and primary highways	SVROR	-14%
Cheng [55]	Utah	Before-after with	Shoulder	Interstate	TOT	-33%

		comparison sites				
Annino [48]	Connecticut	Before-after with comparison sites	Shoulder	Limited-access roadways	SVROR	-32%
Noyce [46]	Delaware	Naïve before-after	Centerline	Rural two-lane road	HO	-95%
Noyce [46]	Delaware	Naïve before-after	Centerline	Rural two-lane road	Drive left of center	-60%
Noyce [46]	Delaware	Naïve before-after	Centerline	Rural two-lane road	PDO	0.13
Noyce [46]	Delaware	Naïve before-after	Centerline	Rural two-lane road	Injury	4%
Noyce [46]	Delaware	Naïve before-after	Centerline	Rural two-lane road	Total	-8%
Karkle, D. [57]	Kansas	Before and after	Centerline	Two-lane rural highway	Fatal and Injury	Reduce 34.05%
Karkle, D. [57]	Kansas	Before and after	Centerline	Two-lane rural highway	Cross-over and ROR	Reduce 67.19% and 19.19%
Kirk [59]	Kentucky	Before-after with comparison sites	Shoulder	Two-lane rural highway	TOT	Reduce crashes significantly

Notes:
HO = Head-On crashes
TOT = Total Crashes
FI = Fatal and Injury
SVROR = Single-Vehicle-Run-Off Road Crashes
ROR = Run-off-Road

Cost of RPMs and Alternatives

Cost of RPMs

Different States report different costs for RPMs and the replacement cycle and maintenance practices for RPMs vary among States. For example, Washington State DOT replaces more than two million RPMs annually at a price of $2.40 per unit. [18] Based on the results of a survey in the State of Indiana, each installed raised pavement marker's price ranges from $13 to $20. Each lens replacement costs about $3.3 to $8. [5] The Virginia Department of Transportation (VDOT) bid data shows that installing an RPM costs over $23. New Jersey Department of Transportation (NJDOT) bid data shows the average price for each installed RPM is $26.35 for the 2015 fiscal year, including materials and installation. According to the Rutgers survey, the lenses of the RPMs are typically inspected every three years to determine if they need to be replaced.

Table 37 - RPM at 40-foot interval Install Cost [63]

Centerline Install Cost – INDOT Contract Prices			
	Quantity per Mile	**Unit Cost**	**Cost per Mile**
RPM (install)	132	$14.15	$1,867.80
Thermo (if)	5280	$0.36	$1,900.80
Paint (if)	5280	$0.13	$686.40
Total with Thermo			$3,768.60
Total with Paint			$2,554.20

Table 38 - RPM centerline at 80-foot interval Install Cost (63)

Centerline Install Cost – INDOT Contract Prices			
	Quantity per Mile	**Unit Cost**	**Cost per Mile**
RPM (install)	66	$14.15	$933.90
Thermo (if)	5280	$0.36	$1,900.80
Paint (if)	5280	$0.13	$686.40
Total with Thermo			$2,834.70
Total with Paint			$1,620.30

Cost of Rumble Strips

New York State Department of Transportation

The installation of centerline rumble strips is around $0.30 per linear foot, which is equivalent to $1,580/mile. Shoulder rumble strips are around $0.60 per linear foot, which is equivalent to $3,160/mile.

Kentucky

The dual application cost of centerline and shoulder rumble strips in Kentucky is $12,000/mile, where the service lives are expected to be 12 to 15 years. Using the discount rate of 7 percent recommended by the FHWA Office of Safety R&D, the annualized cost is $1,511/mile.

Indiana

Indiana DOT found that the lifecycle cost of centerline rumble strips could be lower than RPMs that are biennially repainted at 40-foot or 80-foot intervals.

Table 39 - Centerline rumble strips installation cost (63)

Centerline Install Cost – INDOT Contract Prices			
	Quantity per Mile	**Unit Cost**	**Cost per Mile**
Centerline Rumble Strips (install)	5280	$0.20	$1,056.00
Thermo (if)	5280	$0.36	$1,900.80
Paint (if)	5280	$0.13	$686.40
Total with Thermo			$2,956.80
Total with Paint			$1,742.40

Cost of Traffic Tapes

Table 40 presents the cost analysis of traffic tapes from the literature.

Table 40 - Cost and service life for traffic tapes and rumble strips (29)

Material	Marking Width (inches)	Installation Cost per Linear Foot ($/lf)	Service Life (years)	Cost per Service Life	
				($/lf/yr)	($/mile/yr)
Rumble Strips with Thermo	4	0.5	3	0.167	880
Traffic Tape	4	2.75	6	0.458	2,420
Traffic Tape	6	3.75	6	0.625	3,300

There are many factors affecting the cost-benefit ratios among different alternatives. Some delineation markers may have particularly higher installation costs but a long service life. Safety impacts and traffic delay caused by maintenance activities are not included in this report but will be detailed in chapter 6 – "best practice" of RPMs and alternatives.

Measurements and Visual Performance Analyses for RPM Alternatives

Photometric measurements were made of alternatives to RPMs of two different types (wet reflective pavement marking tape and vertical-mounted delineators). The objective of the measurements was to estimate the luminance of the devices as they would be experienced under nighttime conditions while driving with low beam headlights and to use these luminance values to estimate a driver's visual performance in terms of the speed and accuracy of detecting/identifying them.

<u>Testing Method</u>

White and yellow wet reflective tape samples were mounted onto a piece of black-painted plywood platform fastened to a tripod (Figure 26), and adjusted for height and orientation to be level and either 0° or 1° below the measurement aperture of a handheld luminance meter (Minolta, LS-100), which was mounted onto another tripod 20 ft away (Figure 27). Also attached to the luminance meter was a 40-W incandescent appliance lamp bulb, positioned 4 in. below the luminance meter's aperture (and located 1° below from a distance of 20 ft).

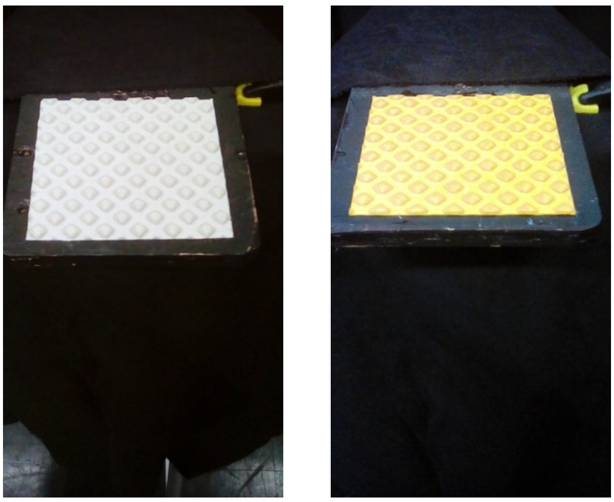


Figure 26. Wet reflective tape samples (left: white, right: yellow)

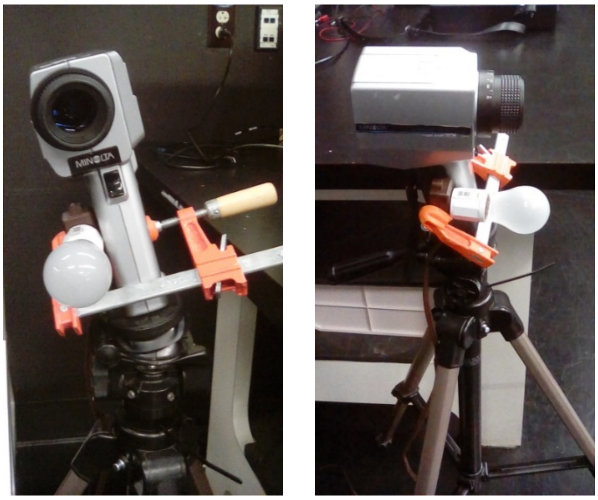


Figure 27. Luminance meter and light source (left: front view, right: side view)

The measurement sample tripod could be moved to different lateral positions to be located directly ahead of the luminance meter (0° horizontal angle), or 5° or 10° to either side of the luminance meter. The height of the tripod could be set to match the height of the luminance meter aperture or 4 inches below (1° below the luminance meter aperture for the measurement distance of 20 ft).

Delineator samples (Figure 28) were attached to a 2-ft-long piece of plywood, which in turn was mounted onto the tripod (Figure 29) and oriented so that the delineator mounting surface was vertical. Because the delineators were designed to be attached to barriers, they were only measured at a vertical angle of 0°, since they would not ordinarily be viewed when at ground level. They were also only measured from horizontal angles of 0°, 5° to the left and 10° to the left since they would be mounted to barriers or guide rails along the center of the roadway.

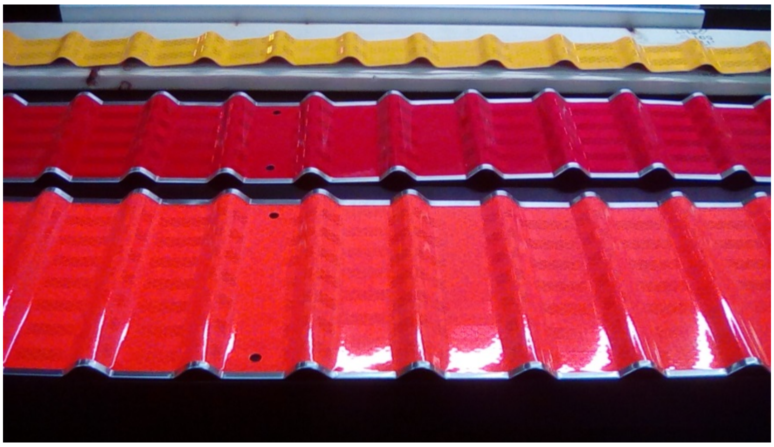


Figure 28. Delineator samples

Figure 29. Yellow delineator sample mounted on tripod

Test Results

Two samples of wet reflective tape were measured: white and yellow. Four types of delineators were measured: white, yellow, orange and red. Table 41 through 46 summarize the measurements and the relative visual performance (RVP) model calculations that were made for each device. Ten combinations of vertical angle (0° and 1° down) and horizontal angle (0°, and 5° and 10° to the left and right) were set up for each pavement tape sample, and three horizontal angles (0°, 5° and 10° to the left; only at the 0° vertical angle) were set up for the delineator samples.

Each table shows the following characteristics:

- Vertical illuminance at the front face of the device (lx)
- Average measured luminance of the 1^{o} luminance meter aperture (cd/m²)
- Actual device luminance, correcting for the aperture size (cd/m²)
- Coefficient of retroreflectivity for the measured illuminance and luminance (cd/lx/m²)
- Low-beam headlight set intensity toward the device for each geometric condition (cd)
- Low-beam headlight illuminance at a distance of 100 m ahead (lx)
- Predicted device luminance under low-beam headlights (cd/m²)
- Relative visual performance (RVP) for the predicted luminance

Relative visual performance (RVP) is a unitless quantity, representing the relative speed and accuracy of visual processing. RVP depends on the light level, the contrast between an object and its background, the size of the object, and the age of the observer (an age of 60 years is assumed for all RVP calculations). RVP values can range from zero at the threshold of identification for an object, to values of one or greater. A value of one corresponds to the level of visibility under a reference visual task similar to reading black laser-printed text under office light levels; higher values are possible, but once an object achieves a high (>0.9) RVP level, further increases in light level, contrast or size will not make substantial improvements in visual performance.

It can be seen from Table 41 through 46 that RVP values for nearly all the devices and geometric conditions are quite high (>>0.9) indicating that they would be highly visible to drivers under all of the geometric conditions included in the present measurements (e.g., horizontal angles between 10° to the left and 10° to the right, and vertical angles between 0° and 1° down). This indicates that the devices do indeed provide high levels of visibility to drivers. In chapter 4, similar photometric measurements of RPMs were summarized. Similarly, high levels of visual performance were found with the RPMs as well.

The results of the luminance measurements, and the subsequent visual performance analyses, suggest that both RPMs and the evaluated alternatives (e.g., wet pavement reflective tape and channel-mounted delineators) provide good visibility under low-beam headlight illumination from a distance of 100 meters. The slightly lower relative visual performance values ($0.7 < x < 0.9$) found for the yellow reflective tape at the leftmost position (horizontal angle of -10 degrees) suggest that under challenging visual conditions (e.g., dirt accumulation, poor headlamp aim or condition), this type of device may become closer to visual threshold sooner than other devices. Nonetheless, under the conditions of the laboratory measurements, new devices of the types measured are likely to provide high visibility levels. Table 41 is an example, showing testing results for white wet reflective traffic tape.

Table 41 - Photometric/Visual Performance Summary:

White Wet Reflective Tape

Tape (white)		*Proj. Area (deg^2):*		0.014247	0.015957
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.7	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.096	0.088	0.087	0.084	0.100
-1 V	0.103	0.095	0.103	0.095	0.099
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	5.29224	4.85122	4.796093	4.63071	5.51275
-1 V	5.069761	4.675994	5.069761	4.675994	4.872878
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	8.820401	6.930315	6.851561	6.6153	9.187917
-1 V	8.449602	6.679991	7.242516	6.679991	8.121463
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
Device Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**1.19**	**1.51**	**12.10**	**6.24**	**2.06**
-1 V	**5.17**	**7.09**	**27.38**	**13.22**	**4.55**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.920**	**0.940**	**0.994**	**0.985**	**0.956**
-1 V	**0.981**	**0.987**	**1.003**	**0.995**	**0.979**

Table 42 - Photometric/Visual Performance Summary:

Yellow Wet Reflective Tape

Tape (yellow)		*Proj. Area (deg ^{2}):*		0.014247	0.015957
Measured Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.6	0.7	0.7	0.7	0.6
-1 V	0.6	0.7	0.7	0.7	0.6
Measured Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.052	0.057	0.047	0.056	0.053
-1 V	0.063	0.06	0.074	0.061	0.061
Actual Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	2.86663	3.142268	2.590993	3.08714	2.921758
-1 V	3.100922	2.953259	3.642353	3.00248	3.00248
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	4.777717	4.488954	3.701418	4.4102	4.869596
-1 V	5.168203	4.218942	5.203361	4.289257	5.004134
Headlight Intensity (cd)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	1346	2186	17660	9434	2240
-1 V	6124	10612	37804	19796	5602
Headlight Illuminance (lx)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	0.1346	0.2186	1.766	0.9434	0.224
-1 V	0.6124	1.0612	3.7804	1.9796	0.5602
Device Luminance (cd/m²)	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.64**	**0.98**	**6.54**	**4.16**	**1.09**
-1 V	**3.17**	**4.48**	**19.67**	**8.49**	**2.80**
RVP Value	Horizontal Angle (degrees)				
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	5 H	10 H
0 V	**0.799**	**0.897**	**0.985**	**0.977**	**0.911**
-1 V	**0.971**	**0.979**	**1.000**	**0.989**	**0.967**

Table 43 - Photometric/Visual Performance Summary:

White Delineator

Delineator (white)	*Proj. Area (deg²):*		0.085488	0.7548
Measured Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.7	0.7	0.7	
Measured Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	8.811	5.327	0.394	
Actual Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	14.49248	8.761939	7.239582	
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	20.70354	12.51706	10.34226	
Headlight Intensity (cd)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	1346	2186	17660	
Headlight Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.1346	0.2186	1.766	
Device Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**2.79**	**2.74**	**18.26**	
RVP Value	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**0.974**	**0.974**	**0.997**	

Table 44 - Photometric/Visual Performance Summary:

Yellow Delineator

Delineator (yellow)	*Proj. Area (deg²):*		0.042744	0.4775
Measured Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.7	0.7	0.7	
Measured Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	2.657	1.858	0.219	
Actual Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	4.370278	3.05607	4.024032	
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	6.243254	4.365814	5.748616	
Headlight Intensity (cd)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	1346	2186	17660	
Headlight Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.1346	0.2186	1.766	
Device Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**0.84**	**0.95**	**10.15**	
RVP Value	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**0.910**	**0.922**	**0.981**	

Table 45 - Photometric/Visual Performance Summary:

Orange Delineator

Delineator (orange)	*Proj. Area (deg²):*		0.085488	0.7548
Measured Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.7	0.7	0.7	
Measured Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	4.165	2.744	0.336	
Actual Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	6.850662	4.513377	6.173857	
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	9.78666	6.447682	8.819795	
Headlight Intensity (cd)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	1346	2186	17660	
Headlight Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.1346	0.2186	1.766	
Device Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**1.32**	**1.41**	**15.58**	
RVP Value	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**0.953**	**0.956**	**0.995**	

Table 46 - Photometric/Visual Performance Summary:

Red Delineator

Delineator (red)	*Proj. Area (deg²):*		0.085488	0.7548
Measured Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.7	0.7	0.7	
Measured Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	3.142	1.834	0.14	
Actual Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	5.168014	3.016594	2.57244	
Coefficient of Retro. (cd/lx/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	7.382877	4.30942	3.674915	
Headlight Intensity (cd)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	1346	2186	17660	
Headlight Illuminance (lx)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	0.1346	0.2186	1.766	
Device Luminance (cd/m²)	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**0.99**	**0.94**	**6.49**	
RVP Value	Horizontal Angle (degrees)			
Vertical Angle (degrees) ↓	-10 H	-5 H	0 H	
0 V	**0.939**	**0.936**	**0.978**	

Visual Performance / Distance Analyses

For wet pavement reflective tape and channel-mounted delineators, their visibility was estimated with a viewing distance of 100 m. Increasing the distance will have two primary impacts on visual performance: the size of the devices will decrease, and the headlight illuminance on the devices will decrease. Both factors will decrease with the square of the distance between the vehicle and the device.

