Safety Evaluation of Wet-Reflective Pavement Markings*

PUBLICATION NO. FHWA-HRT-15-065

OCTOBER 2015

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

* Revised 3/12/2019

FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI–PFS). FHWA established this pooled fund study in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program Report 500 guides as part of implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan. The ELCSI-PFS research provides a crash modification factor and benefit-cost economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member States.

The wet-reflective pavement markings evaluated in this study are intended to reduce the frequency of crashes by improving the level of retroreflectivity during wet-road conditions. Geometric, traffic, and crash data were obtained for freeway sections in Minnesota, North Carolina, and Wisconsin; treated two-lane rural road locations in Minnesota; and treated multilane road sections in Wisconsin. For freeways, the combined results for all States indicate reductions in crashes for injury and wet-road crashes. For multilane roads, significant reductions were estimated for total crashes, injury crashes, run-off-road crashes, wet-road crashes, and nighttime crashes. The results suggest that the treatment, even with conservative assumptions about cost, service life, and the value of a statistical life, can be cost effective.

Monique R. Evans, P.E.
Director, Office of Safety
Research and Development

TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-HRT-15-065	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Safety Evaluation of Wet-Reflective Pavement Markings		5. Report Date September 2015
		6. Performing Organization Code
7. Author(s) Craig Lyon, Bhagwant Persaud, and Kimberly Eccles		8. Performing Organization Report No.
9. Performing Organization Name and Address Vanasse Hangen Brustlin, Inc. (VHB) 8300 Boone Blvd., Ste. 700 Vienna, VA 22182-2626 Persaud Lyon, Inc. 87 Elmcrest Road Toronto, Ontario M9C 3R7		10. Work Unit No.
		11. Contract or Grant No. DTFH61-13-D-00001
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Safety Evaluation
		14. Sponsoring Agency Code: FHWA

15. Supplementary Notes. The Federal Highway Administration Office of Safety Research and Development Contract Task Order Manager was Roya Amjadi. The project team members were Craig Lyon, Dr. Bhagwant Persaud, and Kimberly Eccles.

16. Abstract
The Federal Highway Administration organized a pooled fund study of 38 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. One of the strategies selected for evaluation was the application of wet-reflective pavement markings. This strategy involves upgrading existing markings from standard marking materials to wet-reflective markings applied as a paint, tape, or thermoplastic material. The purpose was to provide an improved level of retroreflectivity in wet-road conditions. Geometric, traffic, and crash data were obtained for treated freeway sections in Minnesota, North Carolina, and Wisconsin; treated two-lane rural road locations in Minnesota; and treated multilane road sections in Wisconsin. To account for potential selection bias owing to regression-to-the-mean, an Empirical Bayes (EB) before–after analysis was conducted. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. Intersection-related, snow/slush/ice*, and animal crashes were excluded from the analysis. For freeways, the combined results for all States indicated reductions in crashes that are statistically significant at the 95-percent confidence level for injury and wet-road crashes, with estimated crash modification factors (CMFs) of 0.881 and 0.861, respectively. For multilane roads, statistically significant reductions were estimated for total crashes (CMF = 0.825), injury crashes (CMF = 0.595), run-off-road crashes (CMF = 0.538), wet-road crashes (CMF = 0.751), and nighttime crashes (CMF = 0.696). For two-lane roads, the sample of crashes was too small to detect an effect with statistical significance for any of the crash types, but there were indications that the treatment had a safety benefit for wet-road crashes. Benefit–cost ratios estimated with conservative cost and service life assumptions were 1.45 for freeways and 5.44 for multilane roads. The results suggest that the treatment—even with conservative assumptions on cost, service life, and value of a statistical life—can be cost effective, especially for multilane roads.

17. Key Words: Wet-reflective pavement markings, Low-cost, Safety improvements, Safety evaluations, Empirical Bayesian	18. Distribution Statement No restrictions. This document is available through the National Technical Information Service Springfield, VA 22161. http://www.ntis.gov/about/contact.aspx

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages: 49	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

* Revised 3/12/2019

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	0.305	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	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	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
		NOTE: volumes greater than 1000 L shall be shown in 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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	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	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	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 TABLES

LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
B/C	Benefit–Cost
CMF	Crash Modification Factor
DCMF	Development of Crash Modification Factors
EB	Empirical Bayes
ELCSI–PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
HSIS	Highway Safety Information System*
KABCO	Scale used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only)
MnDOT	Minnesota Department of Transportation
NCDOT	North Carolina Department of Transportation
PDO	Property Damage Only
SPF	Safety Performance Function
USDOT	U.S. Department of Transportation
WisDOT	Wisconsin Department of Transportation

* Revised 3/12/2019

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and to promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements. Thirty-eight State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), which functions under the DCMF program.

One of the strategies selected for evaluation for this study was the application of wet-reflective pavement markings. This strategy involves upgrading existing markings from standard marking materials to wet-reflective markings applied as a paint, tape, or thermoplastic material. These markings are designed to provide an improved level of retroreflectivity during wet-road surface conditions. A literature review found that although there was some cross-sectional research relating retroreflectivity levels to crashes, there was no published research evaluating the effect on crashes after applying wet-reflective markings.

Geometric, traffic, and crash data were obtained for treated freeway sections in Minnesota, North Carolina, and Wisconsin; treated two-lane rural road locations in Minnesota; and treated multilane road sections in Wisconsin. To account for potential selection bias owing to regression-to-the-mean, an Empirical Bayes (EB) before–after analysis was conducted using reference groups of untreated road sections with similar characteristics to the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. The evaluation was done for the following crash types: total, injury, side-swipe same direction, run-off-road, wet-road, wet-road nighttime crashes, and all nighttime crashes. None of these crash types considered intersection-related, snow/slush/ice*, or animal crashes.

For freeways, the combined results for all States indicated reductions in crashes that were statistically significant at the 95-percent confidence level for injury and wet-road crashes, with estimated crash modification factors (CMFs) of 0.881 and 0.861, respectively. For multilane roads, statistically significant reductions were estimated for total crashes (CMF = 0.825), injury crashes (CMF = 0.595), run-off-road crashes (CMF = 0.538), wet-road crashes (CMF = 0.751), and nighttime crashes (CMF = 0.696). For two-lane roads, the sample of crashes was too small to detect an effect with statistical significance for any of the crash types, but there were indications that the treatment had a safety benefit for wet-road crashes*.

B/C ratios estimated with conservative cost and service life assumptions were 1.45 for freeways and 5.44 for multilane roads. With the U.S. Department of Transportation (USDOT) recommended sensitivity analysis, these values could range from 0.83 to 2.04 for freeways and

* Revised 3/12/2019

3.10 to 7.67 for multilane roads.[1] These results suggest that the treatment—even when making conservative assumptions on cost, service life, and value of a statistical life—can be cost effective, especially for multilane roads.

CHAPTER 1. INTRODUCTION

BACKGROUND ON STRATEGY

Although policies vary by jurisdiction, most roadways with any significant volume of traffic have edge lines, center lines, and in the case of multilane roadways, lane lines. These markings provide guidance to drivers on the intended vehicle path. The strategy investigated in this study involves upgrading these existing markings from standard marking materials to wet-reflective markings. Wet-reflective markings are designed to provide an improved level of retroreflectivity during wet road surface conditions. Wet-reflective markings can be applied as a paint, tape, or thermoplastic material.

Glass beads are normally used in pavement markings to reflect light from the headlights back to the driver. They work well when the road surface is dry, but when the surface is wet, the water can act like a mirror, reflecting light in a different direction and often creating glare. New innovative pavement markings include both glass beads and ceramic elements that better reflect light back toward motorists to help them determine locations of driving lanes, edge lines, and merge indicators when they are dry or covered by a thin film of water.(2)

BACKGROUND ON STUDY

FHWA established the DCMF program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promote those strategies for nationwide implementation by providing measures of their safety effectiveness and B/C ratios through research. State transportation* departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements. Thirty-eight State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the ELCSI-PFS, which functions under the DCMF program.

