Synthesis of Pavement Marking Research

U.S. Department of Transportation
Federal Highway Administration

Safe Roads for a Safer Future
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This report provides a synthesis of recent research focused on longitudinal pavement markings. It offers a review of when and where longitudinal pavement markings are used. It also covers two of the most important parameters in terms of increasing the effectiveness of pavement markings: width and retroreflectivity. These items are within the control of owners and operators. By better understanding how width and retroreflectivity impact operational performance, visibility, and safety, highway agencies can increase the effectiveness of their pavement marking policies. This synthesis is intended to provide a reference about what is known on the subject and what questions still remain. The research recommendations are based on the synthesized material. Ongoing or pending research that is known is noted where appropriate.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.0305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectacres	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME (NOTE: volumes greater than 1000 L shall be shown in $m^{3)}$				
fl oz	fluid ounces	29.57	millileters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
k	kilometers	0.0621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.19	square yard	yd^2
ha	hectacres	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	millileters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	1.8C+32	Celsius	ºC
ILLUMINATION				
lx	lux	0.929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Table of Contents

List of Figures

List of Abbreviations and Symbols

AADT	*Annual average daily traffic*
AASHTO	*American Association of State Highway and Transportation Officials*
FHWA	*Federal Highway Administration*
mcd/m²/lx	*millicandelas per square meter per lux*
MoDOT	*Missouri Department of Transportation*
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	*National Cooperative Highway Research Program*
NCDOT	*North Carolina Department of Transportation*
NPA	*Notice of Proposed Amendments*
QR	*Quick Response*
RFID	*Radio frequency identification*
RRPM	*Raised retroreflective pavement marker*
vpd	*Vehicles per day*

CHAPTER 1: Introduction

BACKGROUND

Pavement markings are a relatively new concept in the overall history of paved roads. Prior to the mid-1900s, the majority of our highways were "naked"—highways without white and yellow pavement markings that exist on all major highways in the United States today. The research on adding markings to naked highways goes back over half a century when most highways did not have markings. While the findings from these studies are based on naïve statistical analysis methods, the studies all clearly indicate that pavement markings provide crash reductions.[1–4] A 2004 synthesis on pavement marking research includes a brief description of the value of installing pavement markings on naked highways.[1]

Pavement markings delineate the travel lanes and other features of the roadway, providing benefits that are inherently linked to safety. Pavement markings provide lane position assistance in the near field and roadway alignment guidance in the far field. They have been designed to be visible to drivers in both day and night conditions. Pavement marking research has covered topics such as durability, visibility, vehicle operational impacts using speed and lane position, and safety impacts using crash types such as run-off-the-road and head-on crashes. Less research has been devoted toward how to cost-effectively optimize the performance of pavement markings—i.e., their durability, best practices on size and brightness, and interactions with other treatments such as roadway lighting or raised pavement markers. Some other questions that may need more research are:

- When are markings needed?
- What types of markings should be used?
- How should the markings be maintained?
- Do narrow highways need both center line and edge line markings? If not, is one safer than the other?
- What width should pavement markings be?
- How bright do they need to be?
- How can pavement markings be optimized when used in areas with roadway lighting and/or raised pavement markers?
- What is the value of different types of glass bead coatings?
- How round do the glass beads (the optics of most markings) need to be?

More research is needed to definitively answer these questions and determine specific methods of enhancing the performance of pavement markings.

PURPOSE OF THIS REPORT

This report provides a synthesis of recent research focused on longitudinal pavement markings. It offers a review of the United States standards for when and where longitudinal pavement markings are used. It also covers two of the most important parameters in terms of increasing the effectiveness of pavement markings: width and retroreflectivity. These items are within the control of owners and operators. By better understanding how width and retroreflectivity impact performance, highway agencies would be able to increase the effectiveness of their pavement marking policies and improve safety.

This synthesis is intended to provide a reference about what is known on the subject and what questions still remain. The research recommendations are based on the synthesized material. Ongoing or pending research that is known is noted where appropriate.

ORGANIZATION OF THIS REPORT

The structure of this report is based on the parameters that impact pavement marking placement and performance. The report is structured as follows:

- **Chapter 2** summarizes when and where longitudinal pavement marking are typically installed.
- **Chapter 3** addresses research findings related to longitudinal pavement marking width.
- **Chapter 4** addresses research findings related to pavement marking retroreflectivity, based on the factors within the control of highway owners/operators.
- **Chapter 5** addresses wet nighttime pavement marking retroreflectivity. Although wet pavement marking retroreflectivity is a subset of retroreflectivity described in Chapter 4, this chapter is separated out due to heightened interest in this area.
- **Chapter 6** addresses the impacts of raised retroreflective pavement markers (RRPMs).
- **Chapter 7** describes research that provides guidance on selecting the most appropriate pavement marking materials.
- **Chapter 8** includes thoughts concerning the future of pavement markings.
- **Chapter 9** briefly describes related topics not specifically addressed in this report.

Chapters 3 through 5 are divided into three key performance metrics: operational impacts, visibility, and safety. Where appropriate, standards and specifications are summarized. Each section of this report includes a brief summary and recommendations for future research. Remarks are also provided where ongoing work is underway or pending.

Specifically excluded from this synthesis are object markers and pavement marking design issues that are the purview of the Manual on Uniform Traffic Control Devices (MUTCD). Additionally, this report does not include pavement marking symbols, crosswalk markings, and marking types other than traditional longitudinal markings. This is a synthesis of research rather than a synthesis of practice.

REPORT SUMMARY

The MUTCD describes when and where longitudinal pavement markings shall and should be installed, using criteria based on traffic volume, roadway width, and functional classification. When the MUTCD criteria were drafted, specific research was not available to help set the criteria. Research results (such as those from the Missouri Department of Transportation [MoDOT] described in Chapter 2) have become available and suggest that there may be enhanced safety benefits to implementing criteria more aggressive than those currently described in the MUTCD warrants. However, additional research may be needed to assess what criteria would be appropriate.

The default pavement marking width is generally 4 inches in the United States, although 6-inch wide pavement markings are also used. The width of pavement markings up to 6 inches has negligible impacts on operating speed and lateral placement on two-lane highways. Additional research regarding the operational performance of pavement markings wider than 6 inches or on highways other than two-lane, two-way facilities may be of interest. Regarding visibility of wider lines, there are some inconsistencies in the research, but the most recent studies indicate that wider pavement markings can increase pavement marking visibility. Research also has shown that wider pavement markings may provide a way to reduce driver workload along horizontal curves.

More research is needed to understand the trade-offs between using wider and brighter pavement markings. Many agencies strive for higher retroreflectivity levels without considering wider markings. Increasing pavement marking width may offer more benefits than installing and/or maintaining markings with relatively high retroreflectivity levels. Wider pavement markings have been shown to have a positive safety relationship on rural two-lane, two-way highways; however, on multilane divided highways, wider pavement markings have not been found to have a significant positive safety impact.

The research on the effects of dry pavement marking retroreflectivity has demonstrated little to no impact on operational measures of performance such as vehicle speed or lateral placement. While research of this type is generally focused within horizontal curves, the findings are likely to be similar along tangent sections. If additional research is performed in this area, it should include new considerations, such as studying the benefits of retroreflectivity when dry conditions are not ideal (e.g., when on-coming vehicles are approaching and nighttime visibility is limited).