Since the RVP values for all devices were close to 1.0, indicating very good visibility from 100 m, the distances were systematically decreased until the RVP value fell below zero, which is defined as the threshold for recognition visibility. Thus, the distances at which the RVP values reach zero is an estimate of the visibility distance for that device under low beam headlight illumination.

Figure 30 and 31 show analyses for the alternative devices: the wet reflective pavement tape (white and yellow) and channel mounted delineators varying in width for four different colors (white, yellow, orange and red). All these alternative devices were from manufacturer A.

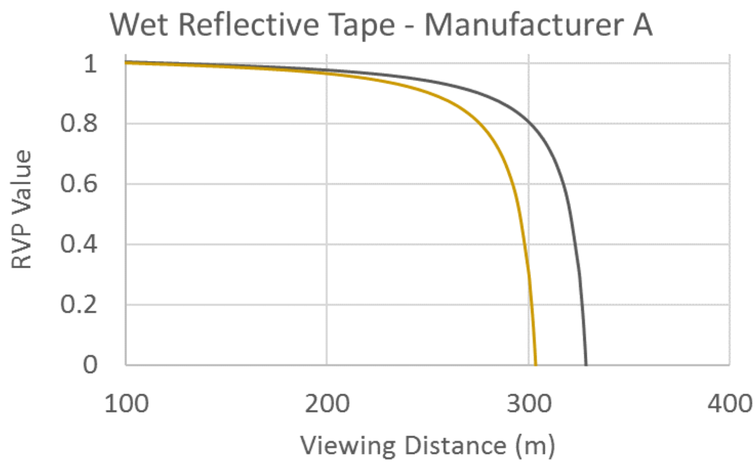


Figure 30. RVP values for the white and yellow wet reflective pavement tape from manufacturer A

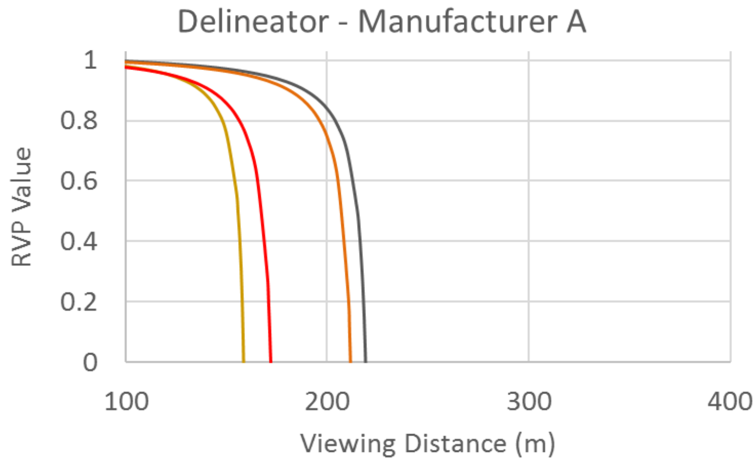


Figure 31. RVP values for the white, yellow, orange and red delineators from manufacturer A

In general, the wet pavement reflective tapes also had visibility distances greater than 300 m. In comparison, the delineators had lower visibility distances from about 150 m to just over 200 m.

However, it should also be noted that for both the delineators and the wet reflective pavement marking tape, these devices tend to be used in a largely continuous application, whereas RPMs are intermittently installed at various spacing intervals. There is evidence that more continuous delineation offers visual acquisition benefits over an array of regularly-spaced points, [64] and this benefit is not quantified by threshold visibility measures. Nonetheless, the curves in Figure 30 and 31 can be useful in assessing how much distance drivers might have when the devices first become visible to estimate the configuration of the roadway.

CHAPTER 6: SURVEY OF BEST PRACTICES OF RPM ALTERNATIVES

RPM Installation and Maintenance Practices

RPMs are widely used as a traffic safety measure to assist drivers by delineating lanes and intersections over a wide range of environmental conditions. In general, there are two main types of RPMs: retroreflective and nonretroreflective. Retroreflective RPMs provide a clear, definitive outline of pavement markings in inclement weather and low-light conditions such as rain, fog, and darkness. Nonretroreflective RPMs are often used, in conjunction with retroreflective RPMs, as an alternative to painted markings to provide daytime visibility while the retroreflective RPMs the nighttime visibility. In addition, there are two subcategories of retroreflective RPMs: nonsnowplowable RPMs and snowplowable RPMs (SRPMs). Nonsnowplowable RPMs, widely used in the southern and western parts of the United States where snowfall is not a concern, have a rounded or square reflector epoxied to the pavement surface. By contrast, SRPMs have a metal housing designed to protect the reflector from snowplow hits. [3] The State of New Jersey and other states with frequent snowfall commonly use SRPMs.

Table 47 - Application of RPM [3]

<table>
<tr><th colspan="2">RPMs Types</th><th>Current practices in United States</th><th>Effects</th></tr>
<tr><td rowspan="2">Retroreflective RPMs</td><td>SRPMs</td><td>Used in states with frequent winter snows such as New Jersey, Illinois, Oregon, Michigan, Maryland, and Massachusetts</td><td rowspan="2">Providing a clear, definitive outline of pavement markings even under adverse visibility conditions</td></tr>
<tr><td>Nonsnowplowable RPMs</td><td>Used in the southern and western parts of the United States where snowfall is not a concern</td></tr>
<tr><td colspan="2">Nonretroreflective RPMs</td><td>Used in conjunction with retroreflective RPMs</td><td>Providing a “wake up call” for the driver who</td></tr>
</table>

		wanders out of the travel lane

RPMs Installation Practices

In 1988, a study by Arizona State University reviewed installation practices for RPMs in several states. The results of this study are summarized in Table 48 and represent the situation of the study in 1988.

Table 48 - State guidelines for installation of RPMs [65]

State	Guideline
Kentucky	Not used on bridge decks or local roads
Delaware	Not used on right edgelines except for delineations
District of Columbia	Installed on: • Wholly unban area • Interstate, divided and two-way median turn lanes
South Carolina	Installed only on interstates and multilane primaries with AADT > 10,000 vpd
Mississippi	Installed on interstates and other multilane divided highways
Iowa	Used only in temporary construction zones
New Hampshire	Not used except in seasonal construction zones
Georgia	Used on Interstate or Interstate type highways under construction except for projects consisting primarily of asphalt resurfacing items
Idaho	Installed on: • Traffic islands with speeds ≤ 30 mph as lane channelization or delineation • Concrete surfaces adjacent to the joints
Utah	Installed on all unlit exit ramps with AADT > 100 vpd
Colorado	Used to delineate lane drops and cross-over operations on some Interstate construction zone projects

Connecticut	Used on non-illuminated expressways
California	Used on two-lane streets, highways, multilane streets and highways
Commonwealth of Virginia	Used recessed markers instead of SRPMs, because of cost & damage of SRPM's due to snow plows.
Montana	Did not use RPMs
Oklahoma	Used for increased visibility and traffic control
West Virginia	Installed on freeway with bituminous concrete pavement surface when AADT > 10,000 vpd
Alaska	Did not use RPMs
Oregon	Used for lane line visibility under wet pavement and poor visibility weather conditions
Nebraska	Limited use due to cost
Maine	Poor experience due to snow removal efforts
Texas	Spacing of RPMs is reduced in Urban Areas or in areas where alignment changes
Vermont	Not used for permanent delineation. Temporary RPMs are used 20 feet Center to Center. All in yellow color and reflect in both directions
Missouri	Installed in two test areas
North Carolina	Only used on permanent installations
Florida	Used on centerlines, lane lines, in case of exit and entrance ramps for edgelines

Notes: AADT = annual average daily traffic, vpd = vehicles per day.

In 2004, NCHRP Report 518 reviewed installation practices for RPMs in several states. [3] In that study, 29 states with known RPM installations were surveyed. Of these 29 states, 14 were using SRPMs, and the rest of the states used nonsnowplowable RPMs. Some of the states (i.e. Kansas, Maine, Maryland, Virginia, West Virginia, and Pennsylvania) installed SRPMs together with recessed markers. Illinois, Indiana, Massachusetts, Michigan, New York, Ohio, and Wisconsin almost exclusively used SRPMs. While in states where snowfall is not a concern, such as Texas and California, nonsnowplowable RPMs were extensively used.

NCHRP Report 518 also classified the usage of RPMs in two categories: non-selective or selective. (3) In Ohio, Texas, and California, RPMs were installed non-selectively on all state-maintained roads. In California, approximately 20 million RPMs, called "Botts Dots", were installed on freeways and highways. In other states, such as Maryland, Massachusetts, Wisconsin, Pennsylvania, Illinois, Indiana and Kansas, RPMs were implemented non-selectively on freeways and installed selectively on other types of roads based on certain characteristics, such as AADT, speed limit, or geometric considerations. (2) Table 49 summarizes statewide installation guidelines for RPMs.

Table 49 - RPM installation guidelines (2,3)

State	Guideline
Illinois	Installed on: • Rural two-lane roads with AADT > 2,500 vpd • Multilane roads with AADT > 10,000 vpd • Horizontal curves where advisory speed more than 10 mph below posted speed limit • Lane reduction transitions, rural left turn lanes, and two-way left turn lanes
Indiana	Installed on: • Rural two-lane roads with AADT > 2,500 vpd • Multilane roads with AADT > 6,000 vpd
Kansas	Installed on roads with AADT > 3,000 vpd and truck AADT > 450 vpd
Maryland	Installed on: • All two-lane roads with speed limit > 45 mph • Horizontal curves where advisory speed more than 10 mph below posted speed limit

	• one-lane bridges, TWLTLs, lane transitions
Massachusetts	Installed on all undivided highways with speed limit > 50 mph
Michigan	Installed on all freeways without illumination
New Jersey	RPMs were to be installed along all centerlines and skip lines, regardless of traffic volume, roadway geometry, and roadway classification
Wisconsin	Installed on all roads with speed limit > 65 mph

Notes: AADT = annual average daily traffic, vpd = vehicles per day.

Proposed Guidelines for Use of SRPMs

Guidelines for the use of SRPMs were developed based on the findings of the literature review and the safety analysis. (2) These guidelines developed two principles:

- SRPMs should be used in situations where they have been demonstrated to show a safety benefit.
- SRPMs should be used in situations where they have been shown to be the only marking material that can provide adequate preview distance during dark, rainy conditions.

Based on previous research, Fontaine and Gillespie recommended the installation of RPMs continuously on all two-lane, two-way roads where the AADT is greater than 15,000 vpd (vehicles per day), all limited access highways with a posted speed limit of 55 mph or higher, and all facilities with a posted speed limit of 60 mph or higher. (2) The RPMs should also be considered for installation if additional delineation is needed. RPMs may be considered for continuous installation on two-lane, two-way roads with AADTs from 5,000 through 15,000 if the sections have few horizontal curves with a degree of curvature greater than 3.5. They may also be considered for continuous installation on multilane roads if the AADT is greater than 10,000 vpd, and the speed limit is 45 mph or greater. It is worth noting that if roadway lighting is present, engineering judgment should be used to determine whether SRPMs are still needed. The Guidelines for Use of SRPMs are summarized in Table 50.

Table 50 - Situations where RPMs should be and may be considered for installation (2)

Guidance Statement	Application
Situations where RPMs should be installed	Two-lane, two-way roads with AADT > 15,000 vpd
	Limited access highways with a posted speed limit ≥ 55 mph
	Facilities with a posted speed limit ≥ 60 mph
Situations where RPMs may be considered to install	Two-lane, two-way roads: • 5,000 vpd ≤ AADT ≤ 15,000 vpd • curvature of horizontal curve ≥ 3.5°
	Multilane roads with AADT ≥ 10,000 vpd and speed limit ≥ 45 mph

Notes: AADT = annual average daily traffic, vpd = vehicles per day.

Issues

Many states studied the cost and effectiveness of RPMs and their use in varying situations. RPMs were widely used by various states for more than 30 years. Although RPMs work well in most cases, it seems reasonable to step back and look at how well they work from two aspects: safety and cost.

Safety

While RPMs are used to improve lane delineation in inclement weather and low light conditions, the RPMs can become loose or damaged from the pavement after longtime exposure to traffic and snowplows, which actually become a danger to drivers.

In April 2006, a fragment of RPM metal casting dislodged and injured a motorist. [2] In February 2014, WCVB reported that a piece of highway pavement marker along I-93 in Wilmington flew into the windshield of car and almost killed the driver. [66] NBC Chicago reported a similar instance that occurred in June 2014 when a Gurnee resident was driving along U.S. Route 41 near Route 137, and a chunk of RPM metal came crashing through the windshield of car. [67]

In 2005, the Missouri DOT conducted a survey on the use of RPMs. [33] It suggested reasons for RPMs failure as "hits from snowplow blades, pavement failures, or improper installation". Because of heavy snowplow operations, which may dislodge even SRPMs, three northern states (Alaska, Montana, and Colorado) do not install RPMs. All-weather paint, tape, low-temperature acrylic paint, and some other pavement marking types were installed in Alaska. [34] The New York State DOT indicated that they use wet night reflective tape as an alternative to RPMs. [27]

Along with motorists, DOTs must consider the safety of their workers. Placing or replacing the markers is a one-at-a-time job, meaning that workers have to get out on the roadway and glue them down one by one. Any time workers are near traffic, they are exposed to dangerous conditions, inebriated drivers, and distracted drivers. Anything that shortens workers' time on the roadway translates to greater safety.