The use of wet-reflective pavement markings was selected as a strategy for evaluation as part of this effort.

LITERATURE REVIEW

A literature review found no published research evaluating the effect on crashes of applying wet-reflective markings. Limited research was available on the relationship between retroreflectivity and crashes in general.

Carlson et al. studied the relationship between crashes and the retroreflectivity readings of edge lines, lane lines, and center lines.(3) Crash types considered were nighttime crashes occurring outside of intersections or interchanges in the non-winter months of April to October. Wet/ice/snow-involved crashes were also excluded. Geometric and retroreflectivity data from Michigan spanning 2002 to 2008 for two-lane roads and freeways were matched to the crash

* Revised 3/12/2019

data. The data were analyzed using negative binomial generalized linear models with blank retroreflectivity readings filled in using average degradation rates and/or information from the closest segment with a reading. For two-lane roads, the effect of yellow line retroreflectivity on nighttime crashes was significant at levels under 150 mcd/m^2/lx and showed crashes decreased as retroreflectivity increased. At higher values, there was no indication of further reduction in crashes. The effect of white edge lines also showed a statistically significant relationship with nighttime crashes and a reduction in crashes with increased retroreflectivity that was not dependent on the range of the level of retroreflectivity used in developing the model. For freeways, the results showed decreases in nighttime crashes when yellow or white edge reflectivity increased. For white lane lines, decreases in nighttime crashes were found when the data were limited to segments with readings less than 200 mcd/m^2/lx.

Smadi et al. investigated the relationship between the retroreflectivity of pavement markings and nighttime run-off-road and cross center line crashes.[(4)] Only rural roadways were considered. Logistic regression modeling was applied to assess the increased probability of a crash when retroreflectivity values were lower. The analysis did not find a correlation between retroreflectivity and crashes except when the level of retroreflectivity was below 200 mcd/m^2/lx. Below that level, an increased probability of a crash was found.

Donnell et al. investigated the relationship between pavement marking retroreflectivity and crashes in North Carolina.[(5)] First, an artificial neural network model was developed to predict the degradation of retroreflectivity over time. Then, the estimated retroreflectivity was combined with road inventory and crash data to estimate target crashes on a monthly basis using cross-sectional regression models. Target crashes were those nighttime crashes related to visibility, including non-work-zone related, non-alcohol related, dry roadway, no roadway contributing circumstance, ran-off-road fixed-object off road, and sideswipe crashes. The results found that on multilane roads with increased retroreflectivity levels for white edge and lane lines, fewer crashes occurred. Where yellow center lines were used, however, an increase in crashes resulted with higher levels of retroreflectivity. For two-lane roads, a decrease in crashes was found for both white edge lines and yellow center lines at higher levels of retroreflectivity, but these results were not statistically significant at the 90-percent confidence level. The findings also indicate that a measureable impact on crashes requires a significant change in retroreflectivity. For instance, a 50-unit increase in the pavement marking retroreflectivity of white edge lines on multilane roadways reduced the expected nighttime target crash frequency by approximately 18 percent. A 50-unit increase in the pavement marking retroreflectivity of white skip lines on multilane highways decreased the expected nighttime target crash frequency by approximately 10 percent. Similarly, a 50-unit increase in the retroreflectivity of yellow edge lines on multilane highways was related to a 35-percent increase in the expected nighttime target crash frequency. Donnell et al. conducted a literature review of several studies but found no relationship between retroreflectivity levels and crashes.[(5)] However, those studies did not account for degradation in retroreflectivity over time.

Bahar et al. developed models of retroreflectivity based on age, color, marker type, climate region, and amount of snow removal.[(6)] These models were then used to evaluate the safety impact of retroreflectivity on nighttime non-intersection/interchange crashes using data from California. The results indicated no relationship between nighttime non-intersection/non-interchange crashes and retroreflectivity level. In reviewing the Bahar et al. report, Carlson et al.

pointed out that California's policy was to restripe higher volume roads up to three times a year with paint and every 2 years with thermoplastic markings.[3] Consequently, few roadways with significant volumes should reach retroreflectivity levels below 100 mcd/m^2/lx, as predicted by the Bahar et al. models applied. Carlson et al. also questioned the grouping of segments that had very low retroreflectivity readings with other segments that had adequate levels of retroreflectivity in the analysis.[3]

CHAPTER 2. OBJECTIVE

This research examined the safety impacts of wet-reflective markings in Minnesota, North Carolina, and Wisconsin. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Intersection-related, animal-related, and ice/snow/sleet-related crashes were excluded. The following target crash types were considered:

- Total crashes (all types and severities combined).
- Injury crashes (K, A, B, and C injuries on the KABCO scale, where K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only).
- Run-off-road crashes (all severities combined).
- Head-on crashes (all severities combined).
- Sideswipe-opposite-direction crashes (all severities combined).
- Sideswipe-same-direction crashes (all severities combined).
- Wet-weather crashes (all types and severities combined).
- Nighttime crashes (all types and severities combined).
- Nighttime wet-weather crashes (all types and severities combined).

The effects for dry-road crashes, which were not specifically evaluated as a target crash type, were inferred from the effects for total and wet-road crashes.

A further objective was to address questions of interest such as the following:

- Do effects vary by roadway type?
- Do effects vary by level of traffic volumes?
- Do effects vary by posted speed limit?
- Do effects vary by horizontal curvature?
- Do effects vary by shoulder width?
- Do effects vary by lane width?
- Do effects vary by the site-specific expected crash frequency prior to treatment?

- What is the overall effect, measured by the economic costs of crashes by crash type and severity?

- What is the B/C value?

The evaluation of overall effectiveness included consideration of the installation costs and crash savings in terms of the B/C ratio.

Meeting these objectives placed some special requirements on the data collection and analysis tasks, including the following:

- Select a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types.

- Identify appropriate untreated reference sites.

- Properly account for changes in safety due to changes in traffic volume and other non-treatment factors.

- Pool data from multiple jurisdictions to improve reliability of the results and facilitate broader applicability of the products of the research.

CHAPTER 3. METHODOLOGY

The EB methodology for observational before–after studies was used for the evaluation. This methodology is considered rigorous in that it accounts for regression-to-the-mean using a reference group of similar but untreated sites. In the process, safety performance functions (SPFs) were used to address the following issues:

- Overcoming the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Accounting for time trends.
- Reducing the level of uncertainty in the estimates of safety effect.
- Properly accounting for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The methodology also provided a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy. The SPFs for roadways without wet-reflective markings were used with observed crash histories to estimate the number of crashes without treatment, and the CMFs developed were applied to this number to estimate the number without treatment.

In the EB approach, the estimated change in safety for a given crash type at a site is given by the equation in figure 1.

$$\Delta Safety = \lambda - \pi$$

Figure 1. Equation. Estimated change in safety.

Where:

λ = Expected number of crashes that would have occurred in the after period without the strategy.
π = Number of reported crashes in the after period.

In estimating λ, the effects of regression-to-the-mean and changes in traffic volume were explicitly accounted for using SPFs, which relate crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (reference sites). Annual SPF multipliers were calibrated to account for temporal effects on safety (e.g., variation in weather, demography, and crash reporting).

In the EB procedure, the SPF was used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed (i.e., reference sites). The sum of these annual SPF estimates (*P*) was then combined with the count of crashes (*x*) in the before period at a strategy site to obtain an estimate of the expected number of crashes (*m*) before the strategy was applied. This estimate of *m* was calculated using the equation in figure 2.

$$m = w(P) + (1 - w)(x)$$

Figure 2. Equation. Empirical Bayes estimate of expected crashes.

Where the EB weight, *w*, was estimated from the mean and variance of the SPF estimate using the equation in figure 3.

$$w = \frac{1}{1 + kP}$$

Figure 3. Equation. Empirical Bayes weight.

Where:

k = Constant for a given model and is estimated from the SPF calibration.

In the SPF calibration process, a negative binomial distributed error structure was assumed with *k* being the overdispersion parameter of this distribution.

A factor was then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor was the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, was an estimate of λ. The procedure also produced an estimate of the variance of λ.