Research shows that pavement marking detection distance provides an objective way to measure pavement marking visibility, although it may not be directly tied to a specific driving task. Subjective studies and visibility modeling have been used to determine visibility-derived recommendations for minimum maintained retroreflectivity levels. If additional research in performed in this area, it should include objective human factors testing with an aim to derive replacement retroreflectivity levels.

As more data become available, research on the relationship between retroreflectivity and safety is starting to show consistent evidence that specifying and maintaining adequate pavement marking retroreflectivity can increase safety. Additional research is needed to strengthen the understanding of how specific retroreflectivity levels impact nighttime safety.

Currently, a national model for a performance-based specification for pavement marking retroreflectivity does not exist. While a test method and specification for handheld pavement marking retroreflectivity measurements exist, similar test methods and specifications for mobile equipment do not. There is also no national certification program for mobile retroreflectivity measurements, which are similar to other mobile measurements such as pavement friction.

Wet-retroreflectivity is one of the newest topics of interest for pavement marking performance. The research on its effects show, like dry pavement marking retroreflectivity, that wet pavement marking retroreflectivity performance does not impact operational measures of performance such as vehicle speed or lateral placement. Additional research in this area could include new considerations, such as determining the benefits of retroreflectivity during wet conditions and when driving can be particularly challenging (e.g., driving on undivided highways with opposing vehicle headlamp glare).

Research has shown that dry retroreflectivity is almost always higher than wet retroreflectivity, but wet performance cannot be predicted based on dry retroreflectivity measures. The wet retroreflectivity performance is very dependent on the pavement marking optics. More work is needed to validate appropriate research recommendations for minimum wet retroreflectivity. Additional research is also needed to understand how wet retroreflective pavement marking visibility affects nighttime crashes.

Markings that provide long-lasting wet retroreflectivity performance are not yet widely available. Initial research results with a new, more controlled ASTM test method for measuring the performance of pavement markings under a continuous condition of wetting indicate placing wet-night markings in a groove may be necessary (at least in climates with regular snow plow activities) to help maintain an adequate performance level. The ASTM test method for continuous wetting has recently been approved; however, there are still some concerns about the repeatability of the test method.

Other items in this report include a discussion of the combined impacts of raised pavement markers, pavement marking selection tools, ideas about the future of pavement markings, and a list and brief description of other important aspects of pavement markings.

CHAPTER 2. MUTCD Warrants

Longitudinal pavement markings (center lines, lane lines and edge lines) are a traffic control device and are included in the MUTCD. The MUTCD defines characteristics of pavement markings such as width, pattern, and color. The MUTCD also includes the standards that define when and where pavement markings are used on roadways in the United States.

The 1993 Department of Transportation Appropriations Act directed the FHWA to include warrants for longitudinal pavement markings in the MUTCD. The Markings Technical Committee of the National Committee on Uniform Traffic Control Devices provided FHWA with warrant criteria recommendations based upon available research and engineering judgment for center line and edge line markings. FHWA concluded a series of rulemaking efforts on January 3, 2000, when the final rule modifying the MUTCD was adopted by establishing warrants for center line and edge line longitudinal pavement markings. The warrants are based on traffic volume, functional classification, and roadway width.

Since the pavement marking warrants were added to the MUTCD, several studies have been conducted regarding the safety effect of applying more aggressive criteria than the MUTCD warrants. The most recent study was released in 2013, in which MoDOT investigated the safety effects of striping edge lines on low-volume rural highways (i.e., roadways with annual average daily traffic [AADT] of 400 to 1,000 vehicles per day [vpd]). Prior to this study, MoDOT's policy was to stripe routes with an AADT of 1,000 vpd or greater with both an edge line stripe and a center line, while routes with traffic volume less than 1,000 vpd only had a center line stripe. By adding edge lines to routes with 400 vpd or greater, MoDOT increased the number of miles of fully striped roadways by nearly 7,500 miles.[5]

MoDOT started the additional edge line striping in 2009 and completed it in 2012. One district completed its eligible routes in 2009—the 570 center line miles of highways in that district were used in this study. A total of 576 crashes occurred on these highways from 2006 to 2008. Of these 576 crashes, 105 involved either a fatal or disabling injury crash (35 severe crashes per year). Of the severe crashes, 79 involved the run-off-the-road right crash type. Overall, there were a total of 340 run-off-the-road right crash types in the combined locations.

The after data included years 2010 and 2011. During this two-year span, a total of 327 total crashes occurred, 46 of which involved either a fatal or disabling injury crash (23 severe crashes per year). Of the severe crashes, 31 involved the run-off-the-road right crash type. Overall, there were a total of 173 run-off-the-road right crash types in the combined locations.

Using the empirical Bayes method for analysis, the study showed a 15.2 percent decrease in total crashes for all crash types (significant at the 95 percent confidence level). In addition, severe crashes decreased by 19.3 percent (though this data was not able to gain statistical significance due to the small sample size).

SUMMARY: The MUTCD warranting criteria are based on traffic volume, roadway width, and functional classification. When the MUTCD warranting criteria were drafted, no specific research was available to help set the criteria. For agencies interested in increasing safety on low volumes highways, there is now research suggesting that enhanced safety benefits can be obtained by implementing more aggressive criteria than those currently in the MUTCD. Additional research is needed to assess specific thresholds for defining the added safety.

CHAPTER 3. Pavement Marking Width

In the United States, most longitudinal markings are nominally 4 inches wide. The MUTCD defines the width of a normal pavement marking as 4 to 6 inches, and a wide pavement marking as at least twice the width of a normal marking (at least 8 inches). In practice, however, many agencies consider 6-inch wide longitudinal pavement markings to be wide markings. As demonstrated in this chapter, much of the research on pavement marking width also considers 6-inch pavement markings to be wide.

OPERATIONAL PERFORMANCE

A 2013 study published by FHWA includes a literature review of the impacts of pavement marking width on observed driver speed and lateral placement; however, the findings of the review were inconclusive.(6) The same FHWA report includes a before-and-after study of vehicle speed and vehicle lateral placement approaching and throughout horizontal curves on two-lane highways. The study produced findings similar to the previous research. While some particular instances of either lateral placement and/or change in speed were found to be statistically significant, the findings were not consistent and the magnitude of the change was not deemed practical. For the conditions studied, it appears that wider edge lines had no practical impact in terms of vehicle lateral placement and speed.

***SUMMARY:** Based on the latest research, the width of pavement markings up to 6 inches has negligible impacts on operating speed and lateral placement on two-lane highways. Additional research regarding the operational performance of pavement markings wider than 6 inches or on highways other than two-lane, two-way facilities may be beneficial.*

VISIBILITY

A motorist operating a vehicle uses pavement markings to guide him or her along the roadway. It is generally believed that, to be effective, pavement markings must be easily seen—increasing the width of the markings is one way to increase their visibility. Some agencies have reported that the visual appearance of wider pavement markings is enough to justify their use because the roadway looks better and even safer compared to 4-inch markings.(7) In general, research provides some evidence to suggest that drivers can see wider markings at longer distances. These improvements may improve lane keeping and positively impact safety.

Researchers have performed multiple studies to evaluate pavement marking visibility as it relates to width. The results of pavement marking width studies from the 1980s and early 1990s are inconclusive in terms of identifying visibility gains. Some research showed increased visibility for wider lines,(8,9,10) while other research showed no consistently statistical or practical differences.(11,12) More recent studies have provided more consistent results.