Cost

DOTs also have to consider whether the first-time and lifetime cost of various markers is justified in all situations. The durability of the marker and the material used to glue it to the pavement are factors in this. The Roadway Delineation Practices Handbook notes that this is often not cost-effective, as some well-functioning markers will be replaced even if they are still providing adequate visibility. [2]

NCHRP Report 518 summarizes the maintenance practices for RPMs in some states. (3) For instance, Pennsylvania and Ohio replace RPM lenses on a fixed 2-year and 3-year cycle, respectively. In other states, such as Indiana, the replacement cycle depends on the roadway type and traffic volume. RPM lens replacement cycles are defined as a function of the average daily traffic (ADT) on a road and the number of lanes present, while on higher volume roads, lenses are replaced more frequently. (3) In Colorado and Iowa, all RPMs were removed and plans for future installations have been halted due to high maintenance costs. (2) Indiana conducted an evaluation of centerline rumble stripes (CLRSs) as an alternative to RPMs on rural, non-interstate roadways.

Current Practices of RPM Alternatives

<u>Rumble Strip Current Practices</u>

Rumble strips, as a low-cost safety countermeasure, are used on the pavement surface of a travel lane or shoulder to reduce lane departure crashes. Rumble strip applications fall into four general categories: shoulder rumble strips, centerline rumble strips, mid-lane rumble strips and transverse rumble strips. Shoulder rumble strips and centerline rumble strips are most commonly used by varying States, and this report will focus on these two types.

In 2005, NCHRP Report 641 surveyed the 50 U.S. state transportation agencies and 12 Canadian provincial transportation agencies to identify existing policies/guidelines governing the design and application of shoulder and centerline rumble strips on rural and urban highways. (45) 27 U.S. state transportation agencies and 4 Canadian provincial transportation agencies responded to the survey. Of the 31 agencies, 30 agencies (96.8%) used shoulder rumble strips, and 25 agencies (80.6%) had a written policy concerning the installation/application of shoulder rumble strips. 23 agencies (74.2%) used centerline rumble strips, and 9 agencies (29.0%) had a written policy for the centerline rumble strips. (45)

In 2015, NCHRP Synthesis 490 [68] surveyed all the State Departments of Transportation (DOTs), and Canadian provinces identified in the AASHTO Highway Subcommittee on Traffic Engineering. 41 U.S. states (82%) and 2 Canadian provinces responded to the survey. Table 51 summarizes DOT practices for installing rumble strips based on the type of roadway and rumble strip position on the roadway. Overall, results show that rumble strips are widely used on rural roadways and that installation varies by the type of rumble strips. [68]

Table 51 - Rumble strip installations by roadway type and rumble strip location [68]

Type of roadway	None	Left shoulder (median)	Center line	Right shoulder (outside)
Urban multilane divided highways	59%	37%	5%	41%
Urban multilane undivided highways	73%	7%	12%	27%
Urban Two-lane Roads	76%	5%	15%	22%
Rural multilane divided highways	5%	88%	5%	95%
Rural multilane undivided highways	5%	39%	59%	85%
Rural two-lane roads	5%	39%	71%	85%

Notes: 41 responding agencies

Shoulder Rumble Strip Installation Practices

Shoulder rumble strips have been proven to be a very effective method to warn drivers that they are about to drive off the road. It is believed that at least 46 out of the 50 states within the United States have installed shoulder rumble strips on at least one type of roadway. [45] However, several state transportation agencies do so without a written policy. 40 states have a written policy concerning the installation/application of shoulder rumble strips. States that have their policy information available online include Arizona, Iowa, Indiana, Minnesota, North Carolina, North Dakota, Nevada, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, and British Columbia. Table 52 shows current U.S. states that use shoulder rumble strips on secondary state highways.

Table 52 - Shoulder rumble strips current practices (45,68)

At least 40 states are using shoulder rumble strips on secondary highways:						
Alabama	Alaska	Arizona	California	Colorado	Delaware	Florida
Georgia	Hawaii	Indiana	Iowa	Kentucky	Maine	Maryland
Michigan	Minnesota	Mississippi	Missouri	Montana	Nebraska	Nevada
New Jersey	New Mexico	New York	North Carolina	North Dakota	Ohio	Oklahoma
Oregon	Pennsylvania	Rhode Island	South Carolina	South Dakota	Texas	Utah
Virginia	Washington	Wisconsin				

Shoulder rumble strips are being installed on a wide variety of roadway types including urban freeways, urban freeway on-ramps and off-ramps, urban multilane divided highways (non-freeways), urban multilane undivided highways (non-freeways), urban two-lane roads, rural freeways, rural freeway on-ramps and off-ramps, rural multilane divided highways (non-freeways), rural multilane undivided highways (non-freeways), and rural two-lane roads. (45)

The Federal Highway Administration released guidance to improve the implementation of shoulder rumble strips in July 2008, (69) which is summarized in Table 53. Shoulder rumble strips are recommended for installation on all new rural freeways and on all new rural two-lane highways with travel speeds of 50 mph or greater. In addition, State 3R (Resurfacing, Restoration, and Rehabilitation) and 4R (Resurfacing, Restoration, Rehabilitation, and Reconstruction) policies should consider installing continuous shoulder rumble strips on all rural freeways and on all rural two-lane highways with travel speeds of 50 mph or above or with a history of roadway departure crashes, where the remaining shoulder width beyond the rumble strip will be 4 feet or greater, paved or unpaved. (69)

Table 53 - FHWA guidance to shoulder rumble strips implement (69)

Guidance Statement	Application
Rumble Strips should be provided on:	• All new rural freeways • All new rural two-lane highways with travel speed ≥ 50 mph
State 3R and 4R policies should consider installing continuous shoulder rumble strips on:	• All rural freeways • All rural two-lane highways with travel speed ≥ 50 mph • All rural two-lane highways with a history of roadway departure crashes, where the remaining shoulder width beyond the rumble strip ≥ 4 feet, paved or unpaved.

New York State began experimental use of shoulder rumble strips in 1978 and made them a common feature on access-controlled highways starting in 1995. Placement was limited to freeways and a very small percentage of the highway system, where there is a high risk of severe run-off-road crashes. Shoulder rumble strips are mainly installed to rural, non-freeway highways with speed limits of 50 mph or greater and shoulders 6 feet or wider. Shoulder rumble strips would also be strongly considered at any locations with a high number of run-off-road accidents. The installation of shoulder rumble strips takes approximately 2.5 percent or 2,800 miles of New York State's total 114,481 miles of highways. (70)

In Washington State, more than 260 miles of shoulder rumble strips have been implemented on the two-lane rural highway system. However, most of these miles are installed in conjunction with centerline rumble strips. The combination of centerline rumble strips installed with shoulder rumble strips have resulted in a 64% reduction in lane departure crashes. (71) Table 54 summarizes the installation criteria of shoulder rumble strips in Washington State.

Table 54 - Shoulder rumble strip installation criteria in Washington State (72)

Divided highways	• Use on rural roads only • Use the Shoulder Rumble Strip Type 1 pattern
Undivided highways	• Use on rural roads only • Posted speed ≥ 45 mph • At least 4 feet of usable shoulder between SRS and the outside edge of shoulder • Not on downhill grades exceeding 4% for more than 500 feet in length where bicyclists are frequently present

In Minnesota, Missouri, and Pennsylvania, significant amounts of shoulder rumble strips have been placed on rural two-lane roads, and where accident records were sufficient to distinguish trends. (45)

Centerline Rumble Strip Installation Practices

Fewer states use centerline rumble strips than shoulder rumble strips, and only a few states that use centerline rumble strips have a written (i.e., formal) policy. The majority of centerline rumble strips have been installed on rural two-lane undivided roads. However, centerline rumble strips have been installed on rural multilane undivided highways and to a lesser degree on urban two-lane undivided roads and urban multilane undivided highways. (45)

NCHRP Report 641 suggests that most states install centerline rumble strips within the boundaries of centerline markings or that a portion of the rumble strips may extend slightly into the travel lane. Only two states install centerline rumble strips on either side of the centerline pavement markings. All states in North America that install centerline rumble strips use milled rumble strips. [45] Table 55 shows the current U.S. states using centerline rumble strips on secondary state highways.

Table 55 - Centerline rumble strips current practices [73]

State or Province	Placement	Minimum requirements for installation		Dimensions	
		AADT	Speed	Length	Depth
Alabama	Into lane	N	N	-	-
Alaska	-	-	-	12”	0.5”
Arkansas	Within PM	N	N	-	-
Arizona	Within PM into lane	N	N	-	-
California	-	-	-	-	-
Colorado	Within PM	N	N	12”	0.375”
Delaware	Into lane	N	N	16”	0.5”
Hawaii	-	-	-	18” – 24”	-
Idaho	Within PM into lane	N	N	-	-
Iowa	Into lane	N	N	-	-
Kansas	-	-	-	12”	0.5”
Kentucky	Into lane	N	N	24”	0.5” - 0.625”
Maine	Into lane	N	N	-	-
Maryland	-	-	-	18” – 24”	0.5”
Massachusetts	-	-	-	16”	0.5”
Michigan	-	-	-	16”	0.375”
Minnesota	Beside PM	N	50 mph	12” – 16”	0.5”
Missouri	Within PM	N	N	12”	0.5”
Nebraska	-	-	-	16”	0.5” - 0.625”

Nevada	Into lane	N	N	-	-
New York	Within PM into lane	2000 vpd	45 mph	12”	0.375”
North Carolina	Into lane beside PM	N	N	-	-
Oregon	Within PM into lane	N	N	16”	0.5”
Pennsylvania	Within PM into lane	2000 vpd	N	16”	0.5” ±0.0625”
Texas	Into Lane	N	N	16”	0.5”
Utah	Into Lane	N	N	12”	0.625”-0.75”
Virginia	Within PM	N	N	16”	0.5”
Washington	Within PM	N	N	16”	0.375”
Wisconsin	-	-	-	-	-
Wyoming	Into Lane	N	N	12”	0.5”

Notes: PM = Pavement Marking

The letter "Consideration and Implementation of Proven Safety Countermeasures" of Federal Highway Administration (FHWA) in 2008 states that centerline rumble strips should be considered for installing on all new rural freeways and on all rural two-lane highways with travel speeds of 50 mph or greater. In addition, State 3R and 4R policies should consider “installing centerline rumble strips on rural two-lane road projects where the lane plus shoulder width beyond the rumble strip will be at least 13 feet wide, particularly roadways with higher traffic volumes, poor geometrics, or a history of head-on and opposite direction sideswipe crashes”. [69] The guidance to centerline rumble strips implementation is summarized in Table 56.

Table 56 - FHWA guidance to centerline rumble strips implementation [69]

Guidance Statement	Application
Rumble Strips should be provided on:	• All new rural freeways • All new rural two-lane highways with travel speed ≥ 50 mph
State 3R and 4R policies should consider installing centerline rumble strips on:	• rural 2-lane road projects where the lane plus shoulder width beyond the rumble strip ≥ 13 feet • roadways with higher traffic volumes, poor geometrics, or a history of head-on and opposite-direction sideswipe crashes

The New York State Department of Transportation began installing centerline rumble strips across the state in 2012. As a low-cost (30 cents per foot and lasting as most as 10 years) measure, centerline rumble strips make a 64 percent reduction in head-on and opposite-direction sideswipe crashes that result in fatalities or injuries in urban areas and a 44 percent reduction in similar fatal and injury crashes in rural areas. [45] They are continuously installed except for placement before intersections, major driveways, crosswalks, left turn lanes, and concrete bridge decks. The implementation criteria of centerline rumble strips in New York State is summarized in Table 57.

Table 57 - Centerline rumble strip implementation criteria in New York State [74]

Guidance Statement	Application
Situations where centerline rumble strips should be implemented:	• Speed limit ≥ 45 mph • AADT ≥ 2,000 vpd • Combined width of lane and shoulder ≥ 13 feet in each direction • Length to be placed ≥ 1,500 feet within a project • Location must not have raised medians, two-way left-turn lanes or median barriers

Notes: AADT = annual average daily traffic, vpd = vehicles per day.

The Washington State Department of Transportation found that the installation of centerline rumble strips resulted in a 37 percent reduction in all crossover collisions and a 57 percent reduction in crossover collisions with serious and fatal injuries. In 2009, Washington State installed an additional 650 miles of centerline rumble strips, bringing their total mileage up to 2,000 centerline miles (38 percent) of their two-lane rural state highways. Olson recommends that centerline rumble strips continue to be implemented to reduce cross-centerline collisions. He also recommends that investment priority is given to locations with AADT < 8,000, combined lane and shoulder width of 12–17 feet, and posted speed of 45–55 mph. [75]

Rumble Strip Issues

Noise Issues

Noise is one of the most critical issues identified by the state DOTs when it comes to rumble strips. NCHRP Synthesis 490 survey found that 24 agencies (60 percent) ranked noise issues as the highest or second highest importance (5 or 4). 27 agencies (66 percent) developed a policy to address noise issues. [(68)]

To address the noise issues, California DOT and Minnesota DOT designed quieter forms of rumble strips, providing for sufficient interior sound to drivers while reducing noise outside the vehicle at the same time. The Ohio DOT adjusted the distance from the edge of where the rumble strips would be installed in residential areas. The Montana DOT modified the dimensions of shoulder rumble strips to reduce noise. Some Canadian provinces simply banned their use in residential areas. [(68)]

Bicycle Issues

NCHRP Synthesis 490 survey found that bicycle issues are second only to noise among issues identified by the state DOTs. 21 agencies (50 percent) ranked bicycle issues as the highest or second highest importance (5 or 4). 34 agencies (83 percent) had developed a policy to address noise issues. [(68)]

To address bicycle concerns, the South Carolina DOT adjusted design standards of rumble strips. The Maryland State Highway Administration required all the design processes of rumble strips to consider bicycle concerns. The Arkansas DOT provided sufficient paved shoulder space beyond the rumble strip to give bicyclists additional space near the edge of the lane. The Ohio DOT simply banned the use of shoulder rumble strips on roadways designated as bicycle routes or having substantial volumes of bicycle traffic unless the shoulder was wide enough to provide a minimum clear path of 4 feet from the rumble strip to the outside edge of the road. Kansas DOT provided a minimum 3 feet of paved area outside the shoulder rumble strip for bicyclists on highway routes. (68)

Pavement Deterioration

Pavement deterioration is of third importance in the NCHRP Synthesis 490 survey. 17 DOTs ranked the issue as important (5 or 4), while 18 rated it as not important (1 or 2). (68)

Milled-in rumble strips may result in pavement deterioration when placed on pavements with inadequate structure. For this reason, they should not be placed on pavements with inadequate structure, nor should they be placed too close to the pavement edge. (72)

Preformed Tape

Preformed tapes are premade strips or patterns of durable reflective material that are easily glued to the pavement surface. These products are commonly used in urban and rural situations for crosswalks, stop bars, symbols, and signs for traffic control such as turn lanes, HOV lanes, bike lanes recommended by the Manual on Uniform Traffic Control Devices. (76) Tapes generally consist of pigments, resins, and reflective materials (glass beads or reflective elements) and come ready to use with or without adhesives. Additional adhesive (primer) can be applied to the pavement to enhance the bond. (77) Tapes fall into one of two categories: permanent and removable tapes.

Permanent Tapes

Permanent tapes are generally laid in the surface of pavement and physically become part of the asphalt. These tapes may require the application of a primer/sealer that resists movement under traffic. Permanent tapes are generally used for crosswalks, longitudinal edgelines, skip lines, stop lines, legends, and symbols. (77)

Removable Tapes

The removable tape is laid over the surface of pavement. These kinds of tapes can be removed (pulled from the pavement surface) manually without using heat, solvents, or special equipment. Generally, removable tapes should be removed within 6 months of installation, leaving the road surface undamaged. (77)

Attributes

Preformed tapes are relatively fast and easy to install. For permanent tape, it is as simple as rolling it into the pavement using compaction equipment when the pavement is still warm. (76) For removable tape, simply clean the surface, roll the tape, and glue it to the pavement surface. Marked roadways can be immediately opened to traffic or limiting road closures.