The estimate of λ was then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes observed during the after period in that group (π_{sum}). The variance of λ was also summed over all sites in the strategy group.

The index of effectiveness (θ) was estimated using the equation in figure 4.

$$\theta = \frac{\pi_{sum} / \lambda_{sum}}{1 + \left(Var(\lambda_{sum}) / \lambda_{sum}^2 \right)}$$

Figure 4. Equation. Index of effectiveness.

The standard deviation of θ was given by the equation in figure 5.

$$StDev(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)^2}}$$

Figure 5. Equation. Standard deviation of index of effectiveness.

The percent change in crashes is calculated as $100(1 - \theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

CHAPTER 4. DATA COLLECTION

Minnesota, North Carolina, and Wisconsin provided data containing locations and dates of the installation of wet-reflective markings. Reference sites were also identified in each State that were similar to the treated sites in terms of traffic volumes and roadway geometry but had standard lane markings. These States also provided roadway geometry, traffic volumes, crash data, and information on other construction activities for both installation and reference sites. This section summarizes the data assembled for the analysis.

MINNESOTA

Installation Data

The Minnesota Department of Transportation (MnDOT) provided a list of installations of wet-reflective markings along two-lane roadways and freeways with the year of installation. Data for the installation year were excluded from the analysis. The total length of installations used for this study was 771 mi. The installation information included the route number, milepost, construction period and, where available, whether the markings were used on the center line, edge line, or lane lines. MnDOT applied 3M™ and Epoplex® wet-reflective products.

No other construction activities were reported at these locations.

Reference Sites

Reference sites were identified by selecting two-lane roadways and freeways with characteristics similar to the treated sites. Although no electronic record of pavement marking type was available, MnDOT officials stated that unless the location was in the treatment site data, the markings would not be of a wet-reflective type.

Roadway Data

Roadway data were obtained from the Highway Safety Information System* (HSIS) for 2003 to 2012. Roadway data included the following variables:

- Roadway class.
- Area type (urban/rural).
- Shoulder width.
- Shoulder type.
- Median width.
- Number of lanes.

Traffic Data

Traffic data were obtained from HSIS for 2003 to 2012 in the form of average annual daily traffic (AADT).

* Revised 3/12/2019

Crash Data

Crash data were obtained from HSIS for 2003 to 2012, including many variables related to the location, time, and characteristics of each crash.

Treatment Cost Data

MnDOT provided estimated cost information of $8,500/mi for ground-in markings and $1,900/mi for striping. These costs are per center line mile and would be doubled to $17,000 and $3,800/mi, respectively, for the four-lane freeway locations.

MnDOT uses a recommended service life of 2 years for pavement markings.

NORTH CAROLINA

Installation Data

The North Carolina Department of Transportation (NCDOT) provided a list of projects that placed wet-reflective markings on the edge line and/or lane lines on urban and rural freeways. The total length of roadway installations used in this study was 95 mi. Among the data provided by the reports were the location (including district, State route number, and mileposts) and the construction dates. Data for the installation year were excluded from the analysis. The records also indicated whether the wet-reflective markings were applied as a restriping project or as part of a resurfacing project.

The following three products were applied:

- Glomarc® 90 manufactured by Epoplex®.
- LS90™ manufactured by Epoplex®.
- Liquid Pavement Marking Series 1200 manufactured by 3M™.

No other construction activities were reported at these locations.

Reference Sites

NCDOT also provided a list of locations that received standard pavement markings, which was used to identify reference sites. The list was further reduced by including only those sites whose roadway class was indicated as being urban or rural freeway.

Roadway Data

Roadway inventory data were obtained from the HSIS for 1998 to 2012. Roadway data included the following variables:

- Area type (urban/rural).
- Functional class.
- Divided versus undivided.
- Median width.

- Terrain.
- Number of lanes.
- Surface width.
- Shoulder type.
- Shoulder width.
- Surface type.
- Speed limit.

Traffic Data

Traffic data were obtained from HSIS for 1998 to 2012 in the form of AADT and percentage of trucks.

Crash Data

Crash data were obtained from HSIS for 1998 to 2012, including many variables related to the location, time, and characteristics of each crash.

Treatment Cost Data

NCDOT provided approximate installation costs of $1.10 and $2.25 per linear ft for polyurea and tape, respectively. The equation in figure 6 is the basis for calculating the cost:

$$\text{Cost per mile} = \text{unit cost per foot} \times 5{,}280 \times (4 + \text{number of skip lines} \times 0.25)$$

Figure 6. Equation. Calculation for treatment costs in North Carolina.

This cost includes marking the four edge lines with a constant application and the skip lines, which cover a quarter of the pavement in marking material. A 4-lane road will have 2 skip lines, a 6-lane road will have 4 skip lines, an 8-lane road will have 6 skip lines, and a 10-lane road will have 8 skip lines.

Service life estimates provided by NCDOT are less than 5 years for tape and 8 years for sprayed polyurea with high initial retroreflectivity values.

WISCONSIN

Installation Data

The Wisconsin Department of Transportation (WisDOT) provided a list of projects in which wet-reflective markings were placed on urban and rural freeways and multilane divided roadways. The total length of roadway installations used in this study was 300 mi. Among the data provided by the reports were the location (linkable to the WisDOT Metamanager data system) and the construction dates. Data for the installation year were excluded from the analysis.

WisDOT applied the following two wet-reflective marking products:

- 380WR marking tape manufactured by 3M™.

- A380AW marking tape manufactured by 3M™.

These markings were installed on the lane lines only. Approximately 50 of the 300 mi used for analysis had shoulder widening and/or shoulder rumble strips installed at the same time. These locations were mostly on freeways. No further construction was reported on these road segments by WisDOT during the study period.

Reference Sites

Reference sites were identified by using those locations that received the wet-reflective markings after the treatment sites used in this study. The sum of reference site mi was 341 mi.

Roadway Data

Roadway inventory data were obtained from the Metamanager system maintained by WisDOT for 2003 to 2012. The data are bidirectional, meaning that unlike the data for Minnesota and North Carolina, each record was for only one direction of travel. Roadway data included the following variables:

- Area type (urban/rural).
- Functional class.
- Divided versus undivided.
- Median width.
- Median type.
- Number of lanes.
- Traveled way width.
- Shoulder type.
- Shoulder width.
- Paved shoulder width.
- Presence of rumble strip.

Traffic Data

The project team obtained traffic data in the form of AADT from WisDOT for 2012 and a projected AADT for 10 years out. WisDOT recommended extrapolating the AADTs for previous years. The percentage of trucks in the traffic stream was also provided.

Crash Data

WisDOT provided crash data for 2003 to 2012 for all treatment and reference sites. The compiled crash data contained many variables related to the location, time, and characteristics of each crash.

Treatment Cost Data

The following costs were provided by WisDOT based on average bid prices on 2012, 2013, and 2014 projects:

- Inlaid into asphalt 4-inch tape—$5,800/mi for single lane line mi.
- Inlaid into asphalt 8-inch tape, placed mainly at ramp gores/channelizing lines—$5,800 per gore.
- Grooved white 4-inch tape—$5,800/mile for single lane line.
- Grooved white 8-inch tape –$5,000 per ramp gore.
- Grooved contrast 4-inch tape—$9,200/mi for single lane line mile.
- Grooved contrast 8-inch tape—$7,300 per gore ramp.

A service life of 8 years was assumed for the grooved treatment. The tape product has only been available for a few years, so the wet reflectivity service life and durability is still unknown.

DATA CHARACTERISTICS AND SUMMARY

Table 1 defines the crash types used by each State. An attempt was made to make the crash type definitions consistent. In all States, intersection-related, animal-related, and snow/slush/ice-related crashes were excluded because these crash types were not correctable by the treatment under study.

Table 2 provides summary information for the data collected for the treatment sites. The information in table 2 should not be used to make simple before–after comparisons of crashes per mi-year because such comparisons would not account for factors, other than the strategy, that may cause a change in safety between the before and after periods. Such comparisons are properly done with the EB analysis as presented later in this report.