A 1995 study found that increasing pavement markings from 4 inches to 8 inches provides a statistically significant increase in average detection distances for young drivers on a left curve.(8) A 2001 study found that 6-inch markings have a statistically significant improvement over 4-inch markings for detection distances among both older and younger drivers under dry conditions at night.(11) A 1996 simulator study found that 8-inch markings provide a marginal improvement in average detection distance over 4-inch markings for both older and younger drivers at low levels of marking brightness.(14)

A 2006 study found that increasing markings from 4 inches to 6 inches resulted in an increase in detection distance, but found no increase in detection distance when increasing width from 6 inches to 8 inches.(13) A 2010 study comparing various 4 inch and 6 inch markings under wet and dry conditions found that some markings can produce marginal improvements in detection distances under wet conditions.(15) The findings show that the structural design of the marking, combined with the type of retroreflective optics, is an important aspect to understand in terms of the relationship between width and visual nighttime performance under both dry and wet conditions. A 2006 empirical study showed that theoretical calculations of marking detection distance as a function of marking width are invalid, and more work is needed to develop the mathematical relationships between marking width and detection distances.[20]

A 2010 eye-tracking study suggests that increasing edge line width from 4 to 6 to 8 inches along horizontal curves provides a reduced driver workload in the driving environment by providing more time for drivers to focus their foveal (central) vision on critical driving tasks.[16] The same study also determined that brighter pavement markings did not impact driver eye-looking patterns. Combined, these findings suggest that increasing the width of pavement markings may be more valuable than increasing their retroreflective performance—at least above a particular retroreflective threshold that may be adequate.

SUMMARY: *Although the research has some inconsistencies, the most recent studies indicate that wider pavement markings can increase detection distance. Research has shown that wider pavement markings may provide a way to reduce driver workload along horizontal curves. More research is needed to understand the trade-offs between using wider and brighter pavement markings. Increasing pavement marking width may provide more benefits than those gained from installing and/or maintaining markings with relatively high retroreflectivity levels.*

SAFETY

Being perhaps the most important performance indicator of the effect of pavement marking width, safety evaluations have been reported for nearly two decades. In general, as more data are available and more advanced study techniques are implemented, the effect of pavement marking width is better understood; however, the effect of increasing pavement marking width by 2 inches has been elusive. Some agencies have reported that the visual appearance of wider pavement markings is enough to justify their use because the roadway looks safer.[7]

In 1987, a study from Virginia evaluated wider edge lines using a before-and-after approach with run-off-the-road and opposite-direction crashes. The data were from three years prior to installing 8-inch wide edge lines and two years after installation at three test sections.[17,18] The analysis resulted in a 13.6 percent reduction in both run-off-the-road and opposite-direction crashes, which was not statistically significant when compared to the comparison sites. Another 1987 before-and-after crash study conducted in New Mexico suggested that wider lines have no safety benefit in terms of reducing crashes.[15] Both of these studies were hampered by insufficient data.

In 2012, researchers presented the most comprehensive analysis yet of wider pavement markings and their impacts on the frequency and severity of non-intersection/interchange non-winter crashes (in terms of frequency and severity).[29] The analysis excluded intersection and interchange crashes as well as those in the winter months of November through March. Researchers studied the data from two-lane highways from three different States using current statistical analysis techniques to handle the unique characteristics of the data, including differences of how, when, and the extent to which States made the transition to wider lines. Also adding to the challenge was the implementation process and timing of transitioning to wider edge lines in each State.

This detailed approach provided a number of results and while there are minor differences among the results, they all indicate consistent and positive safety effects of wider edge lines on two-lane highways. The crash frequency analysis suggests that wider edge lines are effective in reducing the frequency of crashes on rural two-lane highways, especially with regard to relevant target crashes such as single-vehicle crashes and run-off-the-road crashes.[6]

The same study also tried to identify the safety benefits of pavement markings wider than 4 inches on multilane divided highways. Using similar approaches but with less data, the research failed to produce the same conclusive findings. At the same time, the wider edge line markings were not shown to be a detriment either. One of the possible explanations is the standards to which these different types of roads are built. Since many two-lane highways have lower design standards than multilane facilities, it is not unreasonable to expect that subtle changes like adding 2 inches of pavement marking width will have a measurable impact on the lower standard highways. This is an interesting finding because agencies often prioritize the placement of wider pavement markings on multilane divided highways before their two-lane, two-way highways.

In a follow-up study, researchers developed and compared benefit-cost ratios for wide edge line markings and other low-cost safety countermeasures such as rumble strips and post-mounted delineators.(21) Using earlier research findings,(29) specifically the conclusion that wider edge lines have been shown to reduce total target crashes 15 to 30 percent and fatal plus injury target crashes 15 to 38 percent, the researchers estimated that the benefit-cost ratio for wide edge lines is $33 to $55 for each $1 spent. Coincidentally, this benefit-cost ratio is similar to the benefit-cost ratio for rumble strips alone, although there are obvious differences between the two countermeasures. While rumble strips address crashes where the driver is distracted, drowsy, or inattentive and can be effective even when obscured by snow or rain, wider edge lines seem to be most effective where the driver is looking at the roadway/striping, or where the driver's peripheral vision is detecting the marking.(22)

SUMMARY: Wider edge line pavement markings have been shown to have a positive safety relationship on rural two-lane two-way highways. They also provide a high benefit-cost ratio on these roadways. However, on multilane divided highways, wider pavement markings have not been found to have a significant positive safety impact. The North Carolina Department of Transportation (NCDOT) is currently conducting a follow-up study to validate the safety benefits described for rural two-lane, two-way highways. The research described here provides possible justification for wider edge lines on some roads. Future research could be of interest to determine the safety benefits of wider markings on horizontal curves

CHAPTER 4: Dry Pavement Marking Retroreflectivity

In addition to the width of pavement markings, agencies can also control the retroreflectivity level of markings. Retroreflectivity is a nighttime characteristic of the marking, but since crashes are overrepresented during nighttime conditions, the effect of retroreflectivity is a focus of many research projects. Generally speaking, agencies can specify the retroreflectivity of newly installed markings, which is common. Agencies can also specify the performance level of pavement markings as they wear. While this is not as common as specifying retroreflectivity levels for newly installed markings, the concept is being used more frequently.

The vast majority of specified pavement marking retroreflectivity levels are for dry markings, not wet markings. This section summarizes work related specifically to dry pavement marking retroreflectivity. Wet pavement marking retroreflectivity is the focus of Chapter 5.

OPERATIONAL PERFORMANCE

A 2007 FHWA study reported on the effectiveness of pavement marking delineation on curves to induce consistency in vehicle speed and lateral position based on a nighttime driving experiment.[23] This was a well-controlled field study where conditions of a specific two-lane, two-way rural highway were changed from night to night and participants drove the section in an instrumented vehicle. The research showed that the use of brighter pavement markings (during dry conditions) does not improve speed consistency between an approach tangent and the midpoint of a horizontal curve. The same study showed that the use of brighter pavement markings does not affect the driver lane position differential between an approach tangent and the midpoint of a horizontal curve.

SUMMARY: Pavement marking retroreflectivity has not been shown to impact operational measures of performance such as vehicle speed or lateral placement. While research of this type is generally focused within horizontal curves, there is no reason to think that the findings would be different along tangent sections. If additional research is performed in this area, it should include new considerations (e.g., the benefits of retroreflectivity when dry conditions are not ideal, such as when oncoming vehicles are approaching and nighttime visibility is limited).