Preformed tapes are relatively expensive compared to other pavement marking materials. Prices are between $1.50 and $2.65 per linear foot. However, the tape has a much longer service life than a non-durable marking material. They can last between 4 to 8 years if applied properly. Even though the tapes are very durable, they may not provide adequate retroreflectivity throughout their entire life despite the fact that initial levels of retroreflectivity can be as high as 350 mcd and 250 mcd for white and yellow, respectively. (78) The useful life of tapes may be extended in urban areas if roadway lighting is present. (18) The attributes of preformed tapes described above are summarized in Table 58.

Table 58 - Attributes of preformed tapes [78]

Estimated Cost ($ per linear foot)	Estimated Life (Months)	Initial Retroreflectivity (mcd)
$1.50 - $2.65	48 - 96	350 white – 250 yellow
Advantages	• High retroreflectivity • Longer life on low-volume and high-volume roads • Useful in high traffic areas • No beads needed • Reduces worker exposure to road hazards	
Disadvantages	• Subject to damage from snowplows • High initial expense • Best when used on newly surfaced roads – probably not worth the expense for older road in poor condition	

State Practices

In New York State, preformed, wet-reflective tapes are widely used in areas with severe curvilinear alignments, areas prone to flooding, light-deficient, and high-accident locations. Wet-reflective tapes are used as an alternative to SRPMs to supplement long-line pavement markings due to the better reflectivity during nighttime wet weather road conditions. Wet-reflective tapes are more cost-effective than SRPMs, which cost as much as twice the price of wet-reflective tapes per marker placement. [79]

The Oregon Department of Transportation uses three types of tape: patterned, non-patterned, and wet weather tapes. These are used because of simply excellent performance (line presence and retroreflectivity), long lifespan, wet weather retroreflectivity, and protection from infrequent snow plowing. Although these materials are more expensive to install, they have a much longer service life than a non-durable marking material. [80]

The Minnesota Department of Transportation considers using tape and other durable pavement markings due to large volumes of traffic and snowplows during winter months, especially in urban areas. The conventional paints provide up to a three-year life on low-volume roads (AADT $\leq$ 10,000 vpd) and less than a one-year life on high-volume roads (AADT $>$ 10,000 vpd). In areas with high traffic volumes or with frequent turning maneuvers, tapes and other durable materials are considered. (78)

In Virginia State, waffle tape, paint, and thermoplastics make up 90 percent of pavement markings. VDOT reviewed their pavement marking activities and got the conclusion that conventional paints are the most efficient marking material, even though the service life of tape (6 years) is the longest among the entire experimental marking materials. (81)

Selection Criteria

Selecting the most cost-effective pavement marking material in a given situation is difficult due to the variety of factors involved. It depends on three main factors: 1) retroreflectivity, 2) durability and 3) cost. There are several subordinate factors for these three, such as volume of traffic, type of road surface, quality control at the time of installation, orientation with respect to traffic, winter sanding and snow removal practices, schedule of pavement maintenance activities, and inconvenience experienced by the traveling public during installation. (31)

In general, conventional paints are used in areas with low traffic volumes and infrequent winter maintenance activities. Conversely, preformed tapes and other products of higher durability are used in areas that encounter more traffic and instances of sanding and plowing. (76)

Issues

Since the tape is preformed, the only parameter that should be ensured is that the material is correctly installed. The performance of preformed tapes can vary significantly based on the installation conditions. There have been cases where tape failures start soon after improper application. Table 59 summarizes common issues that should be avoided for preformed tapes.

Table 59 - Attributes of preformed tapes (77)

Preformed tape application issues			
Problem	**Cause**	**Effect**	**Remedy**
Material rolls up or shifts	• Not bonded prior to traffic • Tape crossing traffic • No primer adhesive	• Loss of effectiveness	• Replace material with proper tamping, adhesive, and primer
Poor material adherence	• Moisture in pavement • Dirty surface • No primer • Expired shelf life	• Errant delineation • Loss of material • No delineation	• Replace material applying properly

Delineators

Delineators are light-retroreflecting devices continuously used on the roadway surface or at the side of the roadway to indicate its alignment during nighttime wet weather roadway conditions. Delineators can enhance driver safety by calling attention to a changed or changing condition such as abrupt roadway narrowing or curvature. Delineators are particularly beneficial at locations where the alignment might be confusing or unexpected. (82) In extreme weather, delineators often are the only means of guidance available to the driver. (18) Delineators may be used on low-volume roads based on engineering judgment, such as for curves, T-intersections, and abrupt changes in the roadway width. In addition, they may also be used to mark the location of driveways or other minor roads entering a low-volume road. (82)

When used, delineators shall be mounted on suitable supports so that the reflecting unit is about 4 feet above the near roadway edge. The standard color for delineators used along both sides of two-way streets and highways and the right side of one-way roadways shall be white. Delineators used along the left side of one-way roadways shall be yellow. (82)

Delineator applications fall into two general categories: post-mounted delineator and barrier delineator.

Post-Mounted Delineators

Post-mounted delineators are designed to outline the edges of the roadway and to accent critical locations. They usually consist of a retroreflective element, the support or mounting post, and possibly a backplate. As with RPMs, the application of post-mounted delineators is effective for all weather conditions. Driver performance improves significantly with the use of post-mounted delineators on horizontal curves. Accident rates are also significantly lower where post-mounted delineators are used. (18)

Post-mounted delineators rank highly in both visibility and durability among reflective materials. They provide significant nighttime brightness and adequate long-range delineation, especially in adverse weather and low visibility conditions. In general, post-mounted delineators have long service lives when not damaged by encroaching vehicles. A post-mounted delineator can be expected to be in use for as long as 10 years if knockdown or vandalism do not occur. (18)

Post-mounted delineators can be cost-effective due to their long service lives. Maintenance for post-mounted delineators is as simple as cleaning and replacement, which requires neither a large crew nor complex equipment. Post-mounted delineators are not effective in areas with moderate to high ambient light levels and at locations with reliable, fixed roadway illumination. (18)

Barrier Delineators

Barrier delineators are retroreflective units that mount on top or on the side of guardrails, concrete barriers, and bridge parapets. They are white or amber in order to conform to the pavement marking they supplement. The reflective units are made of high-intensity retroreflective sheeting or cube corner retroreflectors. Barrier delineators should not be substituted for post-mounted delineators. (18)

Barrier delineators are individually a one-piece construction for great durability. They are easy to reuse and require few labors to assemble. They can withstand the impact of snow and ice through harsh winters in very cold climates. They can provide effective guidance at night, in low light and adverse weather conditions.

State Practices

By the late 1970s, California State Department of Transportation implemented about 600,000 post-mounted delineators and approximately half needed to be repaired annually. Many delineators are hit several times a year. As a result of this, in 1978, California budgeted almost $1.6 million for post-mounted delineator system maintenance. The California DOT hereafter conducted a study about impact-resistant delineators. It is believed that flexible units equipped with retroreflective sheeting will help prevent damage to the retroreflective unit upon impact. (18)

The Wyoming State Department of Transportation installed flexible delineator posts in certain areas where delineators got repeatedly damaged by vehicles. It can withstand being hit or run over numerous times without breaking. (83)

In Virginia, three types of delineators were used on rural roadways. Delineators were selected according to MUTCD and local practices. All of the three delineators were installed based on the same criteria used to reduce the probability of confusion caused by the differences of delineators. (84)

Issues

The Handbook pointed out how the roadway film and dirt had an important effect on the performance of delineators. It could reduce night visibility from about 1,000 feet to 100 feet under low-beam headlight to post-mounted delineators. Side-mounted barrier delineators have a tendency to collect more dirt and road splash from passing vehicles since they are closer to the road surface. While washing the retroreflectors could improve this condition, rain would also clean them to some extent. (18)

CHAPTER 7: SUPPORTING TOOL FOR CALCULATING TOTAL COST PER CRASH REDUCTION OF IMPLEMENTING RAISED PAVEMENT MARKERS AND THEIR ALTERNATIVES

Objective

Previous chapters show that different safety devices (e.g. RPMs, Rumble Strips and Traffic Tapes) have different costs. In this chapter, we develop a novel, computer-aided decision support tool that can be used to assess the life-cycle cost (LCC) of RPMs versus alternatives given specified operational characteristics. Considering together with the safety benefit of each safety device, we can compare the total cost for per unit crash reduction among different safety devices. The cost tool can support decisions with respect to the optimal use of safety investment.

Graphical User Interface (GUI)

The GUI of our calculator consists of three parts. The left part is for parameter input and the middle part is for result visualization. The results will be reserved in the right part.

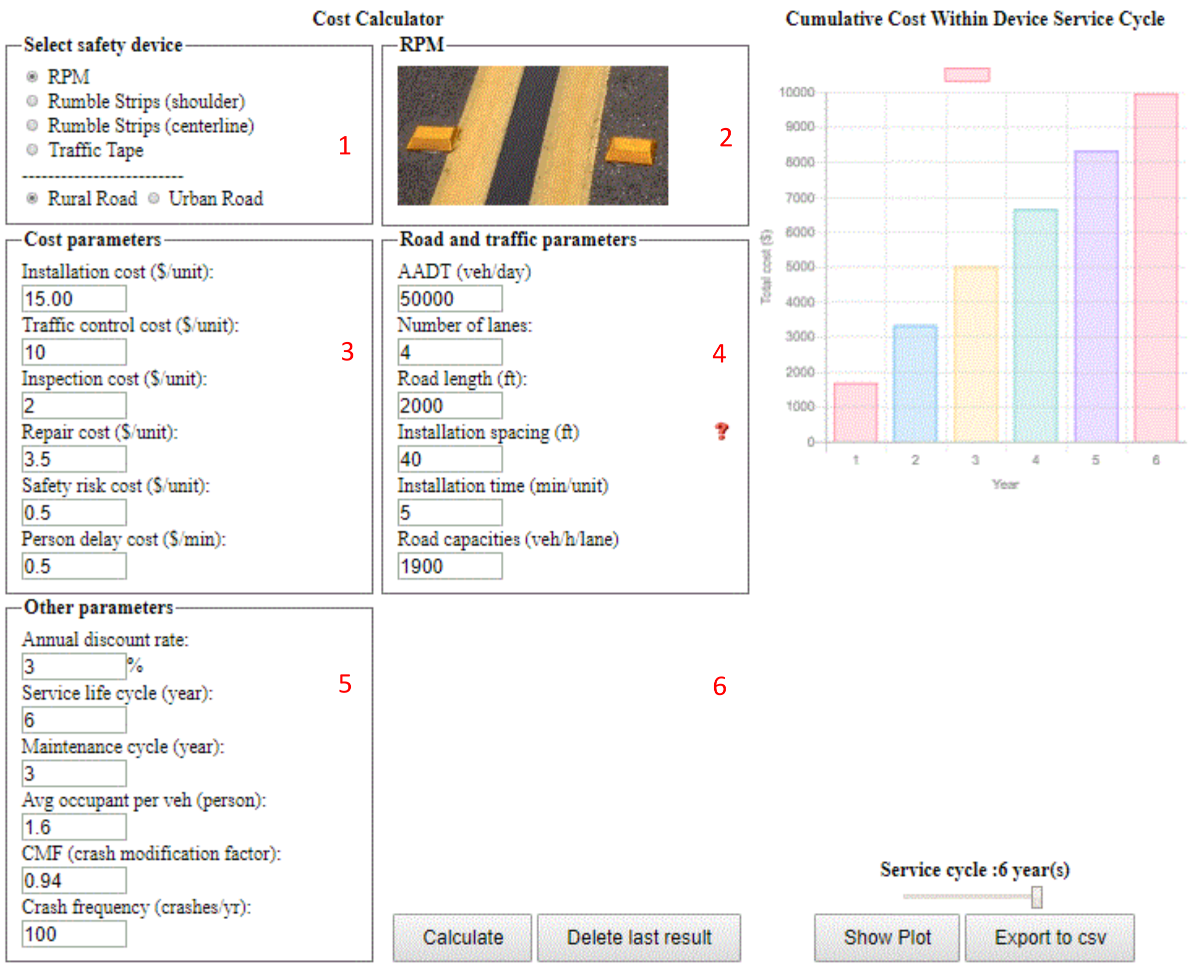


Figure 32. Overall view of parameter input and result visualization

Result Table

Safety device	Road type	Installation cost	Traffic control cost	Inspection cost	Repair cost	Safety risk cost	Person delay cost	AADT	Number of lanes	Road length	Installation spacing	Installation time	Road capacities	Annual discount rate	Service life cycle

Result Table

Installation time	Road capacities	Annual discount rate	Service life cycle	Maintenance cycle	Avg occupant	CMF	Crash frequency	Direct cost	Indirect cost	Maintenance cost	Annual total cost	Total Cost per mile:	Crash reduction:	Annual total Cost per CR:

Figure 33. Overall view of result table

Figure 32 shows the interface of the parameter input which is composed of six following fieldsets (listed as 1, 2, 3, 4, 5, and 6):

- In fieldset 1, users can select one of the four common safety devices, such as RPM, Shoulder Rumble Strips, Centerline Rumble Strips, Traffic Tape or other products to be installed on different type of area;
- Fieldset 2 shows the image of the selected safety device;
- In fieldset 3, six calculation boxes are listed for users to give desired values pertaining to Installation cost, Traffic control cost, Inspection cost, Repair cost, Safety risk cost and Person delay cost. Installation cost refers to the actual unit cost of installing a safety device ($/unit or $/ft) including material, equipment, and labor. Traffic control cost includes the cost of providing work zone signs, attenuation vehicles, and special law enforcement for per unit safety device. Inspection cost is the amount spent to perform inspection for per unit safety device including labor, inspection vehicles, etc. Repair cost refers to the cost of repairing per unit safety device including materials, equipment, and labor. Safety risk cost refers to the cost of safety issues due to the malfunction of safety devices. Person delay cost refers to the loss of income per person due to construction delay;
- Fieldset 4 asks the user to provide values to parameters related to road geometry and device installation. These include traffic volume (AADT), the number of lanes (in two directions), road length, installation spacing if the safety device installed discretely, average installation time per unit device and road capacity, which refers to the maximum service volume of vehicles per lane per hour. To be specific, RPM is discretely installed while Rumble Strips and Traffic Tape are continuously installed;
- In fieldset 5, some other parameters including annual discount rate, Service life cycle of the selected device, Maintenance cycle, average occupant per vehicle, CMF of the selected device corresponding to the road and traffic parameters, and Crash frequency of selected road are requested;

- The last fieldset will show the annual total cost and the annual total cost for per unit crash reduction in the window if the user clicks the "Calculate" button, and the whole calculator is reset if "Reset" is clicked.

The top area of result visualization in Figure 32 would show the graph of the cumulative total cost within a device service cycle if the "Show Plot" button is clicked. The x-axis of the graph is each year within device service cycle, and the y-axis is the cumulative total cost. Under the graph, there is a slider for the user to change the value of device service cycle by dragging, and hence compare the corresponding cost with respect to different device service cycles. The "Show Plot" button activates the plot function and draws the graph.

The input parameter and calculated results will be reserved in "Result Table" in Figure 33 if the "Calculate" button is clicked. This table will help users estimate and compare the cost and safety effectiveness of different devices. Users can remove the latest result by clicking "Delete last result".

Algorithm of Calculating the Total Cost of Per Unit Crash Reduction

Annual Total Cost

The annual total cost is the summation of annual direct cost, indirect cost, and maintenance cost. The relationship and components of each type of the cost are shown in Figure 34.