Table 3 provides summary information for the reference site data. Comparisons of crash rates between States and between treatment and reference sites should consider that the rates were only per mile and traffic volumes were not considered.

Table 1. Definitions of crash types by State.

Crash Type	Minnesota	North Carolina	Wisconsin
Total	Identified as non-intersection; not animal; and not snow, slush, or ice	Identified as non-intersection and not animal and not snow, slush, or ice	Identified as non-intersection related; not deer or other animal: and not snow, slush, or ice
Injury	Resulted in an injury or possible injury	Resulted in an injury or possible injury	Resulted in a fatality or injury
Run-off-road	Diagram of accident is run-off-road-left or run-off-road-right	Accident type is run-off-road	Relation to Roadway is median, outside shoulder left, outside shoulder right, or off roadway location unknown
Sideswipe-same-direction	Diagram of accident is sideswipe-passing	Accident type is sideswipe-same-direction	Manner of Collision is sideswipe-same-direction
Sideswipe-opposite-direction	Diagram of accident is sideswipe-opposing	Accident type is sideswipe-opposite-direction	Manner of Collision is sideswipe-opposite-direction
Head-on	Diagram of accident is head-on	Accident type is head-on	Manner of Collision is head-on
Wet-road	Road Surface Condition is wet or water (standing or moving)	Road Surface Condition is wet	Road Surface Condition is wet
Nighttime	Light Condition is dark	Light Condition is dark	Light Condition is dark
Nighttime wet-road	Light Condition is dark and Road Surface Condition is wet or water (standing or moving)	Light Condition is dark and Road Surface Condition is wet	Light Condition is dark and Road Condition is wet

Table 2. Data summary for treatment sites.

Variable	Minnesota Freeway	Minnesota Two-Lane Undivided	North Carolina Freeway	Wisconsin Freeway	Wisconsin Multilane
Number of mi	34.49	736.39	95.41	179.09	120.74
Mi-years before	172.44	5,539.77	823.03	975.06	551.05
Mi-years after	137.95	1,087.75	512.67	375.96	226.49
Crashes/mi/year before	0.71	0.20	3.84	5.42	2.81
Crashes/mi/year after	0.78	0.16	5.04	3.66	2.10
Injury crashes/mi/year before	0.31	0.10	1.31	1.81	1.02
Injury crashes/mi/year after	0.32	0.08	1.24	1.10	0.69
Run-off-road crashes/mi/year before	0.30	0.09	0.16	0.93	0.24
Run-off-road crashes/mi/year after	0.49	0.07	0.26	0.68	0.27
Head-on crashes/mi/year before	0.01	0.01	0.002	0.02	0.03
Head-on crashes/mi/year after	0.01	0.01	0.014	0.01	0.01
Sideswipe-same-direction crashes/mi/year before	0.05	0.01	0.39	0.79	0.42
Sideswipe-same-direction crashes/mi/year after	0.09	0.01	0.76	0.61	0.42
Sideswipe-opposite-direction crashes/mi/year before	0.01	0.004	0.01	0.02	0.03
Sideswipe-opposite-direction crashes/mi/year after	0.01	0.005	0.01	0.01	0.01
Wet-road crashes/mi/year before	0.07	0.03	0.92	1.17	0.49
Wet-road crashes/mi/year after	0.07	0.02	1.04	0.62	0.31
Nighttime crashes/mi/year before	0.31	0.07	1.01	1.41	0.55
Nighttime crashes/mi/year after	0.22	0.05	1.30	1.02	0.42
Nighttime Wet-road crashes/mi/year before	0.03	0.01	0.24	0.16	0.05
Nighttime Wet-road crashes/mi/year after	0.04	0.01	0.33	0.20	0.08
AADT after[1]	Avg: 15,352 Min: 14,236 Max: 17,775	Avg: 2,202 Min: 39 Max: 13,779	Avg: 47,943 Min: 10,333 Max: 124,214	Avg 19,178 Min: 3,178 Max: 78,335	Avg: 7,274 Min: 1,353 Max: 25,381
Average right shoulder width (ft)	Avg: 8.34 Min: 8.00 Max: 10.00	Avg: 5.25 Min: 0.00 Max: 10.00	Avg: 11.34 Min: 5.00 Max: 19.00	Avg: 11.29 Min: 3.00 Max: 18.00	Avg: 7.92 Min: 0.00 Max: 15.00
Average left shoulder width (ft)	Avg: 3.00 Min: 3.00 Max: 3.00	Avg: 5.25 Min: 0.00 Max: 10.00	Avg: 10.98 Min: 0.00 Max: 14.00	Avg: 7.03 Min: 0.00 Max: 23.00	Avg: 5.12 Min: 0.00 Max: 26.00
Number of lanes	Avg: 4.00 Min: 4.00 Max: 4.00	Avg: 2.00 Min: 2.00 Max: 2.00	Avg: 4.77 Min: 4.00 Max: 10.00	Avg: 4.00 Min: 4.28 Max: 6.00	Avg: 4.18 Min: 2.00 Max: 6.00
Posted speed limit (mi/h)	N/A	N/A	Avg: 64.64 Min: 55.00 Max 70.00	N/A	N/A

Variable	Minnesota Freeway	Minnesota Two-Lane Undivided	North Carolina Freeway	Wisconsin Freeway	Wisconsin Multilane
Surface width (ft)	N/A	N/A	Avg: 30.28 Min: 24.00 Max 96.00	N/A	N/A
Median width (ft)	Avg: 54.00 Min: 54.00 Max: 54.00	Avg 0.00 Min 0.00 Max 0.00	Avg 29.48 Min 0.00 Max 110.00	Avg 42.80 Min 0.00 Max 350.00	Avg 34.94 Min 0.00 Max 380.00
Area type (mi)	Urban: 1.731 Rural: 32.759	Urban: 37.41 Rural: 698.98	Urban: 18.12 Rural: 77.29	Urban: 76.28 Rural: 102.82	Urban: 36.39 Rural: 84.36
Terrain (mi)	N/A	N/A	Flat: 17.86 Rolling: 62.56 Mountainous: 14.99	N/A	N/A

[1]The AADT data provided for Wisconsin were for one direction.
Avg = Average.
Min = Minimum.
Max = Maximum.
N/A = Not applicable.

Table 3. Data summary for reference sites.

Variable	Minnesota Freeway	Minnesota Two-Lane Undivided	North Carolina Freeway	Wisconsin Freeway	Wisconsin Multilane
Number of mi	852.04	9,037.40	231.47	121.27	48.99
Mi-years	8,520.42	90,374.00	3,472.05	919.72	394.86
Crashes/mi/year	6.27	0.10	9.01	3.72	3.12
Injury crashes/mi/year	1.71	0.05	2.85	1.21	1.37
Run-off-road crashes/mi/year	1.14	0.05	1.19	0.64	0.36
Head-on crashes/mi/year	0.06	0.004	0.02	0.02	0.03
Sideswipe-same-direction crashes/mi/year	0.95	0.01	1.44	0.56	0.44
Sideswipe-opposite-direction crashes/mi/year	0.01	0.003	0.01	0.01	0.04
Wet-road crashes/mi/year	1.15	0.01	2.01	0.71	0.59
Nighttime crashes/mi/year	1.47	0.03	2.36	1.06	0.70
Nighttime Wet-road crashes/mi/year	0.34	0.01	0.59	0.15	0.10
AADT[1]	Avg: 62,893 Min: 6,038 Max: 197,250	Avg: 1,637 Min: 100 Max: 16,135	Avg: 60,493 Min: 13,000 Max: 163,000	Avg: 16,898 Min: 4,478 Max: 78,335	Avg: 9,233 Min: 1,813 Max: 30,314
Average right shoulder width (ft)	Avg: 9.68 Min: 0.00 Max: 13.00	Avg: 4.46 Min: 0.00 Max: 17.00	Avg: 11.32 Min: 0.00 Max: 22.00	Avg: 11.27 Min: 0.00 Max: 17.00	Avg: 9.33 Min: 0.00 Max: 14.00
Average left shoulder width (ft.)	Avg: 5.43 Min: 0.00 Max: 15.00	Avg: 4.44 Min: 0.00 Max: 17.00	Avg: 10.36 Min: 0.00 Max: 14.00	Avg: 6.99 Min: 0.00 Max: 22.00	Avg: 4.58 Min: 0.00 Max: 12.00
Number of lanes	Avg: 5.00 Min: 4.00 Max: 10.00	Avg: 2.00 Min: 2.00 Max: 2.00	Avg: 4.98 Min: 4.00 Max: 16.00	Avg: 4.22 Min: 4.00 Max: 8.00	Avg: 4.16 Min: 2.00 Max: 6.00
Posted speed limit (mi/h)	N/A	N/A	Avg: 62.63 Min: 35.00 Max: 70.00	N/A	N/A
Surface width (ft)	N/A	N/A	Avg: 32.46 Min: 24.00 Max: 96.00	N/A	N/A
Median width (ft)	Avg: 32.68 Min: 2.00 Max: 84.00	Avg: 0.00 Min: 0.00 Max: 0.00	Avg: 24.61 Min: 0.00 Max: 110.00	Avg: 44.92 Min: 0.00 Max: 220.00	Avg: 14.54 Min: 0.00 Max: 120.00
Area type (mi)	Urban: 266.32 Rural: 585.72	Urban: 253.11 Rural: 8,784.29	Urban: 84.91 Rural: 146.56	Urban: 60.70 Rural: 60.57	Urban: 22.20 Rural: 26.79
Terrain (mi)	N/A	N/A	Flat: 0.00 Rolling: 215.80 Mountainous: 15.67	N/A	N/A