VISIBILITY

Pavement marking visibility studies typically use detection distance as the measure of effectiveness. Detection distance has been measured in different ways. In a static setup, the driver counts the number of skip lines visible. In a dynamic setup, where the research participant is driving the vehicle, the driver is tasked with detecting either the beginning or end of a long line, an isolated skip line,[24] or a discontinuity such as a taper.[25] The results are reported in maximum nighttime detection distances.

These studies have repeatedly shown that pavement marking detection distances increase as retroreflectivity increases, but the relationship is not linear.[26,27] In other words, if the retroreflectivity level is doubled, the detection distance will increase, but it will not be doubled. Research findings from a human factors experiment are shown in Figure 1. The research included pavement markings with retroreflectivity levels of 100, 300, and 800 mcd/m^2/lx. For the 100 mcd/m^2/lx marking, the average detection distance was about 300 feet. Increasing the retroreflectivity to 300 mcd/m^2/lx produced about another 100 feet of detection distance, and then increasing the retroreflectivity to 800 produced about another 100 feet of detection distance.

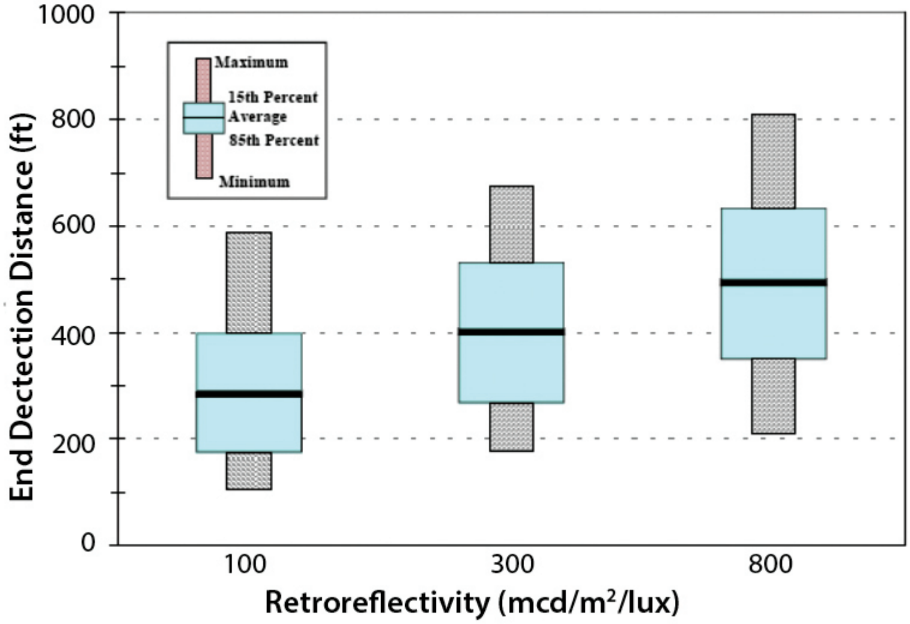

Figure 1. Graph. Pavement marking detection distance as a function of retroreflectivity.[27]

While several studies have been conducted to determine minimum maintained retroreflectivity levels, they have been conducted in different ways. Subjective studies have been performed that use rating of various pavement markings in situ. In these studies, nighttime drives are conducted while the research participant rates the markings. Using measured retroreflectivity levels for the same markings, researchers assess the participants' ratings of the same markings. Most of these types of subjective studies show that markings with retroreflectivity levels of 100 ± 30 mcd/m^2/lx are preferred minimum levels for nighttime driving.[1] Because there is not a definitive minimum retroreflectivity level required for nighttime driving, this value of 100 mcd/m^2/lx has been used several times throughout this report as a reference point to make comparisons and call out important aspects of other research efforts.

As mentioned previously, another way to determine minimum retroreflectivity levels is to use a visibility metric such as the end-detection distance. FHWA's ongoing efforts to revise the MUTCD to add minimum retroreflectivity levels for pavement markings are based on a combination of approaches. The proposed minimum retroreflectivity levels were modeled using a combination of physics associated with retroreflectivity and results from related human factors studies.[28] The FHWA-proposed minimum maintained retroreflectivity levels are visibility derived—in other words, they specify the retroreflectivity that is needed under specific situations to maintain a specified amount of preview time. There is a belief that visibility performance is a reasonable surrogate for safety.

SUMMARY: Pavement marking detection distance provides an objective way to measure pavement marking visibility, although it may not be directly tied to a specific driving task. Subjective studies and visibility modeling have been used to determine visibility-derived recommendations for minimum maintained retroreflectivity levels. If additional research is performed in this area, it should include objective human factors testing with an aim to derive replacement retroreflectivity levels based on nighttime driver needs.

SAFETY

Similar to pavement marking width, pavement marking retroreflectivity and its effect on nighttime crashes has been studied for years. There is a general belief that a positive relationship exists, but researchers have not been able to fully describe it. The amount and quality of retroreflectivity data have been increasing, however, because mobile retroreflectometers have become more prevalent. Some agencies have been collecting system data periodically for nearly a decade, providing researchers more opportunity to discover the impacts of retroreflectivity on safety.

In 2006, researchers in New Zealand studied the safety impacts of brighter pavement markings and reported that there was not a conclusive improvement in safety.(30) This study took advantage of a 1997 policy change in New Zealand that required a minimum maintained retroreflectivity level of 70 mcd/m^2/lx. Using a before-and-after approach, the authors compared crash rates before the change in policy. One assumption of the study was that markings were brighter during the after period. These results may not be directly applicable to the United States, since in New Zealand roadways are delineated as a function of traffic volume. As volumes increase, they progressively apply the following treatments: delineators, center lines, edge lines, and then raised retroreflective pavement markers (RRPMs). Roadways with center lines also have delineators. As a side note, research has shown that supplemental delineation treatments, such as delineators or RRPMs, overpower the potential effect of pavement markings.(31)

Also in 2006, the results of a National Cooperative Highway Research Program (NCHRP) study concluded: "…the difference in safety between new markings and old markings during non-daylight conditions on non-intersection locations is approximately zero."(32) This finding has been discussed and debated for years, and continues to fuel debate in the highway safety space. A close evaluation of the study reveals several points that are worth noting:

- While the study incorporated large amounts of crash data and used contemporary statistical techniques, there were limitations. For instance, the research only included crashes from California and modeled retroreflectivity (no measurements were made).
- While the study included efforts to overcome the possible limitations in modeling retroreflectivity, these efforts presupposed that markings in California reach a value where there is an adverse impact on safety.
- The pavement marking maintenance policy of California is such that higher volume highways are restriped up to three times a year with paint or every two years with thermoplastic markings. As a result, there is only the occasional roadway with retroreflectivity levels below 100 mcd/m^2/lx (in other words, most markings were adequate for nighttime driving).

In addition to the concerns regarding the modeled retroreflectivity levels, the researchers binned the retroreflectivity levels in bins divided in a linear fashion. The lowest bins for the edge lines included retroreflectivity levels from 21 to 183 mcd/m^2/lx, thus including markings ranging from inadequate to adequate in the same bin (according to a synthesis of perception studies reported elsewhere(35)). Eight additional bins included retroreflectivity levels up to 413 mcd/m^2/lx. It might have been more productive to form the bins in a logarithmic function since the performance of retroreflectivity has been repeatedly shown to be best modeled logarithmically rather than linearly.(33,34)

In 2007, researchers reported results from an effort using North Carolina that aimed to develop a statistical association between measured pavement marking retroreflectivity and traffic crash frequency.(36) The results suggest that increased levels of the average pavement marking retroreflectivity on multilane highways may be associated with lower expected target crash frequencies. However, the association was small in magnitude and not statistically significant. On two-lane highways, the association between pavement marking retroreflectivity and crash frequency was larger in magnitude and marginally significant. The retroreflectivity levels used in this study were above 100 mcd/m^2/lx with an overall average of 240 mcd/m^2/lx.