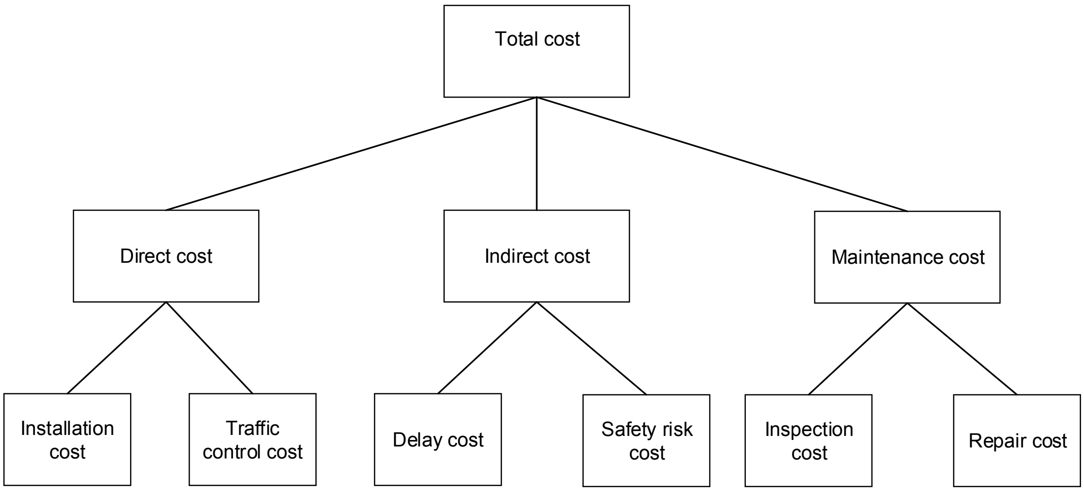


Figure 34. Components of total cost

The following will introduce each type of the cost and the algorithms to calculate the total cost.

a. Direct cost refers to the actual cost of installation per unit safety device including material, equipment, labor, providing work zone signs, attenuation vehicles, and special law enforcement per safety device. **Direct cost consists of installation cost and traffic control cost.**

The formula for the direct cost per unit safety device is:

$$A_d = \frac{COST_d * i(1+i)^n}{(1+i)^n - 1}$$

Where

A_d = Annual direct cost ($) per unit safety device

$COST_d$ = Direct cost ($) per unit safety device

i = Annual discount rate

n = Number of years of device service cycle

b. Indirect cost includes the cost of traffic delay due to construction, accident or other safety issues due to a defective safety device. **Indirect cost includes delay cost and safety risk cost**.

The formula for indirect cost per unit safety device is:

$$A_i = \frac{COST_i * i(1+i)^n}{(1+i)^n - 1}$$

Where

A_i = Annual indirect cost ($) per unit safety device

$COST_i$ = Indirect cost ($) per unit safety device

i = Annual discount rate

n = Number of years of maintenance cycle

c. Maintenance cost refers to the cost of inspection and repair per unit safety device according to the maintenance cycle and includes the cost of materials, equipment, and labor. **Maintenance cost consists of inspection cost and repair cost**.

The formula for maintenance cost per unit safety device is:

$$A_m = \frac{COST_m * i(1+i)^n}{(1+i)^n - 1}$$

Where

A_m = Annual maintenance cost ($) per unit safety device

$COST_m$ = Maintenance cost ($) per unit safety device

i = Annual discount rate

n = Number of years of maintenance cycle

Therefore, the annual total cost per unit safety device is:

$$A = A_d + A_i + A_m$$

Given the road length and installation spacing, it is easy to calculate the total cost of the selected safety device.

Annual Crash Reduction

The expected annual total number of crash reduction on the selected road is the product of CMF and Crash frequency. the Highway Safety Manual (HSM) presents a variety of CMFs for safety devices on roadway segments and at intersections.

The formula for annual crash reduction of the selected safety device is:

$$CR = (1 - CMF) * N$$

Where

CR = Annual crash reduction of the selected road
CMF = The Crash Modification Factor (CMF) of the selected device corresponding to road and traffic parameters
N = Crash frequency of the selected road

Total Cost of Per Unit Crash Reduction

Divide the annual total cost by annual crash reduction, we will get the total cost of per unit crash reduction of selected safety device on the selected road.

Case Study

In our calculator, we already developed default values for users to easily implement the tool regardless of which safety device is selected in fieldset 1.

- Default values for cost parameters: The cost parameters in fieldset 3 are developed based on NJDOT 2016 bid data and various state practices. The installation cost for RPM, shoulder rumble strip, centerline rumble strip, and traffic tape are around $15.00/unit, $0.20/ft, $0.20/ft, $2.75/ft, respectively, based on Table 37 to Table 40. The Traffic Control Cost for each installed RPM is around $10/unit ($1,320/mile) according to NCHRP Report 518, which is equivalent to $0.25/ft for continuous installation. In New Jersey, RPMs are visually inspected and they are then replaced as needed. The inspection cost is assumed to be about $2.00/unit ($264/mile or $0.05/ft) for RPM and $0.05/ft for other three devices. Safety risk cost is estimated at $0.5 per unit for RPM and $0.01 per ft for rumble strips and traffic tapes. Person delay cost is calculated on a $30 hourly salary assumption.

Table 60 - Default values for cost parameters

Parameter \ Device	RPM	Shoulder rumble strip	Centerline rumble strip	Traffic tape
Installation cost ($)	15.0/unit	0.20/ft	0.20/ft	2.75/ft
Traffic control cost ($)	10.0/unit	0.25/ft	0.25/ft	0.25/ft
Inspection cost ($)	2.0/unit	0.05/ft	0.05/ft	0.05/ft
Repair cost ($)	3.5/unit	0.17/ft	0.17/ft	0.46/ft
Safety risk cost ($)	0.5/unit	0.01/ft	0.01/ft	0.01/ft
Person delay cost ($/min)	0.5	0.5	0.5	0.5

- Default values for road and traffic parameters: according to MUTCD, RPMs are recommended to be installed at a 40 ft or 80 ft spacing. In our example, RPMs are discretely installed for every 40 ft, while rumble strips and traffic tape are installed continuously. Furthermore, we assume the installation time for RPMs, rumble strips and traffic tape is 5min/unit, 0.1 min/ft, 0.02 min/ft, respectively, based on authors' knowledge and experience. The default value for road capacity developed in highway capacity manual (2010) is 1,900 passenger cars per lane per hour.

Table 61 - Default values for road and traffic parameters

Parameter \ Device	RPM	Shoulder rumble strip	Centerline rumble strip	Traffic tape
AADT (veh/day)	50,000	50,000	50,000	50,000
Number of lanes	4	4	4	4
Road length (ft)	2,000	2,000	2,000	2,000
Installation spacing (ft)	40	NA	NA	NA
Installation time (min)	5.00/unit	0.10/ft	0.10/ft	0.02/ft
Road Capacity (veh/h/lane)	1,900	1,900	1,900	1,900

- Default values for other parameters: it is assumed that the annual discount rate is 3 percent. The service life and maintenance cycle for safety devices are generated based on state practices discussed in chapter 5. In general, RPM has an average life of 6 years with fixed 2- to 3-year maintenance cycles. The 2001 National Household Travel Survey by U.S. Department of Transportation shows that the weighted occupancy rate of personal vehicle trips in the nation is 1.6 persons per vehicle mile. In 2010, the American Association of State Highway and Transportation Officials (AASHTO) published the Highway Safety Manual (HSM), which presents a variety of CMFs for safety treatments on roadway segments and at intersections. The CMFs for installing RPMs and other devices are summarized in Table 62.

Table 62 - CMFs of RPM, traffic tape, and rumble strip (3)

Road type			CMF			
			RPM (nighttime; all types; all severities)	Traffic tape	Rumble Strip	
					Shoulder rumble strip	Centerline rumble strip
Rural	Two-lane road	AADT < 5,000	1.16	0.76	-	-
		5,000 ≤ AADT ≤ 15,000	0.99	0.76	-	0.85
		AADT > 15,000	0.76	0.76	-	-
	Multilane road	AADT < 20,000	1.13	0.76	0.81	-
		20,000 ≤ AADT ≤ 60,000	0.94	0.76	0.81	-
		AADT > 60,000	0.67	0.76	-	-
Urban	Two-lane road	AADT < 5,000	1.16	0.76	-	-
		5,000 ≤ AADT ≤ 15,000	0.99	0.76	-	-
		AADT > 15,000	0.76	0.76	-	-
	Multilane road	AADT < 20,000	1.13	0.76	-	-
		20,000 ≤ AADT ≤ 60,000	0.94	0.76	-	-
		AADT > 60,000	0.67	0.76	-	-

Sample results are presented next.

Example 1: Cost of RPMs

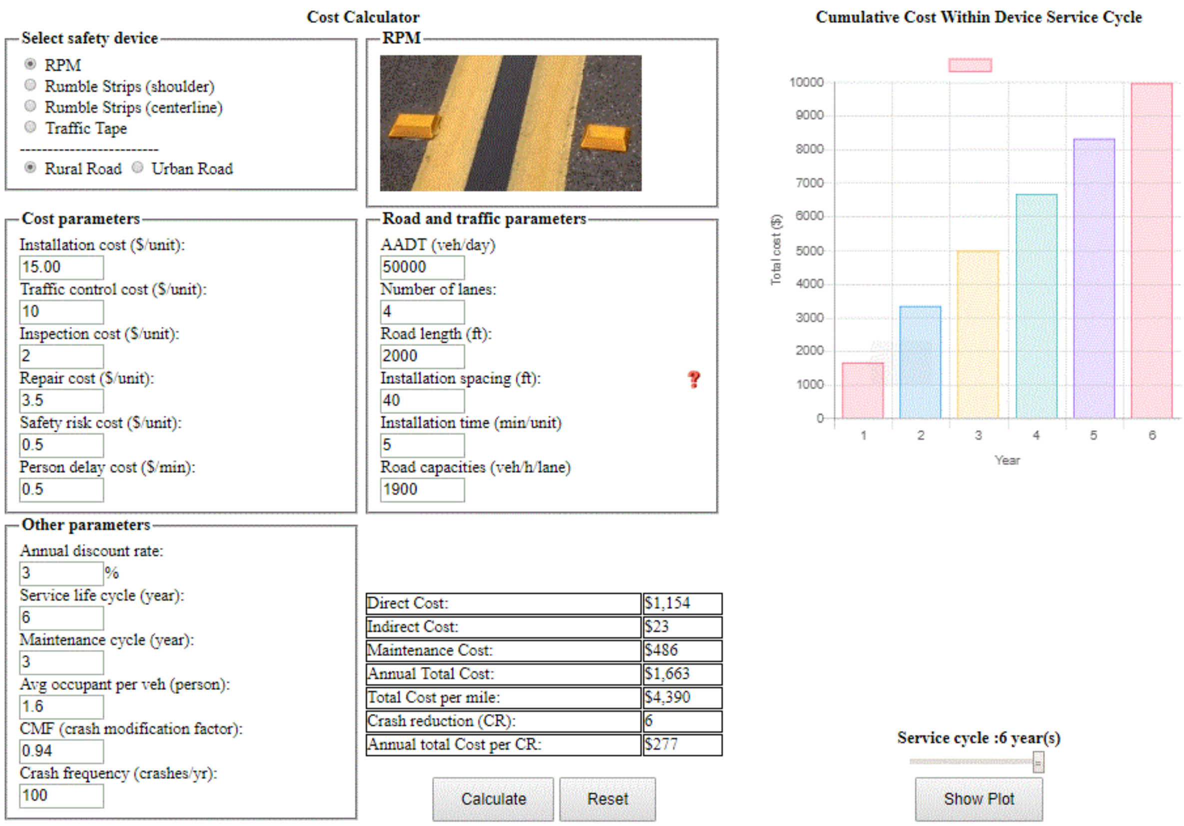


Figure 35. RPMs life cycle cost

Let us look at a 2,000 ft four-lane rural road segment with an average 50,000 daily traffic installed with RPMs for every 40 ft. It is assumed that crash frequency for this segment is 100 crashes per year and the average installation time per unit RPM is 5 minutes. The road capacity is around 1,900 passenger cars per lane per hour. From Table 62, the CMF for installing RPMs on a four-lane rural road with 50,000 daily traffic is 0.94. The annual total cost of this 2,000 ft road segment within a 6-year service cycle is $1,663 ($4,390 per mile) and it will prevent 6 crashes per year. The annual total cost per unit crash reduction is $277.

Example 2: Shoulder Rumble Strips

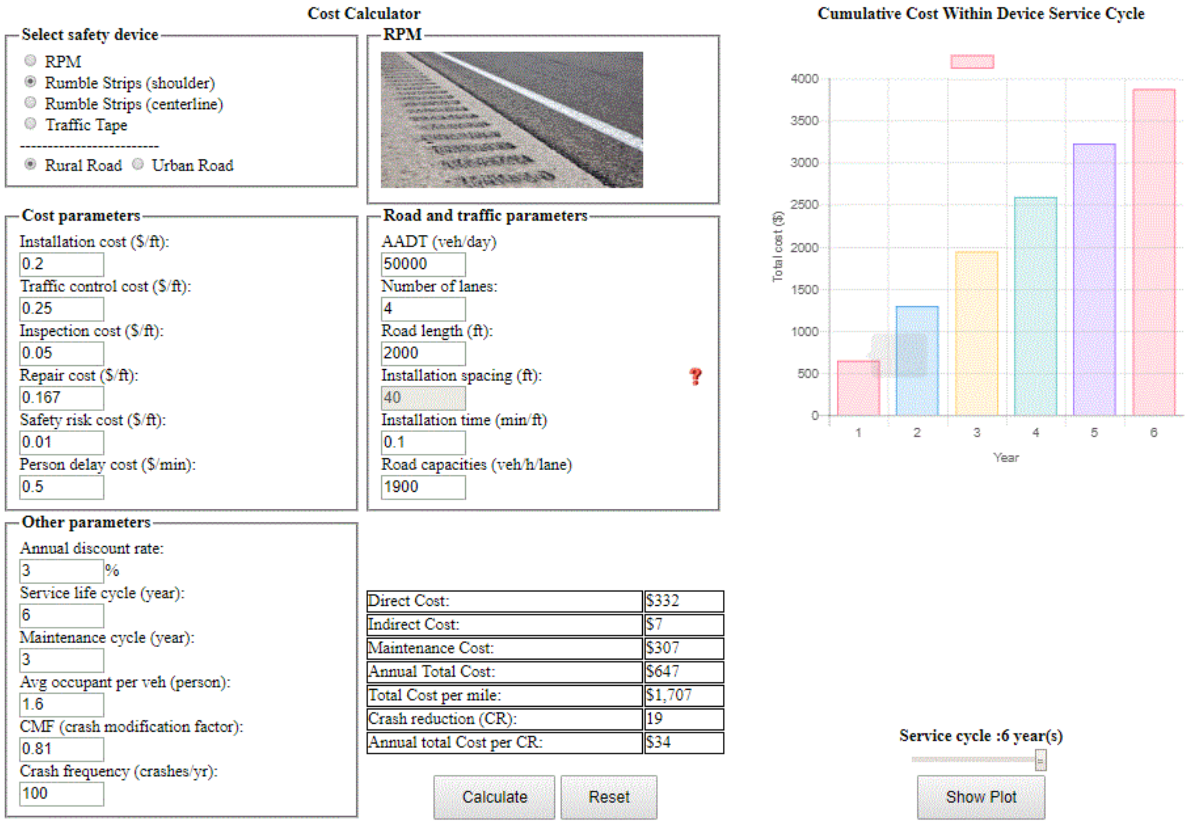


Figure 36. Cost of shoulder rumble strips

If we look at the same segment installed with Shoulder Rumble Strips, assuming the installation time is 0.1 minute per linear foot (or it is installed 10 ft per minute), it could prevent 19 crashes per year and the annual cost of this 2,000 ft road segment within a 6-year service cycle is $647 ($1,707 per mile). The annual total cost of per unit crash reduction is $34.