[1]The AADT data for Wisconsin were for one direction.
Avg = Average.
Min = Minimum.
Max = Maximum.
N/A = Not applicable.

CHAPTER 5. DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This section presents the SPFs developed for each State. The SPFs were used in the EB methodology to estimate the safety effectiveness of this strategy.[7] Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. In specifying a negative binomial error structure, the overdispersion parameter, *k*, was estimated iteratively from the model and the data. For a given dataset, smaller values of *k* indicate relatively better models.

SPFs were calibrated separately for Minnesota, North Carolina, and Wisconsin using the corresponding reference sites from each State. The SPFs developed are presented by State in the following sections. Urban and rural segments were combined for modeling because of the limited sample sizes, particularly for some crash types. Factor variables were attempted for all models to account for any differences between urban and rural areas in terms of expected crashes.

Note that for sideswipe-opposite-direction crashes the number of crashes was very low, and these crashes were not analyzed.

NORTH CAROLINA

The form of the SPFs for North Carolina freeways, which are presented in table 4, is shown in figure 7.

$$\text{Crashes/mi/year} = \exp^{(a)} AADT^{b} \exp^{(lanes*c+medwid*d+URBRUR*e)}$$

Figure 7. Equation. Form of SPFs for North Carolina.

Where:

AADT = Average annual daily traffic volume.
lanes = 1 if a four-lane road; 0 if greater than four lanes.
medwid = Median width in ft.
URBRUR = 1 if urban; 0 if rural.
a, b, c, d, e = Parameters estimated in the SPF calibration process.
k = Overdispersion parameter of the model.

Table 4. North Carolina freeway SPFs.

Crash Type	Parameter Estimates (Standard Error)					
	a	***b***	***c***	***d***	***e***	***k***
Total	-11.5356 (1.4658)	1.3273 (0.1286)	-0.2662 (0.1664)	-0.0130 (0.0039)	—	1.5431
Injury	-12.6811 (1.3749)	1.3152 (0.1201)	-0.2428 (0.1571)	-0.0094 (0.0036)	—	1.2591
Run-off-road	-7.5439 (1.9691)	0.6848 (0.1802)	-0.5109 (0.1953)	-0.0083 (0.0053)	0.7401 (0.1926)	1.6316
Sideswipe-same-direction	-20.6539 (0.9716)	1.9422 (0.0901)	—	—	—	0.9485
Wet-road	-7.2571 (1.5024)	0.8176 (0.1313)	-0.6663 (0.1651)	-0.0130 (0.0045)	—	1.5109
Nighttime	-10.9313 (1.3845)	1.1479 (0.1212)	-0.2865 (0.1572)	-0.0117 (0.0037)	—	1.2428
Nighttime wet-road	-9.0525 (1.5366)	0.8603 (0.1341)	-0.5965 (0.1683)	-0.0119 (0.0044)	—	1.1739

— Indicates that the variable associated with parameter was not included in the SPF.

WISCONSIN

In Wisconsin the data were directional, so the SPFs apply to one direction of travel only. The form of the SPFs for Wisconsin, which are presented in table 5 for freeways and table 6 for multilane roads, is shown in figure 8.

$$\text{Crashes/mi/year} = \exp^{(a)} AADT^{b} \exp^{(lshtotwd*c+rsl*d)}$$

Figure 8. Equation. Form of SPFs for Wisconsin.

Where:

AADT = Average annual daily traffic volume.
lshtotwd = Total width left shoulder in feet.
rsl = 0 if rumble strip is present on left shoulder; 1 if not present (only applies for freeways).
a, b, c, d = Parameters estimated in the SPF calibration process.
k = Overdispersion parameter of the model.

Table 5. Wisconsin freeway SPFs.

Crash Type	Parameter Estimates (Standard Error)				
	a	*b*	*c*	*d*	*k*
Total	-14.4921 (0.9000)	1.6163 (0.0915)	-0.1155 (0.0218)	0.1729 (0.1369)	0.5117
Injury	-15.4639 (1.0433)	1.6091 (0.1050)	-0.1250 (0.0252)	0.2276 (0.1521)	0.4627
Run-off-road	-6.5392 (1.0811)	0.6094 (0.1097)	-0.0548 (0.0265)	0.2825 (0.1457)	0.3635
Sideswipe-same-direction	-20.4391 (1.2177)	2.0075 (0.1159)	-0.0943 (0.0258)	—	0.3287
Wet-road	-17.3779 (1.2207)	1.7533 (0.1182)	-0.1301 (0.0294)	—	0.6121
Nighttime	-14.6122 (1.1014)	1.4966 (0.1100)	-0.1220 (0.0251)	0.4171 (0.1615)	0.4998
Nighttime wet-road	-18.2917 (1.9027)	1.7034 (0.1786)	-0.1354 (0.0411)	—	0.5154

— Indicates that the variable associated with parameter was not included in the SPF.

Table 6. Wisconsin multilane divided SPFs.

Crash Type	Parameter Estimates (standard error)			
	a	*b*	*c*	*k*
Total	-11.1106 (1.6615)	1.3452 (0.1723)	-0.2588 (0.0326)	0.5833
Injury	-11.1247 (2.2012)	1.2609 (0.2273)	-0.2642 (0.0424)	0.7870
Run-off-road	-7.1200 (1.5806)	0.5964 (0.1740)	—	0.2558
Sideswipe-same-direction	-14.1156 (2.5936)	1.4600 (0.2686)	-0.2794 (0.0407)	0.2880
Wet-road	-15.6008 (3.1910)	1.6419 (0.3310)	-0.2483 (0.0528)	1.0507
Nighttime	-12.0965 (2.1780)	1.2711 (0.2257)	-0.1661 (0.0380)	0.4843
Nighttime wet-road	-19.8380 (4.2743)	1.8316 (0.4600)	—	1.8614

— Indicates that the variable associated with parameter was not included in the SPF.

MINNESOTA

The form of the SPFs for Minnesota, which are presented in table 7 and table 8, is shown in figure 9:

$$\text{Crashes/mi/year} = \exp^{(a)} AADT^{b} \exp^{(URBRUR*c+AVGSHLD*d)}$$

Figure 9. Equation. Form of SPFs for Minnesota.

Where:

AADT = Average annual daily traffic volume.
URBRUR = 1 if Urban area; 0 if Rural.
AVGSHLD = Average shoulder width in feet.
a, b, c, d = Parameters estimated in the SPF calibration process.
k = Overdispersion parameter of the model.

Table 7. Minnesota freeway SPFs.