In 2008, a similar effort in Iowa included three years of measured retroreflectivity.(37) These data were analyzed along with crash records from the same year. The distributions and models of the entire database, and a subset including only two-lane highways, did not show that pavement marking retroreflectivity correlated to crash probability. Truncating the data to only records with retroreflectivity values less than 200 mcd/m^2/lx revealed a statistically significant relationship.

In 2010, researchers in Iowa expanded their effort to study the statistical relationship between crashes and longitudinal pavement marking retroreflectivity.(38) While this effort included five years of retroreflectivity data, it was only on certain segments—the crash data set included 1,343 records, which constitutes approximately 1.6 percent of all records statewide. This small sample size was noted as a challenge for the statistical analyses, since the occurrence is a rare event within the whole data set. Retroreflectivity was found to be a significant parameter in the probability of crash occurrence when only data from the interstate roads were analyzed and when the data were divided into three subsets by line type (white edge lines, yellow edge lines, and yellow center lines). In the final set of analyses for white edge lines and yellow center lines, crash occurrence probability was found to increase when longitudinal pavement marking retroreflectivity decreased. While the extent of the study and the data set are not sufficient to identify a definitive relationship, the researchers noted that the results represent a potential relationship that supports additional analyses to link pavement marking retroreflectivity and highway safety through crashes.

Another study on the relationship between retroreflectivity and safety was published in 2013.(39) Using data from Michigan, the researchers evaluated relationships between crashes and longitudinal pavement marking retroreflectivity. The retroreflectivity data consisted of pavement marking measurements representing white edge lines, white lane lines, yellow edge lines, and yellow center lines. The data included crashes and retroreflectivity measurements from 2002 to 2008.

This study only considered nighttime crashes that occurred under dry conditions at non-intersection and non-interchange segments from April through October. The following specific types of crashes were initially identified as target crashes for this study:

- Nighttime.
- Single-vehicle nighttime.
- Fatal plus injury nighttime.
- Single-vehicle nighttime fatal plus injury.

The results were different for yellow center line and white edge lines:

- The effect of retroreflectivity of the yellow center lines on nighttime crashes and single-vehicle nighttime crashes with low retroreflectivity (≤150 mcd/m^2/lx) was found to be statistically significant. The results suggest that expected crash frequency decreases as the center line retroreflectivity increases, specifically in the low range (≤150 mcd/m^2/lx).
- The retroreflectivity for white edge lines was found statistically significant for nighttime crashes and single-vehicle nighttime crashes. The results suggest that the expected crash frequency decreases as the white edge line retroreflectivity increases.

The findings lend support to the positive safety effects of maintaining the retroreflectivity of pavement markings. There was no attempt to develop or validate thresholds of retroreflectivity; however, the findings do provide compelling evidence demonstrating that maintenance of pavement marking retroreflectivity can have a positive effect on safety.

A follow-up analysis of the Michigan data was presented in 2014 with a focus on how the combined associations of edge line and center line retroreflectivity levels relate to nighttime crashes on two-lane rural highways.(40) This study included only two-lane highways (no freeways) and only actual retroreflectivity readings (no imputed retroreflectivity records).

The results of this follow-up work continue to provide evidence that the retroreflectivity of pavement markings relates to safety (this time for two-lane highways in Michigan). In particular, this analysis found that the retroreflectivities of both white edge and yellow center lines jointly contribute to the relationship between nighttime crashes. The relationship was captured by two parameters:

- The sum of the edge line and the center line retroreflectivities.
- The difference of retroreflectivity values (i.e., white–yellow).

The sum of retroreflectivities was found to relate to nighttime crashes in inverse proportion. Conversely, the difference of retroreflectivities was found to relate to night crash frequency in direct proportion. In other words, sites with brighter pavement markings tend to have fewer nighttime crashes.

A follow-up paper published in 2015 builds from the retroreflectivity-safety analysis.[41] Data from North Carolina were obtained and used to continue to evaluate how pavement marking retroreflectivity relates to nighttime safety on rural two-lane highways. The North Carolina data were used to test the robustness of the statistical models derived from the Michigan data. Additional analyses were also explored and described. Using the results from this paper, previous research, and the state of the practice, recommendations and their implications were developed for safety-derived minimum retroreflectivity levels for pavement markings.

SUMMARY: The relationship between pavement marking retroreflectivity and safety has proven elusive. As more data are becoming available, research is beginning to show consistent findings regarding the positive relation between retroreflectivity and nighttime crashes. The research findings described in this section provide consistent evidence that specifying and maintaining adequate pavement marking retroreflectivity can increase safety. However, additional research could potentially strengthen the understanding of how specific retroreflectivity levels impact nighttime safety.

TEST METHODS AND SPECIFICATIONS

The current test method for measuring retroreflectivity under dry conditions is ASTM E1710. This test method states that equipment used to measure pavement marking retroreflectivity has to meet certain criteria, such as having a measurement geometry of 30 meters. ASTM E1710 is written for handheld measurement equipment and includes a precision and bias statement to provide users an indication of the errors associated with such measurements.

While various types of mobile measurement equipment are being used around the United States, there is no national specification for mobile equipment. The Texas Department of Transportation currently requires that all users of mobile retroreflectivity equipment have their equipment and operators certified on an annual basis.

The most common specifications for pavement markings include American Association of State Highway and Transportation Officials (AASHTO) M247, which describes most beads used for pavement markings. In addition, ASTM D7585 includes sampling procedures for inspection of pavement marking retroreflectivity.

A performance-based specification for thermoplastic markings is under development within ASTM D04.38. Discussions have been held to initiate a more comprehensive performance-based specification within ASTM, but the work has not yet started. There is no national model for a performance-based pavement marking specification.

CHAPTER 5: Wet Pavement Marking Retroreflectivity

The interest in pavement marking performance during wet nighttime conditions has increased in recent years. Research on wet retroreflective pavement marking performance was practically nonexistent a decade ago, but more recently a number of efforts have sought to better understand wet retroreflective pavement marking performance. Much of the research is related to visibility gains in wet nighttime conditions and the durability of marking performance in wet nighttime conditions. The potential safety benefits of wet pavement marking retroreflectivity is a topic of recent interest but to date there has not been an established relationship. There are also concerns that increased visibility of markings in wet conditions could potentially result in more drivers going too fast for the wet conditions.

OPERATIONAL PERFORMANCE

In 2013, research documented findings related to speed and lateral placement in active highway work zones, with pavement markings designed to have high-performing wet nighttime retroreflectivity levels. Five test sites were selected in North Carolina and Ohio. The researchers used the vehicle travel speed, rate of lane encroachment, and linear lane displacement to evaluate the effectiveness of the markings. The initial retroreflectivity of the prototype markings was higher than that of comparable markings, but not consistently higher. These findings produced inconclusive results, similar to the results from dry retroreflectivity studies.[(42)]

SUMMARY: Like dry pavement marking retroreflectivity performance, wet pavement marking retroreflectivity performance has not been shown to impact operational measures of performance such as vehicle speed or lateral placement. If additional research is performed in this area, it should include new considerations (e.g., the benefits of retroreflectivity during wet conditions and when driving can be particularly challenging, such as on undivided highways with opposing vehicle headlamp glare).