Example 3: Centerline Rumble Strips

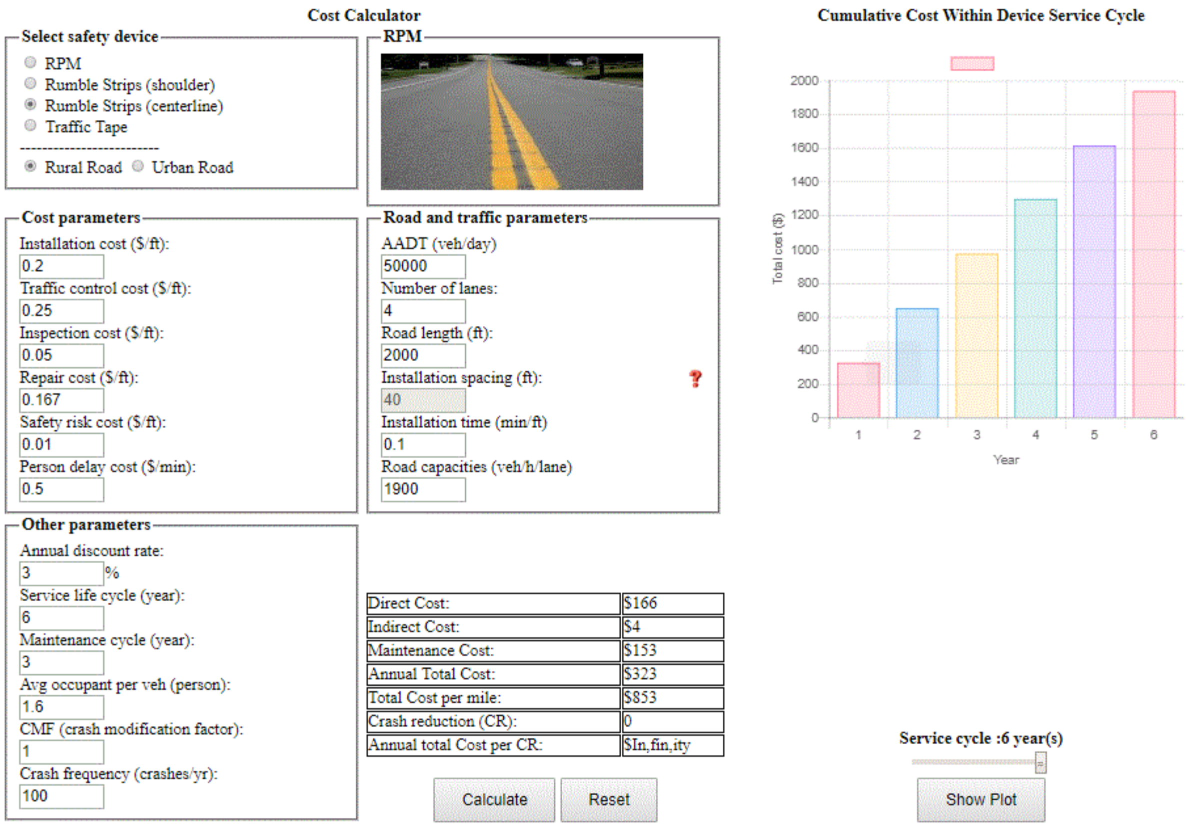


Figure 37. Cost of centerline rumble strips

Fewer states use centerline rumble strips than shoulder rumble strips. The majority of centerline rumble strips have been installed on rural two-lane undivided road. It is not common to use centerline rumble strips on multilane road. Moreover, there is no existing CMF of centerline rumble strips installing on multilane road on HSM and other published researches.

Example 4: Traffic Tape

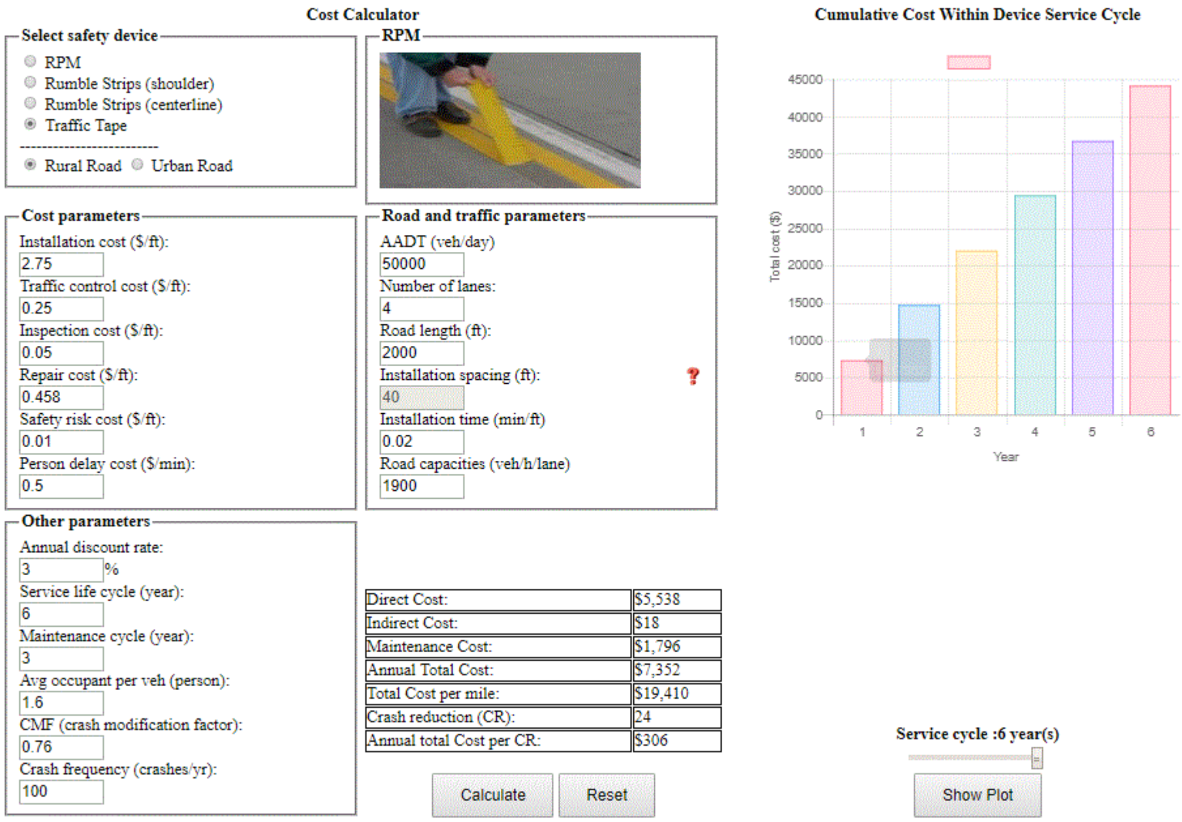


Figure 38. Cost of traffic tape

Assuming the installation time for traffic tape is 0.02 minute per linear foot (it can be installed around 50 ft per minute). On the same segment, traffic tape could prevent 24 crashes per year and the annual cost within a 6-year service cycle is $7,352 ($19,410 per mile). The annual total cost of per unit crash reduction is $306.

Life Cycle Cost Comparisons between RPMs and Alternatives

In the above cases, we adjust the values of Installation cost, Repair cost, Installation time and CMFs, and keep the rest constant for the four safety devices. The summary table is shown below.

Table 63 - Example parameters in the calculator (all values are subject to change depending on the information available to the users)

Parameter \ Device	RPM	Shoulder Rumble Strip	Centerline Rumble Strip	Traffic Tape
Installation cost ($)	15.00/unit	0.20/ft	0.20/ft	2.75/ft
Traffic control cost ($)	10.00/unit	0.25/ft	0.25/ft	0.25/ft
Inspection cost ($)	2.00/unit	0.05/ft	0.05/ft	0.05/ft
Repair cost ($)	3.50/unit	0.17/ft	0.17/ft	0.46/ft
Safety risk cost ($)	0.50/unit	0.01/ft	0.01/ft	0.01/ft
Person delay cost ($/min)	0.5	0.5	0.5	0.5
AADT (veh/day)	50,000	50,000	50,000	50,000
Number of lanes	4	4	4	4
Road length (ft)	2,000	2,000	2,000	2,000
Installation spacing (ft)	40	NA	NA	NA
Installation time (min)	5.00/unit	0.10/ft	0.10/ft	0.02/ft
Road capacity (veh/h/lane)	1,900	1,900	1,900	1,900
Annual discount rate	3%	3%	3%	3%
Service life cycle (years)	6	6	6	6
Maintenance cycle (years)	3	3	3	3
Avg occupant (person/veh)	1.60	1.60	1.60	1.60
CMF	0.94	0.81	1	0.76
Crash frequency (crashes/yr)	100	100	100	100

Table 64 - Cost components

Cost item \ Device	RPMs	Shoulder rumble strips	Centerline rumble strips	Traffic tape
Direct cost	$1,154	$332	$166	$5,538
Indirect cost	$23	$7	$4	$18
Maintenance cost	$486	$307	$153	$1,796
Total cost	$1,163	$647	$323	$7,352

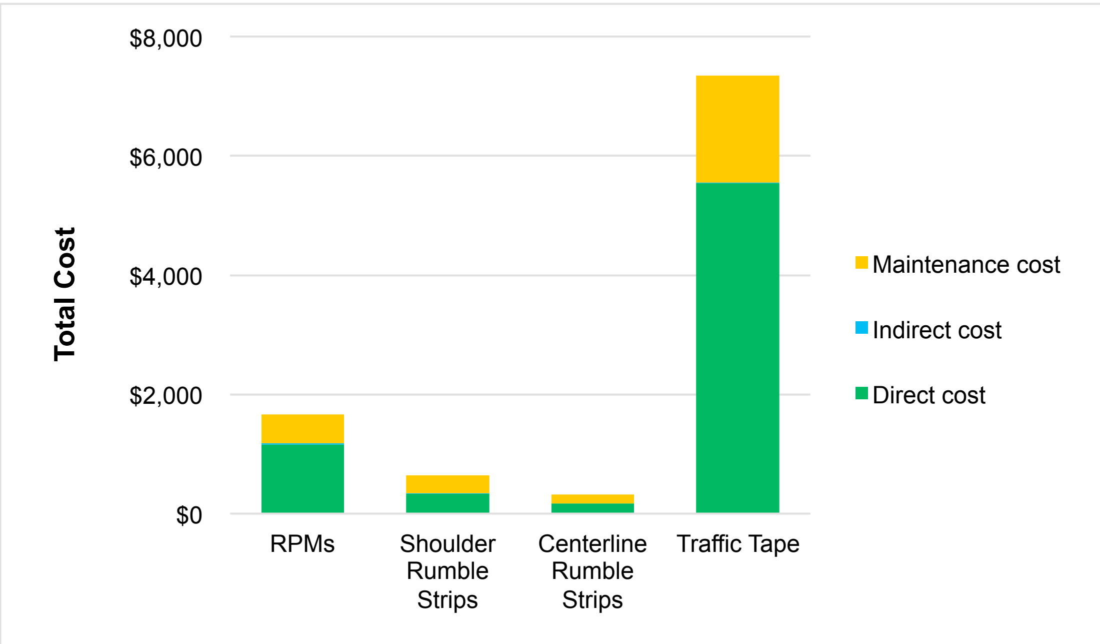


Figure 39. Comparison of components of total cost by safety device

Table 65 - Crash reduction

Benefit item \ Device	RPMs	Shoulder rumble strips	Centerline rumble strips	Traffic tape
CMF	0.94	0.81	1	0.76
Crash frequency (crashes/yr)	100	100	100	100
Crash reduction (crashes/yr)	6	19	0	24
Total cost per crash reduction	$277	$34	-	$306

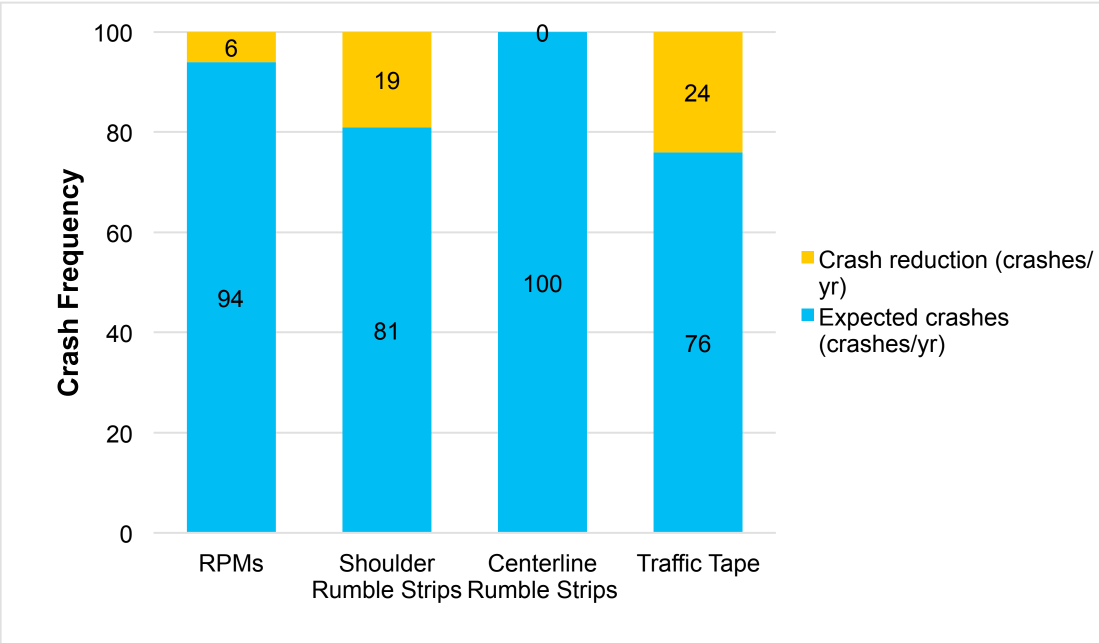


Figure 40. Comparison of components of crash reduction by safety device

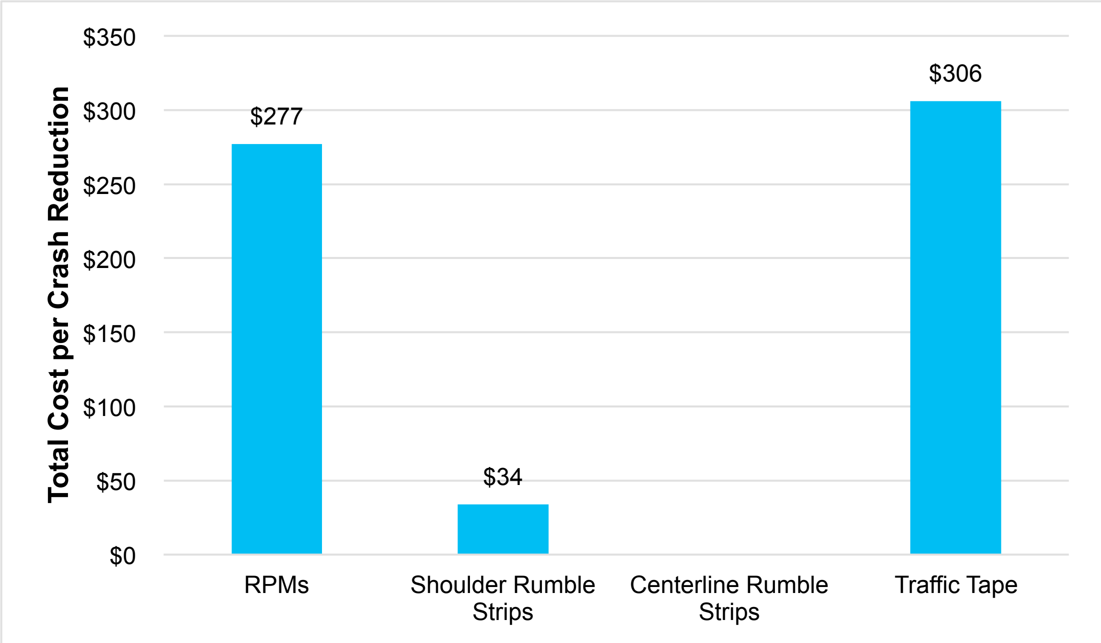


Figure 41. Comparison of components of total cost per crash reduction within each safety device

From Table 64, 65 and Figure 39, 40, 41 the following observations are made on a hypothetical, 2,000 ft, with an average 50,000 daily traffic, four-lane segment:

- Shoulder rumble strips have the lowest annual total cost for per crash reduction and second highest crash reduction among the three (not considering Centerline Rumble Strips). Although the annual total cost for RPMs is also very low, the total number of crash reduction is the least of all, which only takes 30 percent crash reduction of shoulder rumble strips and 25 percent of traffic tape. However, the choice should also consider the real-world situation. For example, the noise caused when driving on rumble strips makes it better to be installed inside and outside shoulders of interstate highways, expressways or beltways in rural area; RPMs can increase visibility of the road by retroreflecting headlights; and traffic tape is often used on a road surface in order to convey information for drivers and pedestrian. With that being said, one should carefully examine the environment, road geometry, and life cycle cost before making the decision on what kind of device should be selected.
- For all the four types of safety devices, if the AADT exceeds some certain threshold values, most of the total cost will be the indirect cost while delay cost explains most of the indirect cost. For example, if we install the safety devices on

the same road segment but with an 80,000-daily traffic, the indirect cost will increase extremely due to person delay (Figure 42). To cut the cost in the implementation of those safety devices, it's necessary to study the delay cost. From our definition, delay cost is correlated with the length of the road under construction, person delay cost, AADT, installation time and the average delay time in construction zone. Since we are comparing the same road segment, AADT, average delay and person delay cost may remain constant, so the only parameter we can control is installation time in construction zone.