Crash Type	Parameter Estimates (Standard Error)				
	a	***b***	***C***	***d***	***k***
Total	-14.3723 (0.4805)	1.5230 (0.0508)	0.3279 (0.0975)	-0.0396 (0.0138)	0.5708
Injury	-14.5068 (0.5238)	1.4270 (0.0551)	0.2286 (0.1045)	-0.0408 (0.0141)	0.5316
Run-off-road	-10.0870 (0.3655)	1.0144 (0.0367)	—	-0.0427 (0.0142)	0.5299
Sideswipe-same-direction	-17.6510 (0.6394)	1.6061 (0.0642)	0.5061 (0.1239)	—	0.6457
Wet-road	-16.8656 (0.6190)	1.6012 (0.0643)	0.4080 (0.1211)	-0.0558 (0.0158)	0.6772
Nighttime	-15.4123 (0.5732)	1.4999 (0.0599)	0.1988 (0.1152)	-0.0435 (0.0152)	0.6361
Nighttime wet-road	-18.7804 (0.8346)	1.6686 (0.0852)	0.4004 (0.1615)	-0.0657 (0.0185)	0.8175

— Indicates that the variable associated with parameter was not included in the SPF.

Table 8. Minnesota two-lane undivided SPFs.

Crash Type	Parameter Estimates (Standard Error)				
	a	***b***	***c***	***d***	***k***
Total	-8.3936 (0.1057)	0.9379 (0.0158)	0.5104 (0.0577)	-0.0843 (0.0055)	0.4390
Injury	-8.1365 (0.1298)	0.7822 (0.0197)	0.3747 (0.0730)	-0.0512 (0.0070)	0.4106
Run-off-road	-7.1823 (0.1337)	0.6443 (0.0208)	-0.2317 (0.0911)	-0.0406 (0.0076)	0.5454
Sideswipe-same-direction	-14.9362 (0.4288)	1.4366 (0.0584)	0.6093 (0.1558)	-0.1260 (0.0168)	1.1590
Wet-road	-11.1087 (0.2432)	1.0215 (0.0353)	0.7042 (0.1066)	-0.0828 (0.0114)	0.5333
Nighttime	-8.4612 (0.1569)	0.7791 (0.0237)	0.4400 (0.0849)	-0.0738 (0.0084)	0.4770
Nighttime wet-road	Use model for total with factor of 0.050				
Head-on	Use model for total with factor of 0.040				
Sideswipe-opposite-direction	Use model for total with factor of 0.034				

Because models for nighttime wet-road, head-on, and sideswipe-opposite-direction crashes could not be calibrated because of low numbers of crashes, predictions for those crash types used the model for total crashes with a multiplier for the proportion of total crashes that were of the respective crash type.

CHAPTER 6. BEFORE–AFTER EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 9 through table 14 provide the estimates of expected crashes in the after period without treatment, the observed crashes in the after period, and the estimated CMF and its standard error for all crash types considered. Sideswipe-opposite-direction crashes were not analyzed because of the very low number of crashes. The effects for dry-road crashes, which were not specifically evaluated as a target crash type, were inferred from the effects for total and wet-road crashes; they are shown in these tables for information purposes. Results are provided separately for each State as well as all States combined. All results obtained are reported in this section. Recommended CMFs are presented in chapter 8.

The results for North Carolina freeways in table 9 indicate reductions for injury, wet-road, and nighttime wet-road crashes although only the reductions for injury and wet-road crashes were statistically significant at the 95-percent confidence level. All other crash types indicate a slight increase in crashes, but only the increase for dry-road was statistically significant.

Table 9. Results for North Carolina freeways.

Metric	Total	Injury	Run-Off-Road	Sideswipe-Same-Direction	Wet-Road	Dry-Road	Nighttime	Nighttime Wet-Road
EB estimate of crashes expected in after period without strategy	2,502.24	727.42	124.21	388.47	615.70	1,886.53	637.75	183.27
Number of crashes observed in after period	2,583	634	135	392	532	2,051	664	167
Estimate of CMF	1.032	**0.871**	1.081	1.006	**0.863**	**1.087**	1.040	0.907
Standard error of estimate of CMF	0.028	**0.044**	0.122	0.073	**0.051**	**0.034**	0.055	0.093

Note: CMF estimates that are statistically significant at the 95-percent confidence level are shown in boldface.

The results for Wisconsin freeways in table 10 indicate reductions for total, injury, run-off-road, wet-road, dry-road, and nighttime crashes that are all statistically significant at the 95-percent confidence level. Sideswipe-same-direction and nighttime wet-road crashes had non-statistically significant increases.

Table 10. Results for Wisconsin freeways.

Metric	Total	Injury	Run-Off-Road	Sideswipe-Same-Direction	Wet-Road	Dry-Road	Nighttime	Nighttime Wet-Road
EB estimate of crashes expected in after period without strategy	1,497.71	444.37	283.82	217.45	255.89	1241.82	426.64	60.53
Number of crashes observed in after period	1,329	397	247	221	223	1106	373	71
Estimate of CMF	**0.887**	**0.893**	**0.870**	1.015	**0.870**	**0.890**	**0.874**	1.170
Standard error of estimate of CMF	**0.030**	**0.051**	**0.061**	0.075	**0.065**	**0.033**	**0.052**	0.149

Note: CMF estimates that are statistically significant at the 95-percent confidence level are indicated in boldface.

The results for Wisconsin multilane roads in table 11 indicate reductions for total, injury, run-off-road, wet-road, dry-road, and nighttime crashes that were all statistically significant at the 95-percent confidence level. Sideswipe-same-direction crashes had non-statistically significant decreases, while nighttime wet-road crashes had negligible and non-statistically significant increases.*

Table 11. Results for Wisconsin multilane roads.

Metric	Total	Injury	Run-Off-Road	Sideswipe-Same-Direction	Wet-Road	Dry-Road	Nighttime	Nighttime Wet-Road
EB estimate of crashes expected in the after period without strategy	556.77	256.08	110.93	93.17	92.62	465.15	133.13	16.71
Count of crashes observed in the after period	460	153	60	88	70	390	93	17
Estimate of CMF	**0.825**	**0.595**	**0.538**	0.941	**0.751**	**0.838**	**0.696**	1.001
Standard error of estimate of CMF	**0.051**	**0.059**	**0.078**	0.115	**0.108**	**0.058**	**0.082**	0.270

Note: CMF estimates that are statistically significant at the 95 percent confidence level are indicated in boldface.

The results for Minnesota two-lane roads in table 12 indicate reductions for total, wet-road, dry-road, nighttime, and nighttime wet-road crashes, none of which were statistically significant at the 95-percent confidence level. However, the results for wet-road crashes were statistically significant at the 90-percent confidence level. Injury, run-off-road, and sideswipe-same-direction crashes and nighttime wet-road crashes had non-statistically significant increases. For Minnesota two-lane roads, the total numbers of crashes were low, so lack of statistical

* Revised 3/12/2019

significance in the analysis results was not unexpected. The indications of reductions in wet, nighttime, and nighttime wet-road crashes do still support the hypothesis that wet-reflective markings reduce these types of crashes.

Table 12. Results for Minnesota two-lane roads.

Metric	Total	Injury	Run-Off-Road	Sideswipe-Same-Direction	Wet-Road	Dry-Road	Nighttime	Nighttime Wet-Road
EB estimate of crashes expected in after period without strategy	186.26	84.43	79.19	10.61	24.76	161.50	52.04	8.48
Count of crashes observed in after period	176	89	81	14	17	159	51	7
Estimate of CMF	0.944	1.053	1.022	1.310	0.685	0.984	0.979	0.823
Standard error of estimate of CMF	0.075	0.116	0.118	0.365	0.169	0.083	0.141	0.313

The results for Minnesota freeways in table 13 indicate reductions for total, injury, sideswipe-same-direction, wet-road, and nighttime crashes but none were statistically significant at the 95-percent confidence level. The results for wet-road crashes were statistically significant at the 90-percent confidence level. Run-off-road and nighttime wet-road crashes had non-statistically significant increases. For Minnesota freeways, as with the Minnesota two-lane roads, the total numbers of crashes were low, so the statistical insignificance was not unexpected. However, the indications of reductions in wet and nighttime crashes do still support the hypothesis that wet-reflective markings reduce these types of crashes.