VISIBILITY

Early studies of wet nighttime pavement marking performance were conducted with the retroreflectivity measurements based on ASTM E2176, which required almost 10 inches of water per hour on the markings during measurements. The more recent studies summarized here have used the superseding test method, ASTM E2832, which is based on 2 inches of water per hour during measurements.

Several significant studies have involved the performance and visibility of pavement markings in wet conditions. One of the initial key studies was conducted in Texas in 2007. This study included visibility measurements of 18 different pavement markings in an intensity-controlled rain tunnel, where participants drove through simulated rain looking for randomly positioned lane line markings.[(12)] The results show that wet retroreflectivity cannot be predicted by dry retroreflectivity. In general, dry retroreflectivity is typically higher than wet retroreflectivity. The study of retroreflectivity, and particularly wet retroreflectivity, is very dependent on the characteristics of the pavement marking materials.

The researchers formatted the results in terms of preview times provided by various pavement markings (and RRPMs). The study produced results showing that pavement markings, even those specifically designed for wet nighttime performance, are not a replacement for RRPMs in terms of visibility and cost of visibility per mile. The costs of the RRPMs were based on surface-applied RRPMs, which are mostly used in areas with no or very little snow plow operations. This study did not include any aspect of durability. All of the markings used were performing as if they were newly installed.

In 2009, researchers reported an evaluation of pavement marking performance using specially designed optics for wet nighttime visibility. This study included three prototype optics-on-paint marking systems employing high-refractive-index, dual-optics, drop-on elements.(43) These markings were evaluated at night under dry, wet-recovery, and continuous wetting conditions. Two commercially available marking systems (one glass beads-on-paint system and one wet-reflective removable tape) were also evaluated as industry benchmarks. Thirty participants driving through simulated work zones on a closed course viewed all of the marking types at night under all three weather conditions. Each driver's task was to identify the direction of work zone lane shift tapers delineated by the markings. In wet recovery, all three prototype marking systems and the wet-reflective tape sustained 60 to 80 percent of their dry average detection distances. In rain, they sustained 50 to 70 percent of their dry average detection distances. In contrast, the average wet-recovery and rain detection distances for the conventional glass beads-on-paint benchmark system dropped to 28 and 17 percent of the dry detection distance, respectively. In addition, participants failed to detect the conventional glass beads-on-paint benchmark system in nearly half of the observations in the rain condition.

A 2012 Virginia study evaluated the detection distance of several pavement marking types in wet conditions.(22) The markings were surface applied, recessed, and installed over a rumble strip (often called a rumble stripe). While there were differences among the pavement marking products studied, the wet nighttime performance of the markings degraded to 100 mcd/m^2/lx or less after the first year. The research team was able to derive a minimum required level for wet nighttime retroreflectivity of 150 mcd/m^2/lx. This level was based on their data and assumptions about how much preview time is needed for safe nighttime driving.

SUMMARY: The dry retroreflectivity performance of a marking does not indicate how the marking will perform under wet conditions. In general, dry retroreflectivity is almost always higher than wet retroreflectivity. The wet retroreflectivity performance is very dependent on the pavement marking optic materials. Additional research will be needed to validate appropriate research recommendations for minimum wet nighttime retroreflectivity. Additional research is also needed to understand how wet retroreflective pavement marking visibility affects nighttime crashes.

DURABILITY

As noted in the previous section, the durability of wet nighttime pavement marking performance has been reported to be relatively short, at least compared to dry pavement marking performance. This is an area where research is just starting to emerge, although several evaluations are currently underway and more results are expected soon.

In Iowa, research was performed in 2011 on 16 variations of pavement markings over a two-year period to assess their performance and durability in wet conditions.(44) The study included yellow edge line and white lane line markings that were both surface applied and recessed. They were measured under dry and wet conditions over a period including two winters. The research found that:

- For the yellow edge line markings, the initial wet retroreflectivity measurements showed that only 7 of the 16 sections measured above 100 mcd/m^2/lx. After one winter, only three sections measured above 100 mcd/m^2/lx. (Again, the performance of these sections is very dependent on the materials used and the application techniques.) After two winters, only two sections measured above 100 mcd/m^2/lx.
- For the white lane line markings, the initial wet retroreflectivity measurements showed that 13 of the 16 sections measured above 100 mcd/m^2/lx. After one winter, six sections measured above 100 mcd/m^2/lx (and all of these were grooved). After two winters, only one section measured above 100 mcd/m^2/lx.
- The results indicate that placing markings in a groove can protect them from plowing operations.

SUMMARY: Markings that provide long-lasting wet retroreflectivity performance are not yet widely available. Even with a new, more controlled ASTM test method for measuring the performance of pavement markings under a continuous condition of wetting, there are some concerns that the durability of markings designed specifically for wet nighttime visibility is too short. Placing markings in a groove can help maintain an adequate performance level in areas with snow plowing operations.

TEST METHODS AND SPECIFICATIONS

In the United States, there are two test methods for measuring wet retroreflectivity:

- ASTM E2177. This test method measures pavement markings in a condition of wetness but not actually being wetted. This test method represents how quickly a pavement marking can recover from the rain.
- ASTM E2832. This test method measures how well markings can perform under a standard condition of wetting (i.e., representing rain conditions). This supersedes ASTM E2176.

Both of these test methods were designed around handheld measurement equipment. Both test methods include a precision and bias statement to provide users an indication of the errors associated with such measurements. There are still some concerns about the repeatability of the test method for continuous wetting.

CHAPTER 6: Combined Impacts of Markers

Pavement markings are intended to provide the road user an indication of lane position and roadway alignment. Under wet nighttime conditions, many traditional pavement markings lose much—if not all—of their retroreflective performance. As noted in the previous chapter, significant progress has been made in terms of developing pavement markings that maintain their dry retroreflectivity performance in various conditions of wetting. However, the traditional way to provide wet nighttime visibility is the use of RRPMs. Research efforts have been undertaken to understand the durability of RRPMs, but little research has been conducted to understand how the performance of RRPMs and pavement markings can be combined.

One of the most recent studies was a multi-phase study commissioned by the FHWA that focused on understanding the combined impacts of center line and edge line pavement marking retroreflectivity and pavement markers.[45, 46, 47] The initial focus of this effort was to determine how the presence of markers might impact the need for various pavement marking retroreflectivity levels.

The first part of the study, published in 2003, consisted of a simulator study designed to address the question, "How much can the retroreflectivity of roadway pavement markings be reduced if raised pavement markers of a certain retroreflectivity are installed on the road?" The researchers discussed the concept of a trading ratio, which refers to trading off the retroreflectivity of markings with the installation of markers. Curve recognition distance was used to determine the trading ratio of markers to marking condition.[45] The study concluded that the trading ratio was 0.55 for yellow center lines on non-freeway roads, which means pavement markings could degrade as much as 45 percent with the addition of pavement markers and still maintain the same overall curve detection distances.

A second simulator experiment, published in 2004, investigated the interaction between center line and edge line luminance on driver curve recognition distances.[46] Just as the addition of pavement markers increases road delineation luminance, the addition of edge lines to center lines also increases the delineation luminance. In a parallel to their previous experiment, the researchers looked for the trading ratio for the addition of edge lines that would allow for degradation in center line retroreflectivity while maintaining the same curve detection distance. The researchers calculated the trading ratio between center lines and edge lines to be 0.41, which means center line luminance may be allowed to degrade by as much as 59 percent with the addition of edge lines, while maintaining the same curve detection distances.