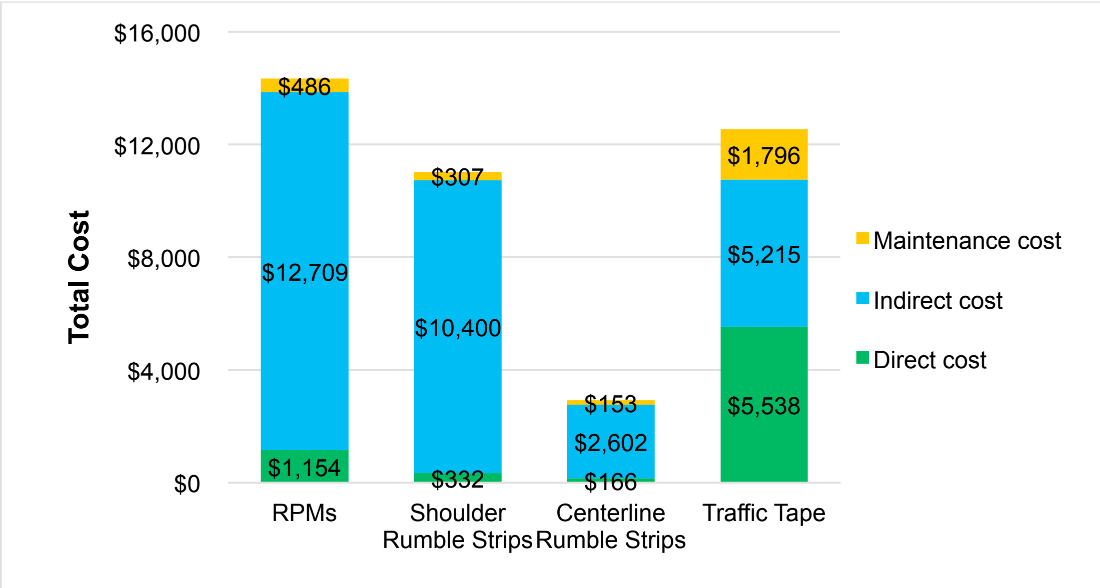


Figure 42. Comparison of components of total cost within each safety device

What-if Scenario Analysis

This section analyzes the circumstances that which device has a lower life-cycle cost than alternatives via what-if scenario analyses. For illustration, we change the installation time for each type of safety device on the same road segment with an 80,000-daily traffic.

Table 66 - Installation time sensitivity analysis

Scenario \ Device	RPMs	Shoulder rumble strips	Centerline rumble strips	Traffic tape
1	5 min/unit	0.1 min/ft	0.1 min/ft	0.02 min/ft
2	4 min/unit	0.1 min/ft	0.1 min/ft	0.02 min/ft
3	5 min/unit	0.2 min/ft	0.2 min/ft	0.02 min/ft

Table 67 - Total cost of each device under different scenarios

Scenario \ Device	RPMs	Shoulder rumble strips	Centerline rumble strips	Traffic tape
1	$14,349	$11,039	$2,921	$12,548
2	$9,782	$11,039	$2,921	$12,548
3	$14,349	$42,215	$10,715	$12,548

Our what-if analysis (see Table 67) shows that in scenario 1, implementing RPMs costs more than rumble strips and traffic tape. In scenario 2, RPMs become the most cost-justified device among the three (not considering the centerline rumble strips) as long as shortening installation time by 1 min/unit. In scenario 3, shoulder rumble strips have the highest life-cycle cost if increasing installation time to 0.2 min/ft. Users can change the value of installation according to their requirements to see the change in the total cost of each device.

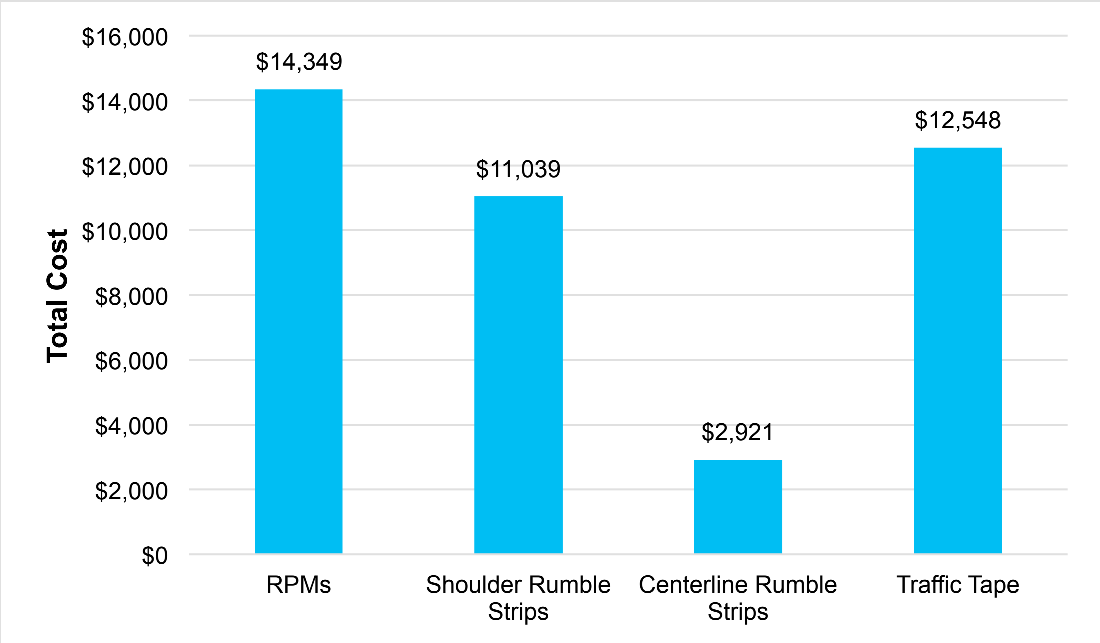


Figure 43. Cost comparison in scenario 1

Using the parameters above, the total cost of RPMs is higher than rumble strips and traffic tape. Rumble strips are the least-cost choice (Figure 43).

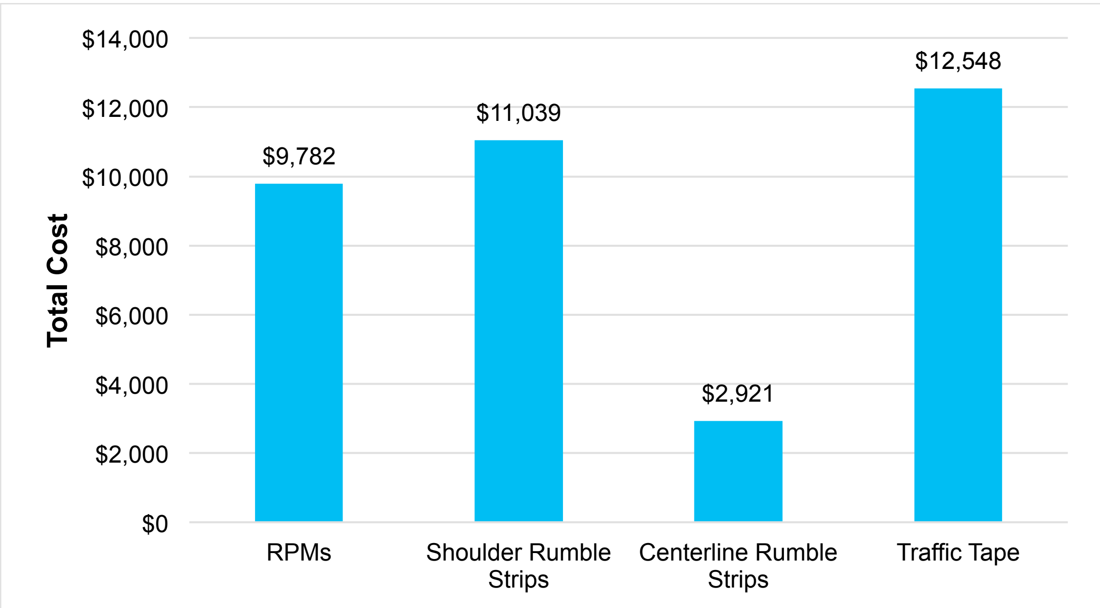


Figure 44. Cost comparison in scenario 2

If the installation time of RPMs goes from 5 min/unit to 4 min/unit, RPMs become the least-cost safety device among the three (not considering the centerline rumble strips). Traffic tape has the highest total cost (Figure 44).

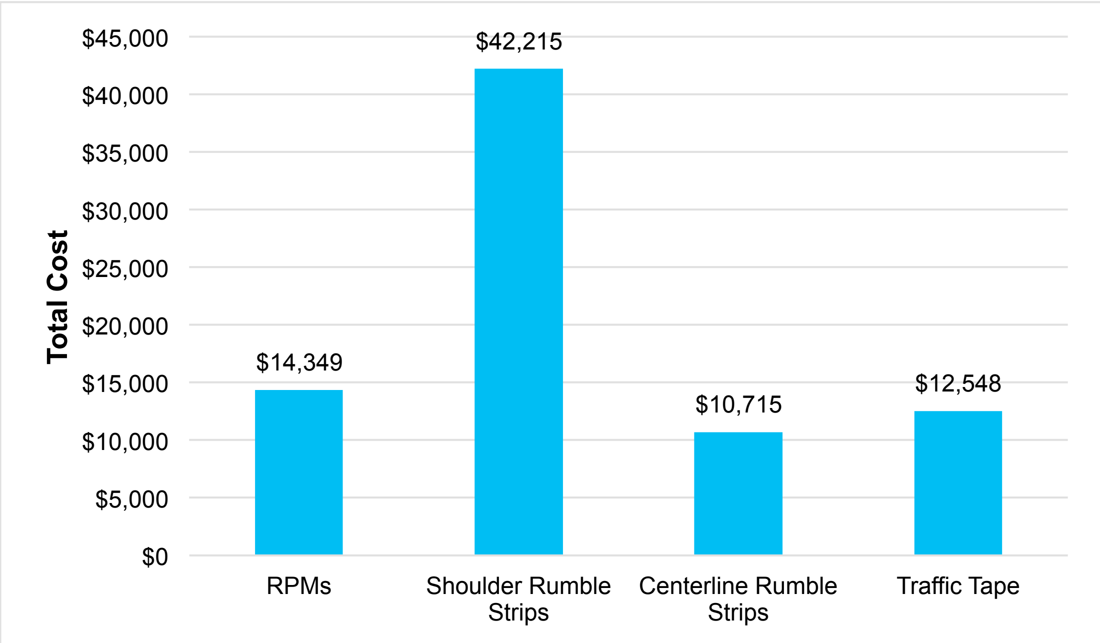


Figure 45. Cost comparison in scenario 3

If installation time of rumble strips increases by 0.1 min/ft, then the cost of shoulder rumble strips becomes the highest.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

Raised pavement markers (RPMs) have been extensively used throughout the nation. A review of the prior literature found that there is no consensus regarding whether and how RPMs affect roadway crash rate. Depending on the scope and data, different studies report different magnitudes of safety changes (positive or negative) after RPMs are implemented. Also, there are various alternatives and modifications possible for RPMs, such as rumble stripes, traffic tapes, and others. The use of these alternatives varies by state.

A survey showed different installation, inspection and maintenance practices of RPMs among different states. Most of the responding states install RPMs on selective locations, some other states install RPMs non-selectively, and a few others do not install RPMs. When installing RPMs selectively, the states use various criteria (e.g. traffic volume, accident history, weather conditions) to determine RPM installation location. According to the survey response, the RPMs are usually replaced every 2-4 years, but it varies according to different criteria used.

In the State of New Jersey, RPMs are used along all centerlines and skip lines, regardless of traffic volume, roadway geometry, or roadway classification. Therefore, a direct before-after safety evaluation of RPMs on state roadways in New Jersey is not feasible for this project. However, some county roadways have RPMs while others do not. Hence, this research used the county roadways without RPMs as the comparison group. The crash rates on county roadways with RPMs were calculated and compared to the crash rates on the county roadways without RPMs. On average, the crash rates on county roadways with RPMs decreased by 19 percent compared to county roads without RPMs. The most significant decrease in crash rate occurred in nighttime, wet weather conditions. This seems to indicate that RPMs may have more safety effects under wet weather conditions and in the nighttime. However, the conclusion might be subject to uncertainty due to the sensitivity of daytime and nighttime crash rates to the assumptions made for hourly traffic distribution.

Besides safety performance, the costs of RPMs and alternative safety devices were also considered in this project. A computer-aided decision support has been developed to assess the life cycle cost (LCC) of RPMs versus alternatives given specified operational characteristics. Considering together with the safety benefit of each safety device, we can compare the total cost for per unit crash reduction among different safety devices. The cost tool can support decisions with respect to the optimal use of safety investment.

The laboratory measurement data and analyses of visual performance under road lighting conditions demonstrate that RPMs and alternatives, such as wet reflective pavement marking tape and barrier-mounted reflective delineators, provide highly visible elements along the nighttime roadway environment for a wide range of geometric conditions at distances of 100 meters away. Used RPMs measured in this study had luminances 20% to 30% lower than new RPMs; such reductions were of little consequence to visual performance. Although all of the devices measured resulted in very high visual performance for a 100-meter viewing distance, differences among the luminances of different devices could result in large differences in the threshold visibility distances (at which the devices first cab be identified). While this would give drivers more time and distance to respond to these devices, further study is needed to assess whether they would reduce nighttime crashes.

One factor not addressed by these analyses is the spacing or degree of continuous delineation that drivers need for safety. Although the barrier-mounted reflective delineators had slightly lower visual performance than the RPMs that were tested in this study, such devices are meant to provide continuous delineation similar to that produced by wet reflective pavement marking tape. In airport applications, for example, pilots could identify the configurations of taxiways and runways more rapidly when airfield lights were placed 100 feet apart than when they were 200 feet apart. Extrapolating this work to a roadway context would require further validation, but suggests that continuous roadway delineation can be advantageous over intermittent delineation.