Table 13. Results for Minnesota freeways.

Metric	Total	Injury	Run-Off-Road	Sideswipe-Same-Direction	Wet-Road	Dry-Road	Nighttime	Nighttime Wet-Road
EB estimate of crashes expected in after period without strategy	112.02	47.98	58.34	12.33	15.90	96.12	39.24	4.89
Number of crashes observed in after period	107	44	68	12	10	97	30	6
Estimate of CMF	0.949	0.907	1.153	0.949	0.614	1.002	0.756	1.181
Standard error of estimate of CMF	0.117	0.165	0.182	0.305	0.211	0.133	0.159	0.515

The combined results for all freeway sites (North Carolina, Wisconsin, and Minnesota) in table 14 indicate reductions for total, injury, run-off-road, wet-road, nighttime, and wet-road nighttime crashes, but only those for injury and wet-road crashes were statistically significant at the 95-percent confidence level. The results for sideswipe-same-direction and dry-road crashes showed negligible and non-statistically significant increases for these crash types.

Table 14. Results for combined States freeways.

Metric	Total	Injury	Run-Off-Road	Sideswipe-Same-Direction	Wet-Road	Dry-Road	Nighttime	Nighttime Wet-Road
EB estimate of crashes expected in after period without strategy	4,111.97	1,219.76	466.37	618.28	887.49	3224.48	1,103.63	248.69
Count of crashes observed in after period	4,019	1,075	450	625	765	3254	1,067	244
Estimate of CMF	0.977	**0.881**	0.964	1.010	**0.861**	1.009	0.966	0.979
Standard error of estimate of CMF	0.020	**0.033**	0.054	0.054	**0.040**	0.024	0.038	0.080

Note: CMF estimates that are statistically significant at the 95 percent confidence level are indicated in boldface.

DISAGGREGATE ANALYSIS

An attempt was made to further analyze the combined freeway dataset for wet-road crashes to identify site characteristics for which the safety benefits were greater. Only wet-road crashes were considered because this was the principal target crash and the only one with a consistent and statistically significant effect in each of the three States. Only freeways were considered because the datasets for multilane and two-way roadways had too few crashes for such an analysis.

A number of variables were investigated, including the following:

- Surface width.
- Shoulder width.
- Area type (urban versus rural).
- Number of lanes.
- Presence of shoulder rumble strip.
- AADT.
- Expected wet-road crash frequency per mi prior to treatment.

No differences or clear trends were seen for any of these variables and the estimated CMFs. Therefore, for this dataset, the expected effect of this strategy on wet-road crashes on freeways was the same regardless of differences in these aspects of the roadway environment.

CHAPTER 7. ECONOMIC ANALYSIS

An economic analysis was conducted to determine the estimated B/C ratio for this strategy for multilane roads and for freeways. (For two-lane roads, an economic analysis could not be performed because the crash reductions were too small and were statistically insignificant.) The statistically significant reduction in total crashes for Wisconsin was used as the benefit in the analysis of multilane roads. For freeways, the results for all States combined were used to derive the benefit in the analysis. Specifically, because the reduction in total crashes was not statistically significant, the reduction for the targeted wet-road crashes was used as the benefit.

On the cost side, for the installations on multilane roads in Wisconsin, the analysis conservatively assumed, in the absence of details of each installation, that the grooved contrast 4-inch tape, costing $9,200/mi for a single lane line treatment, was used for all installations. In total, 259.76 lane mi were installed at an estimated cost of $2,389,792. For freeways, the same per mile treatment cost was assumed for Wisconsin. For the North Carolina installations, NCDOT indicated that the polyurea treatment costing $1.10 per linear ft was applied. For Minnesota, the analysis conservatively assumed that the ground-in markings cost $17,000/mi. With these assumptions, the total estimated cost for freeway installations in the three States was $6,765,373.

The analysis assumed the useful service life for safety benefits was 2 years. This was based on information from MnDOT, which found that the retroreflectivity lasted 2 years under wet conditions and 4 years under dry conditions. Service lives reported by NCDOT and WisDOT indicated longer periods, so a 2-year life was assumed as the conservative option.

Based on information from the Office of Management and Budget *Circular A-4*, a real discount rate of 7 percent was used to calculate the annual cost of the treatment based on the 2-year service life.(8) With this information, the installation costs convert to annual costs of $3,741,928 for freeways in the three States and $1,321,794 for multilane roads in Wisconsin.

For the benefit calculations, the most recent FHWA mean comprehensive crash costs disaggregated by crash severity, location type, and speed limit were used as a base to derive comprehensive 2014 unit crash costs of $147,181 for freeways and $139,316 for multilane roads.*(9) Council et al. developed these costs based on 2001 crash costs and found that the unit costs (in 2001 dollars) for property damage only (PDO) and fatal plus injury crashes for speed limits posted greater or equal to 50 mi/h (assumed for freeways) from that report were $7,800 and $206,015, respectively. For all speed limits combined (assumed for multilane roads) the costs were $7,428 and $158,177, respectively. These were updated to 2014 dollars by applying the ratio of the USDOT 2014 value of a statistical life of $9.2 million to the 2001 value of $3.8 million.(1) Applying this ratio of 2.42 to the unit costs for PDO and fatal plus injury crashes, and then weighting by the frequencies of these two crash types in the after period (2,944 and 1,075 for freeways from table 14 and 307 and 153 for multilane roads from table 10), aggregate 2014 unit costs for total crashes were obtained as shown in figure 10 and figure 11.

$$2.42(7{,}800 \times 2{,}944/(2{,}944 + 1{,}075) + 206{,}015 \times 1{,}075/(2{,}944 + 1{,}075)) = \$147{,}181$$

Figure 10. Equation. Freeway calculation.

* Revised 3/12/2019

$$2.42(7{,}428 \times 307/(307 + 153) + 158{,}177 \times 153/(307 + 153)) = \$139{,}316$$

Figure 11. Equation. Multilane calculation.

Fatal crashes were not considered on their own because of the very low numbers of such crashes in the data, which would skew the results.

The crash reduction was calculated by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The number of crashes saved per year was 36.87 wet-road crashes for freeways and 51.59 total crashes for multilane roads, which were obtained by dividing the crash reductions (122.49 and 96.77, respectively) by the average number of after period years per site (3.32 and 1.88, respectively).

The annual benefits (i.e., crash savings) of $5,426,563 and $7,187,312 for freeways and multilane roads, respectively, were the product of the crash reductions per year (36.87 and 51.59) and the aggregate costs of a crash, with all severities combined ($147,181 and $139,316). The B/C ratio was calculated as the ratio of the annual benefit to the annual cost. The B/C ratios were estimated to be 1.45 for freeways and 5.44 for multilane roads. The USDOT recommends that sensitivity analysis be conducted by assuming values of a statistical life 0.57 and 1.41 times the recommended 2014 value.[(1)] These factors can be applied directly to the estimated B/C ratios to obtain a range of 0.83 to 2.04 for freeways and 3.10 to 7.67 for multilane roads. These results, which are summarized in table 15, suggest that the treatment—even with conservative assumptions on cost, service life, and the value of a statistical life—can be cost effective, especially for multilane roads.

Table 15. Economic analysis results.

Type of Road	B/C Ratio		
	Point Estimate	Lower Bound	Upper Bound
Freeways	1.45	0.83	2.04
Multilane Roads	5.44	3.10	7.67

CHAPTER 8. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness of wet-reflective pavement markings as measured by crash frequency. The study used data from three States—Minnesota, North Carolina, and Wisconsin—to examine the effects for specific crash types, including total, fatal plus injury, run-off-road, sideswipe-same direction, wet-road, nighttime, and nighttime wet-road crashes. Table 16 shows the various crash types for which a statistically significant CMF at the 95-percent confidence level could be estimated. Crashes occurring at or related to an intersection and snow/slush/ice and animal-related crashes were not included and should not be included when applying the recommended CMFs.