The limited contrasts available with their simulator in both simulator experiments were 150:1, which is "far below those likely to be experienced on a real roadway at night." This limitation in contrast emphasized the need for a field validation study. The researchers conducted the field validation of the two previous experiments.[47] The field study was conducted on a newly constructed highway, not opened to other traffic, and delineated to look like a two-lane rural highway; 12-foot wide lanes matched the lanes used in the two previous simulator studies. The road grade was a constant 0.84 percent downhill, and there was no illumination by fixed roadway lighting. The closed road did have some ambient illumination from nearby buildings and other roads. Six trials were conducted, which took about nine hours per participant over seven nights.

The field validation called into question the use of simulators for pavement marking studies. The researchers found that, because of the limited contrast ratios simulators can project, simulators are poor representations of real-world conditions. The researchers revised the previous simulator findings to say that their trading ratios between center line markers and markings are valid only for markers that are very faded or have low retroreflectivity. In the field, pavement markers were so much brighter than the pavement markings that they produced trading ratios that were practically zero (less than 0.001). In other words, the effect of pavement markers is so much more powerful than pavement markings in curve detection distances that yellow center lines could be allowed to deteriorate by more than 99 percent in retroreflectivity if new pavement markers were added. The researchers therefore questioned the concept of a trading ratio in providing useful engineering information. In general, the issue of "trading" the retroreflectance of longitudinal lines with lines that have pavement markers is not entirely resolved or agreed upon by the research community. Findings from the second simulator study were validated in that low-luminance edge lines combined with low-luminance center lines produced higher curve detection distances than low-luminance center lines alone.

Also in 2004, an NCHRP report was published focusing on the safety effectiveness of snowplowable raised pavement markers on two-lane and four-lane highways.[48] Crash prediction models were developed for various crash types: total, fatal and injury, nighttime, nighttime fatal and injury, daytime, daytime fatal and injury, wet weather, dry weather, and guidance-related. Using data from four northern States, the authors discovered that nonselective use of raised pavement markers on two-lane roadways, overall, does not significantly reduce total or nighttime crashes, nor does it significantly increase these crash types. Mixed results were discovered for selective use (e.g., poor crash history) of raised pavement markers on two-lane roadways. On four-lane freeways, the use of raised pavement markers showed neither a positive nor a negative overall safety effect on total and nighttime crashes. However, some significant reductions were recorded for wet weather crashes at those locations on four-lane freeways, and there are indications that they are only effective in reducing nighttime crashes where the AADT exceeds 20,000 veh/day.

In 2011, researchers measured luminance (instead of retroreflectivity) to assess the visibility of various delineation treatments including pavement markings and markers. To assess their performance, the visibility level was used instead of retroreflectivity. This metric allows the results to be normalized for direct comparison. It can also provide an indication of the impacts of continuous versus intermittent delineation.[49] An example of the results is shown in Figure 2.

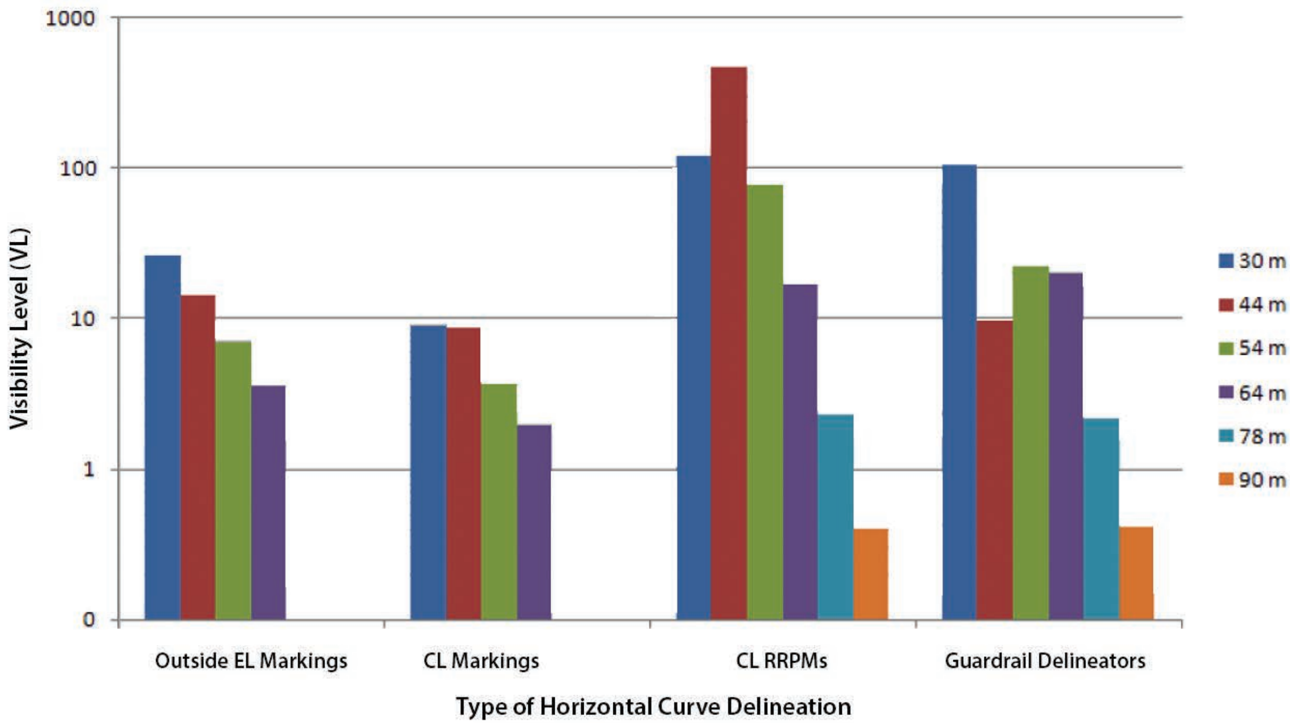

Figure 2. Bar chart. Comparison of visibility by delineation type.[46]

In this example, the markings were applied within the week prior to the measurements using low volatile organic compound paint and Type I AASHTO M247 beads. The RRPMs were non-plowable and were installed in a 0.5-inch deep groove according to the contract specification. The guardrail delineator tabs were the butterfly variety and were seven years old. The results demonstrate the added value of RRPMs for wet nighttime conditions. They also provide some evidence that performance metrics other than retroreflectivity can lead to better understanding the impacts of various delineation treatments such as pavement markings.

SUMMARY: The use of simulators to study the combined impacts of center line and edge line pavement marking retroreflectivity and pavement markers did not result in definitive findings. Additional work from the field suggests that visibility metrics other than retroreflectivity may be more useful to better understand how various delineation treatments perform in terms of providing visibility. Overall, the use of snowplowable markers has been shown to have mostly negligible impact (positive or negative) on nighttime safety. An NCHRP research project is currently being planned that is designed to develop enhanced RRPM recommendations (NCHRP Project 05-21).

CHAPTER 7. Pavement Marking Selection Tools

Research has produced various pavement marking material selection tools.[See references 50 through 55] These studies were generally conducted at the State level and produced recommended marking materials using a matrix of factors. Criteria for marking material selection in the various reports included traffic volume, road surface, environmental conditions, remaining expected road surface life, placement of new markings vs. restriping existing markings, costs, and location of marking.