References

1. Persaud, B., Bahar, G., Mollett, C., & Lyon, C. Safety evaluation of permanent raised pavement markers. Transportation Research Record 1897, 148-155, 2004.
2. Fontaine, Michael D., and Gillespie, James S. Synthesis of Benefits and Costs of Alternative Lane Marking Strategies. No. FHWA/VTRC 09-R24. 2009.
3. Bahar, G., Mollett, C., Presaud, B., Lyon, C., Smiley, A., Smahel, T., & McGee, H. Safety Evaluation of Permanent Raised Pavement Markers. NCHRP Report 518. Transportation Research Board, 2004.
4. Wright, P.H., Zador, P. L., Park, C. Y., & Karpf, R. S. Effect of pavement markers on nighttime crashes in Georgia. Washington, DC, Insurance Institute for Highway Safety, 1982.
5. Jiang Yi. The Effectiveness and Criteria for Placement of Raised Pavement Markers (synthesis study) [R]. Washington DC: Federal Highway Administration, 2006.
6. Hammond, J. L., & Wegmann, F. J. (2001). Daytime effects of raised pavement markers on horizontal curves. ITE Journal, 38-41.
7. Kugle, C. L., Pendleton, O. J., & Von Tress, M. S. An Evaluation of the Accident Reduction Effectiveness of Raised Pavement Markers. College Station, Texas, 1984.
8. Mak, K. K., Chira-Chavala, T., & Griffin, L. I. Evaluation of the Safety Effects of Raised Pavement Markers. College Station, Texas, Texas Transportation Institute, 1987.
9. Griffin, L. I. Using the Before-and-After Design with Yoked Comparisons to Estimate the Effectiveness of Accident Countermeasures Implemented at Multiple Treatment Locations. College Station, Texas, Texas Transportation Institute, 1990.
10. Pendleton, O. J. Evaluation of accident methodology. College Station, Texas, Texas Transportation Institute, 1996.
11. New York State Department of Transportation (NYDOT). Highway Safety Improvement Program - Annual Evaluation Report. Albany, NY, 1989.
12. New York State Department of Transportation (NYDOT). Raised Reflectorized Snowplowable Pavement Markers: A Report to the Governor. Albany, NY, 1997.

13. Orth-Rodgers and Associates, Inc. Safety and Congestion Management Research and Advanced Technology Applications - Final Report (technical assistance to the RPM task force). Research Work Order Number 1. Philadelphia, PA, 1998.
14. Tsyganov, A. R., R. B. Machemehl, N. M. Warrenchuk, and Y. Wany. Before-After Comparison of Edgeline Effects on Rural Two-Lane Highways. CTR Technical Report 0-5090-2. Austin, Texas: Center for Transportation Research, Texas Department of Transportation, 2006.
15. Smadi, O., N. Hawkins, I. Nlenanya, and B. Aldemir-Bektas. Pavement Markings and Safety. Trans Project Report 08-306. Center for Transportation Research and Education, Iowa State University, Ames, Nov. 2010.
16. Das. S, Sun. X, Rasel. S, Wang. F, Investigating Safety Impact of Raised Pavement Markers on Freeways in Louisiana. TRB 2013 Annual Meeting, 2013.
17. Jordan, Joe. Road Safety Backfires: State Set to Pay $1.5 Million. NebraskaWatchdog.org. [Online] February 25, 2010.
18. Migletz, J., Fish, J. K., and Graham, J. L., "Roadway Delineation Practices Handbook." FHWA-SA-93-001, Washington, DC, Federal Highway Administration, U.S. Department of Transportation,1994.
19. Gibbons, R.B., J.M. Hankey, I. Pashaj, B.H. Cottrell, and C. Anderson. Wet Night Visibility of Pavement Markings. VTRC 05-CR3. Virginia Transportation Research Council, Charlottesville, 2004.
20. Schnell, T., F. Aktan, and Y. Lee. Nighttime Visibility and Retroreflectance of Pavement Markings Under Dry, Wet, and Rainy Conditions. In TRB 82nd Annual Meeting Compendium of Papers. CD ROM. Transportation Research Board, Washington, D.C., 2003.
21. Aktan, F., and T. Schnell. Performance Evaluation of Pavement Markings under Dry, Wet, and Rainy Conditions in the Field. In TRB 83rd Annual Meeting Compendium of Papers. CD ROM. Transportation Research Board, Washington, D.C., 2004.
22. Cottrell, B. H. Evaluation of Pavement Markings for Improved Visibility during Wet Night Conditions. VTRC 96-R33. Virginia Transportation Research Council, Charlottesville, 1996.

23. Agent, Kenneth R. and Green, Eric R. Evaluation of the Use of Snowplowable Raised Pavement Markers. Lexington, Kentucky: Kentucky Transportation Center University of Kentucky, 2009.
24. Patterson, K., and J. Fitch. Evaluation and Comparison of Snowplowable Raised Pavement Markings (SRPMs). Vermont Agency of Transportation, Montpelier, 2007.
25. Mitkey, S.R.; Brennan, T.M.; Davis, A.D.; Grimmer, G.; Hainen, A.M.; Morris, R.; and Michael, P.; "Retroreflectivity Durability Comparison of Rumble Stripes vs. Painted Line," Purdue University, November 2011.
26. FHWA. Safety Evaluation of Centerline Plus Shoulder Rumble Strips. Report No. FHWA HRT-15-048. Federal Highway Administration, Washington, D.C., 2015.
27. Markow, M.J. Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts, and Sidewalks. NCHRP Synthesis 371. Transportation Research Board, Washington, D.C., 2007.
28. Migletz, J., and J. Graham. Long-Term Pavement Marking Practices. NCHRP Synthesis 306. Transportation Research Board, Washington, D.C., 2002.
29. Carlson, P., J. Miles, A. Pike, and E. Park. Evaluation of Wet Weather and Contrast Pavement Marking Applications: Final Report. Report 0-5008-2. Texas Transportation Institute, College Station, 2007.
30. Carlson, P., J. Miles, A. Pike, and E. Park. Evaluation of Wet Weather Pavement Markings: First Year Report. Report 0-5008-1. Texas Transportation Institute, College Station, 2005.
31. Migletz, J., J. Graham, D. Harwood, and K. Bauer. Service Life of Durable Pavement Markings. In Transportation Research Record: Journal of the Transportation Research Board, No. 1749. Transportation Research Board, Washington, D.C., 2001, pp. 13-21.
32. Federal Highway Administration. Manual on Uniform Traffic Control Devices. Washington, D.C., 2009.
33. American Association of State Highway and Transportation Officials, Research Advisory Committee. AASHTO RAC Email Survey Results: Snowplowable Raised Pavement Markers. Conducted by the Missouri Department of Transportation. January 27, 2005.

34. FHWA. Pavement Marking Demonstration Projects: State of Alaska and State of Tennessee. Report No. FHWA-HRT-12-048. Federal Highway Administration, Washington, D.C., 2013.
35. Fontaine, M., & Diefenderfer, B. Factors That Affect Failures of Snowplowable Raised Pavement Markers in Virginia. Transportation Research Record: Journal of the Transportation Research Board, (2258), 71-79, 2011.
36. Bryden, J.E. Long-Term Performance of Grooved Stripe-reflective Markers. New York State Department of Transportation, Albany, 1979.
37. Doerr, G.L., R. Walker, and S. Henrichs. Evaluation of Snowplowable Reflective Pavement Markers for Effective Delineation. North Dakota Department of Transportation, Bismark, 2005.
38. Filice, J. Study of Snowplowable Raised Pavement Markers. Alberta Transportation. Edmonton, Alberta, Canada, 2006.
39. Cottrell, B. H. and Hanson, R. A. Determining the effectiveness of pavement marking materials. FHWA/VTRC 01-R9. Virginia Transportation Research Council; United States. Federal Highway Administration; Virginia. Department of Transportation, 2001.
40. Andrady, A. Pavement Marking Materials: Assessing Environment-Friendly Performance. NCHRP Report 392. Transportation Research Board, Washington, D.C., 1997.
41. Grant, A. R., and Bloomfield, J. R., "Guidelines for the Use of Raised Pavement Markers." FHWA-RD-97-152, McLean, VA, Federal Highway Administration, 1998, pp. 1-58.
42. Traffic Laws annotated, US Department of Transportation, 1979.
43. B. Schoettle et al., A Market Weighted Description of Low Beam Headlighting Patterns in the U.S., Ann Arbor, MI, 2004
44. Griffith, Michael S.Technical Advisory for Shoulder and Edge Line Strips and Center Line Rumble Strips. s.l.: Federal Highway Administration, 2011.
45. NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips. Washington D.C.: Transportation Research Board, 2009.
46. Noyce, D.A. and Elango, V.V. Safety Evaluation of Centerline Rumble Strips: A Crash and Driver Behavior Analysis. Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C., 2004, pp. 44-53.

47. Patel, R. B., F. M. Council, and M. S. Griffith, Estimating the Safety Benefits of Shoulder Rumble Strips on Two Lane Rural Highways in Minnesota: An Empirical Bayes Observational Before-After Study, Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2007.
48. Annino,J.M., Rumble Strips In Connecticut: A Before/After Analysis of Safety Benefits, Connecticut Department of Transportation, 2003.
49. Per Garder and Michael Davies, Safety Effect of Continuous Shoulder Rumble Strips on Rural Interstates in Maine, Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C., 2006, pp. 156-162.
50. Michigan Department of Transportation (MDOT), Painted Rumble Strips on Michigan Freeways: Driver and Community Perceptions, Survey conducted by Public Sector Consultants Inc., May 2006.
51. Marvin and D.J. Clark. An Evaluation of Shoulder Rumble Strips in Montana, Montana Department of Transportation, 2003.
52. Perrillo, K., The Effectiveness and Use of Continuous Shoulder Rumble Strips, Federal Highway Administration, Albany, NY, 1998.
53. Hickey, Shoulder Rumble Strip Effectiveness, Drift-Off- Road Accident Reductions on the Pennsylvania Turnpike." In Transportation Research Record 1573. TRB, National Research Council, Washington, D.C., 1997, pp. 105-109.
54. Porter, Eric. Donnell, etc. Evaluation of Effects of Centerline Rumble Strips on Lateral Vehicle Placement and Speed. Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C., 2004, pp. 10-16.
55. Cheng, E. Y. C., E. Gonzalez, and M. O. Christensen, Application and Evaluation of Rumble Strips on Highways, Utah Department of Transportation, Compendium of Technical Papers, 64th ITE Annual Meeting, Dallas, Texas, 1994.
56. Paul J. Carlson and Jeff D. Miles, Effectiveness of Rumble Strips on Texas Highways: First Year Report. FHWA/TX-05/0-4472-1. Texas Department of Transportation, September 2003.
57. Karkle, D. Effects of Centerline Rumble Strips on Safety, Exterior Noise, And Operational Use of The Travel Lane. Ph.D. Kansas State University, 2011.
58. C.S. Chen and B.H. Cottrell, Jr. Guidelines for Using Centerline Rumble Strips in Virginia. Virginia Transportation Research Council 05-R30, June 2005.

59. Kirk, A., Evaluation of the Effectiveness of Pavement Rumble Strips, Research Report KTC-08-04/SPR319-06-1F. Kentucky Transportation Center, University of Kentucky, College of Engineering, January 2008.
60. Spainhour and Mishra, Analysis of Fatal Run-Off-the-Road Crashes Involving Overcorrection, Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C., 2008, pp. 1-8.
61. Tarek Sayed, Paul deLeur, and John Pump, Impact of Rumble Strips on Collision Reduction on Highways in British Columbia, Canada. Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C., 2010, pp. 9-15.
62. El-Basyouny and Tarek Sayed， Linear and Nonlinear Safety Intervention Models Novel Methods Applied to Evaluation of Shoulder Rumble Strips, Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C., 2012, pp. 28-37.
63. Thomas M. Brennan, Stuart R. Mitkey, Darcy M. Bullock. Alternatives to Raised Pavement Markers (RPMs). FHWA/IN/JTRP－2014/01, February 2014
64. Bullough, J. D. and N. P. Skinner. 2014. Do LEDs increase the accuracy of LED aviation signal light color identification by pilots with and without color-deficient vision? Federal Aviation Administration Worldwide Technology Transfer Conference, Galloway, NJ, August 5-7. Washington, DC: Federal Aviation Administration.
65. Matthias, J.S. Spacing of Raised Reflective Pavement Markers. Arizona State University, Tempe, 1988.
66. WCVB_2014_Highway Pavement Marker Flies into Car's Windshield in Wilmington http://www.wcvb.com/article/highway-pavement-marker-flies-into-car-s-windshield-in-wilmington/8195764
67. NBC Chicago_2014_Loose Highway Markers Create Road Hazards http://www.nbcchicago.com/investigations/Loose-Highway-Markers-Create-Road-Hazards-265322521.html
68. Omar Smadi and Neal Hawkins. Practice of Rumble Strips and Rumble Stripes: A Synthesis of Highway Practice. NCHRP Synthesis 490. Transportation Research Board (TRB), Washington, D.C., 2016.

69. FHWA_2008_ACTION: Consideration and Implementation of Proven Safety Countermeasures. https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/resources/memo_rumstrips071008.cfm
70. New York State Department of Transportation _2016 Shoulder Rumble Strips https://www.dot.ny.gov/programs/rumblestrips
71. Olson D., Sujka M., and Manchas B. Performance Analysis of Centerline and Shoulder Rumble Strips Installed in Combination in Washington State. WSDOT Research Report, April 2013.
72. 2016 Design Manual. Washington State Department of Transportation. http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/M22-01.13Revision.pdf
73. Wilder R.D. Centerline Rumble Strips on Secondary Highways. New York State Department of Transportation, August 2011.
74. New York State Department of Transportation _2016 Centerline Rumble Strips https://www.dot.ny.gov/programs/rumblestrips/centerrumblestrips
75. Olson D., Manchas B., Glad R.W., and Suika M. Performance Analysis of Centerline Rumble Strips in Washington State. WSDOT Research Report, March 2011.
76. Cuelho E., Stephens J., and McDonald C. A Review of the Performance and Costs of Contemporary Pavement Marking Systems. FHWA/MT-03-001/8117-17, 2003.
77. Virginia State Department of Transportation _2012 Preformed Tape http://www.virginiadot.org/business/resources/Materials/MCS_Study_Guides/bu-mat-PaveMarkCh8.pdf
78. Montebello D. and Schroeder J. Cost of Pavement Marking Materials, Syntesis Report 2000-11. Minnesota Department of Transportation, March 2000.
79. New York State Department of Transportation_2006_Special Specification 688.10XX-18 Preformed, Wet-Reflective Tape (Grooved Pavement Method). https://www.dot.ny.gov/portal/page/portal/main/business-center/consultants/forms-publications-and-instructions/engineering-information-issuance-system/ei-repository/ei06008.pdf7
80. Oregon Department of Transportation Pavement Marking Design Guidelines, July 2015.

81. Cottrell B.H. and Hanson R.A. Determining the Effectiveness of Pavement Marking Materials. Virginia Transportation Research Council. VTRC 01-R9, February 2001.
82. Manual on Uniform Traffic Control Devices for Streets and Highways. Washington D.C.: U.S. Department of Transportation, Federal Highway Administration, 2009 Edition. p. 432/864.
83. Wyoming State Department of Transportation. http://www.dot.state.wy.us/news/wydot-installs-flexible-delineators-for-safer-roads
84. Jennings B.E. and Demetsky M.J. Evaluation of Curve Delineation Signs on Rural Highways, Virginia State Department of Transportation. Virginia Transportation Research Council. VTRC 84-R16, December 1983.