Table 16. Recommended CMFs and standard errors.

Type of Road	Total[1]	Injury	Run-Off-Road	Wet-Road	Nighttime
Freeways	—	0.881 (0.033)	—	0.861 (0.040)	—
Multilane roads	0.825 (0.051)	0.595 (0.059)	0.538 (0.078)	0.751 (0.108)	0.696 (0.082)

[1]Total crashes and other crash types do not include those related to intersections, animals, or snow/slush/ice conditions.

— Indicates no recommended CMF is available.

B/C ratios estimated with conservative cost and service life assumptions were 1.45 for freeways and 5.44 for multilane roads. With the USDOT recommended sensitivity analysis, these values could range from 0.83 to 2.04 for freeways and 3.10 to 7.67 for multilane roads.(1) These results suggest that the treatment—even with conservative assumptions on cost, service life, and the value of a statistical life—can be cost effective.

With additional data, future research may provide statistically significant results for those crash types for which a CMF could not be recommended, as well as more informative analyses to develop disaggregate* CMFs.

* Revised 3/12/2019

APPENDIX. ADDITIONAL INSTALLATION DETAILS FROM STATES

The following appendix presents additional details provided by the three participating States regarding the installation of the subject strategies in that State. State transportation departments were asked to provide responses to the following questions:

1. Can you provide any installation guidelines for the markings? For example, width, spacing, minimum levels of initial retroreflectivity?
2. Are there any criteria for deciding which roads receive the wet-reflective markings? For example, a certain level of AADT, a critical crash rate etc.?
3. Were any other safety countermeasures installed in conjunction with the wet-reflective markings at the treatment sites evaluated by this study?
4. Please describe any notable challenges related to the markings installation and how you overcame them.
5. Please describe any notable challenges related to the markings maintenance and how you overcame them.
6. What lessons learned or recommendations would you share with another State interested in the widespread application of wet-reflective markings?

RESPONSES FROM MINNESOTA

1. Widths and spacing follow normal striping practices. Some wet reflective markings are recessed. Minimum levels of retroreflectivity follow standard specifications: Latex: White-275, Yellow-180, Epoxy: White-300, Yellow-200, Tape: White-600, Yellow-500.
2. Districts decide where they would like to install wet reflective markings based on their needs. In general, it will be roadways with an ADT > 1,500.
3. These were stand-alone striping projects.
4. One challenge we have noticed when looking at wet reflective installations after the fact is that the distribution of the larger elements is sometimes sporadic. Some areas will have good coverage and some will have light coverage. This may be remedied by making sure striping companies have double drop systems and their application ratio of bead/elements is following the manufacturer's specifications. Another possible challenge is groove depth. Substandard grooving contributes to accelerated wear on the wet reflective elements.
5. One maintenance challenge is the shorter life span of the wet reflectivity of these markings. From our experience, wet reflectivity lasts around 2 years. Beyond that, the dry reflectivity is still well beyond minimums. It would be great to have a way to refresh wet retroreflectivity.
6. We would recommend recessing all wet reflective markings. Inspect installations to make sure element/bead coverage is good.

RESPONSES FROM NORTH CAROLINA

1. The only "wet-reflective" marking we have approved is cold-applied plastic. Although it is approved, we do not have a detailed specification for wet-reflective markings. The minimum

initial retroreflectivity for this cold applied plastic is 250 mcd/lux/m^2 for white and yellow. The only reason this is approved is due to the manufacturer only makes this type of tape.

2. At this time, we don't have any safety data showing a positive impact for wet-reflective marking. There are no specific criteria for installation. If a need is seen to install wet reflective markings due to an unusual circumstance it may be done. There is no AADT at which we do or don't install these types of markings.
3. No other safety countermeasures were installed in conjunction with the wet-reflective markings.
4. Our biggest challenge to marking installation is improper installation. This is not a regular occurrence, but it does happen. This is usually do to improper surface preparation and/or cleaning or poor workmanship (not applying the material correctly, applying too much or too little material, etc.). We overcome this by working with the installer to find out what the installation issue is and how it can be corrected. Additionally, we have an annual pavement marking training for DOT and contractors.
5. We now know enough about the types of markings we use, that if it's installed correctly we can predetermine its life-cycle (through studies and historical performance). One of our biggest challenges to marking maintenance is snowplowing. We overcome this by installing lower profile markings (polyurea) in locations that see moderate to heavy snowplowing.
6. Show us a benefit.

RESPONSES FROM WISCONSIN

1. Standard pavement markings specifications are used for wet-reflective products. The minimum required retroreflectivity is 250 mcd. based on the ASTM E2177 test.
2. On newly paved or resurfaced roads wet-reflective tape is applied for the lane lines and gore areas on freeways, expressways or multilane divided roads. On existing pavements 3 years old or greater wet-reflective tape is used to supplement sprayed epoxy markings at the end of lane lines on concrete and faded asphalt freeways/expressways.
3. Some locations had either shoulder widening and/or shoulder rumble strips installed. (NOTE: This amounted to approximately 113 mi of the 600 mi used, mostly on freeways).
4. Initially, all of the wet reflective tape was inlaid into the asphalt surface which shortened the longevity of the tape. For several years, all tape is now grooved in a 120 mils slot no matter the surface of asphalt or concrete. The initial 10 day wait requirement for grooving in asphalt was causing completion delay so with the agreement of manufacturer and those at WisDOT in the pavement area, it was lowered to 5 days.
5. Inlaid tape was being removed by snowplow activity, thereby increasing the frequency of replacement/maintenance of the tape. Placing the tape in a groove decreased this problem.
6. Place all wet reflective tape in a grooved slot.

ACKNOWLEDGEMENTS

This report was prepared for FHWA, Office Safety Research and Development under Contract DTFH61-13-D-00001. The FHWA Contract Officer's Technical Manager for this project was Ms. Roya Amjadi.

The project team gratefully acknowledges the participation and assistance of the following organizations for this study:

Minnesota Department of Transportation.
North Carolina Department of Transportation.
Wisconsin Department of Transportation.

REFERENCES

1. U.S. Department of Transportation. (2014) "Guidance on Treatment of the Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2014 Adjustment." Memo, June 13, 2014. http://www.dot.gov/sites/dot.gov/files/docs/VSL_Guidance_2014.pdf. Accessed November 12, 2014.
2. Minnesota Department of Transportation. (2015) "Pavement Markings & Delineation." http://www.dot.state.mn.us/trafficeng/pavement/index.html. Accessed August 12, 2015.
3. Carlson, P., Park, E., and Kang, D. (2013) "Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety." *Transportation Research Record 2337*, p. 59–66. Transportation Research Board, Washington, DC.
4. Smadi, O., Souleyrette, R.R., Ormand, D.J., and Hawkins, N. (2008) *An Analysis of the Safety Effectiveness of Pavement Marking Retroreflectivity.* 87th Annual Meeting of the Transportation Research Board, TRB 2008 Annual Meeting CD-ROM.
5. Donnell, E.T., Karwa, V., and Sathyanarayanan, S. (2009) *A Methodology to Explore the Relationship Between Pavement Marking Retroreflectivity and Traffic Crash Frequency on Highways in North Carolina: Application of Artificial Neural Networks and the Generalized Estimating Equations*. TRB 88th Annual Meeting Compendium of Papers CD-ROM. Washington, DC.
6. Bahar, G., Masliah, M., Erwin, T., Tan, E., and Hauer, E. (2006) *Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time*. National Cooperative Highway Research Program Web-Only Document 92.
7. Hauer, E. (1997) *Observational Before-After Studies in Road Safety—Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Pergamon, Oxford, UK.
8. Office of Management and Budget. (2003). *Circular A-4*. https://www.whitehouse.gov/omb/circulars_a004_a-4/. Accessed August 12, 2015.
9. Council, F., Zaloshnja, E., Miller, T., and Persaud, B. (2005) *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries*. FHWA-HRT-05-051, Federal Highway Administration, Washington, DC.

Recycled
Recyclable

HRDS-20/10-15(200)E