An FHWA study nearing completion has the goal of developing a pavement marking selection tool to aid in selecting the most appropriate material for a given situation.[50] The report and tool are expected to provide a more effective and uniform guide to select pavement marking material. The tool was designed to take user inputs, perform service life and cost analysis, and then provide recommendations for selecting pavement marking materials. The tool has retroreflectivity degradation factors based on pavement marking test deck data from the National Transportation Product Evaluation Program and other sources in the literature.

The computational procedure of the tool consists of the following steps:

1. A user enters site characteristics, cost data, and material choices for the analysis.
2. A computational engine selects initial retroreflectivity models that fit the site characteristics to estimate initial retroreflectivity values for all the material options. The computed values use the default initial values unless a user provides specific initial values instead.
3. A computational engine selects bi-exponential decay models that fit the site characteristics to estimate the expected service life for each material choice. The expected service life is defined as the time that it takes for the pavement marking retroreflectivity to reach the specified minimum retroreflectivity values. A Solver add-in in Microsoft® Excel® is used to perform this analysis.
4. A computational engine performs cost analysis for each material to estimate the expected unit cost over the remaining road surface life.
5. A computational engine ranks the material by cost within the given constraints. The tool provides the top two cost-effective materials as recommended options.

Figure 3 shows the results screen, which provides the top two materials based on the life cycle cost analysis, given the project characteristics and constraints. Each recommendation includes the expected unit cost of material, expected project cost, annual life-cycle cost, and expected service life of the recommended material.

Recommended Materials

Suggested Marking Material #1	*Waterborne Paint*
Expected Unit cost ($/ft)	*$ 0.200*
Expected Project Cost ($/job)	*$ 5,280*
Life Cycle Cost ($/yr)	*$2,377*
Expected Service Life (months)	*28*

Suggested Marking Material #2	*High Build Paint*
Expected Unit cost ($/ft)	*$ 0.360*
Expected Project Cost ($/job)	*$ 9,504*
Life Cycle Cost ($/yr)	*$4,278*
Expected Service Life (months)	*29*

Figure 3. Screenshot. Results screen. [50]

SUMMARY: Based on the amount of available research on this topic, it is clear that agencies are looking for assistance to select the most appropriate pavement marking materials. The ongoing work described in this chapter provides the most recent and comprehensive pavement marking selection tool. Once the ongoing work is completed and vetted, it will be clear if more work is needed.

CHAPTER 8. Future of Pavement Markings

The most commonly known ongoing work related to pavement markings is the FHWA effort to develop national standards for minimum maintained pavement marking retroreflectivity levels for the MUTCD. In addition, there is interest to determine crash modification factors associated with pavement marking retroreflectivity levels. As connected vehicle and automated vehicle applications and technologies are deployed over the next decade or two, the potential to significantly improve vehicle safety may depend on the use of enhanced or innovative pavement markings.

Connected vehicles are currently one of the main areas of focus of the U.S. Department of Transportation's Intelligent Transportation Systems Joint Program Office (JPO). Connected vehicle safety applications will enable drivers to have 360-degree awareness of hazards and situations they cannot even see. Through in-car warnings, drivers will be alerted to imminent crash situations, such as unintended lane departures, unintended run off the roadway situations, or when a vehicle ahead brakes suddenly. By communicating with enhanced or innovative infrastructure such as pavement markings, drivers will be alerted to potential safety, operational and environment vulnerabilities well in advance, helping them to eliminate or mitigate potentially hazardous situations.

Vehicle manufacturers such as General Motors have reported to Congress that pavement markings are one of the most significant infrastructure elements needed to guide automated vehicles and realize the estimated safety benefits of such vehicles. Knowing that pavement marking is one of the key highway elements used to guide automated vehicles, work is needed to better understand how to quantify characteristics and interactions between onboard sensors and pavement markings so that they will be detectable by the vehicle system in as many conditions as possible—that is, rain, low sun, high glare, and fog. The variety of contrast enhancements used for pavement markings also need to be evaluated—determining how the vehicle systems will read these markings, which are intended to improve human vision but may not be as beneficial for machine vision. Non-reflective raised pavement markers and profiled markings are also of interest.

Another issue of interest is adding more technology to markings to increase their usefulness, such as magnetic markings or markings with Quick Response (QR) codes or radio frequency identification (RFID) tags. These enhanced markings could be used in strategic areas such as in advance of horizontal curves. Vehicles could read these enhanced markings and compute safe speeds for the specific vehicle and specific roadway conditions (as opposed to one advisory speed that does not adapt to vehicles or roadway conditions).

One more area that looks potentially promising is solar roads and digital pavement markings.[56]

CHAPTER 9. Other Topics of Interest

Other topics that are of possible interest but that are not included in this report are:

- **Optics**. Optics include glass beads and other types of retroreflective optics. NCHRP Report 743 describes a test method that can be used to assess the initial quality of Type I beads, but it is not a field test. Field tests are needed. There is also a need to look at some of the specified characteristics of markings—for instance, bead roundness is a specification within M247 , but it seems the specification was written around the distribution of roundness that is typically produced from the process of using recycled glass. Data exist that demonstrate the rounder the glass, the better the retroreflectivity. Other characteristics of M247 should also be reconsidered. In addition, there are characteristics of beads that are not addressed in M247 or elsewhere that are known to impact retroreflective performance, such as inclusions and crazing.
- **Coatings**. Various coatings are used on glass beads to prevent clogging, encourage wicking, and change buoyancy for embedment. There is very limited knowledge in the public domain concerning the effectiveness of these coatings. Field tests would be very useful for inspectors.
- **Binder.** There is a need to determine what types of innovative binders are available to promote durability and bead retention.
- **Texturing**. A variety of texturing techniques are used for markings for various reasons. The effectiveness of the texturing has not been studied.
- **Contrast markings**. There are a variety of ways to add contrast to markings. There is no uniformity across the United States, and there has been little study of the effectiveness of contrast markings.
- **Color.** It has been over a decade since NCHRP Report 484 documented the feasibility of having the United States go to an all-white pavement marking system. The environmental reasons driving the effort have since been resolved, and there seems to be little interest in moving toward an all-white system. However, white markings typically have higher initial and maintained retroreflectivity levels.
- **Eye tracking.** Recent research shows that markings are the focus of unfamiliar drivers as they negotiate horizontal curves, even when there are other in-curve devices present such as chevrons; however, the research was not able to quantify the value of markings due to limited resources. There appears to be promise in using eye trackers to help better understand how drivers use markings to maintain their lane position and prepare for upcoming roadway features such as curves.
- **Heavy metals in glass beads.** While this was an issue a couple of years ago, legislation has passed to place limits on heavy metals. The issue seems to have faded.
- **Measurements of retroreflectivity.** Measuring pavement marking retroreflectivity on profiled markings, rumble stripes, and open-graded and large-aggregate surfaces continues to be a challenge. Wet retroreflectivity measurements are also an issue since they typically require traffic control, which limits their use in specifications.
- **Specifications.** There is some momentum among agencies to move toward a performance-based specification rather than a method-based specification. In a performance-based specification, an agency specifies the minimum retroreflectivity it desires, initially and/or over a specified period (such as a year or more).
- **Photoluminescent markings**. In early 2014, a demonstration project in the Netherlands featured photoluminescent edge line markings. While the demonstration project was popular on social media, little technical information has been released about the markings, such as how the brightness is maintained throughout the night, whether photoluminescence works in wet conditions, and what colors are available besides radioactive green. Additional work is needed to determine the feasibility of photoluminescent markings.

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http://www.safety.fhwa.dot.gov

FHWA Office of Safety
Cathy Satterfield
cathy.satterfield@dot.gov

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