Safety Evaluation of Profiled Thermoplastic Pavement Markings

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

FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI–PFS). FHWA established this PFS 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 (AASHTO) 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 profiled thermoplastic pavement markings evaluated in this study are intended to reduce the frequency of crashes by improving the visibility of pavement markings and providing a rumble effect. Geometric, traffic, and crash data were obtained from Florida and South Carolina. The combined results for the two States indicate consistent, though statistically insignificant, reductions in nighttime wet-weather crashes, the primary targets of the treatment. The results suggest that the treatment, even with conservative assumptions for cost, service life, and the value of a statistical life, can be cost effective. This document is intended for safety engineers, highway designers, planners, and practitioners at State and local agencies involved with AASHTO Strategic Highway Safety Plan implementation.

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

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16. Abstract
The Development of Crash Modification Factors (CMFs) program conducted safety evaluation of profiled thermoplastic pavement markings for the Evaluation of Low-Cost Safety Improvements Pooled Fund Study. This study evaluated application of profiled thermoplastic pavement markings. This strategy involves upgrading existing markings from flat-line thermoplastic or other standard markings to the profiled product. These profiled markings are designed to provide an improved level of vision to drivers, particularly during wet-road surface conditions. Geometric, traffic, and crash data were obtained for two-lane and multilane road sections in Florida and South Carolina where the treatment was applied to the edge lines. To account for potential selection bias related to regression-to-the-mean, an empirical Bayes before–after analysis was conducted. The analysis 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. Only nighttime wet-road crashes, a principal target crash type, exhibited a material change—an estimated CMF of 0.908. Although the estimated CMF was based on a small sample of crashes and was not statistically significant at the 95-percent confidence level, it was consistent between the two States, which suggests that its use might be justifiable. The benefit–cost ratio for flat-line thermoplastic markings was 3.65:1 based on the consistent reduction in nighttime wet-road crashes and estimated with conservative cost and service life assumptions. Applying the sensitivity analysis recommended by the U.S. Department of Transportation, this value could range from 2.01:1 to 5.04:1. These results suggest that the treatment—even with conservative assumptions on cost, service life, and the value of a statistical life—can be applied cost effectively despite the relatively small crash reduction effects.

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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	0.305	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)

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
B/C	benefit–cost
CMF	crash modification factor
DCMF	Development of Crash Modification Factors (program)
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
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)
PFS	pooled fund study
ROR	run-off-road
SCDOT	South Carolina Department of Transportation
SE	standard error
SPF	safety performance function
USD	U.S. dollar
USDOT	U.S. Department of Transportation

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 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 broad applications of new strategies for safety improvements. Forty State transportation departments have provided technical feedback on safety improvements to the DCMF program and have implemented 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.

This study selected profiled thermoplastic pavement markings as a strategy for evaluation. This strategy involved upgrading existing markings from flat-line thermoplastic or other standard markings to the profiled product. These markings are designed to provide an improved level of vision to drivers, particularly during wet-road surface conditions. The profiled nature also provides a rumble effect for errant vehicles. A literature review found no published research evaluating the effect on crashes after profiled thermoplastic pavement markings were applied.

The project team obtained geometric, traffic, and crash data from Florida and South Carolina, where the treatment was applied to edge lines of two-lane and multilane roads. To account for potential selection bias related to regression-to-the-mean, an empirical Bayes (EB) before–after analysis was conducted using reference groups of untreated road sections with characteristics similar 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, run-off-road (ROR), head-on, sideswipe-opposite-direction, sideswipe-same-direction, wet-road, nighttime wet-road crashes, and all nighttime crashes. None of these crash types included intersection-related, snow/slush/ice, and animal crashes.

Only nighttime wet-road crashes, a principal target crash type, exhibited a material change, with an estimated crash modification factor (CMF) of 0.908. Although the estimated CMF was based on a small sample of crashes and was not statistically significant at the 95-percent confidence level, it was consistent between the two States, which suggests that its use might be justifiable.

The B/C ratio for flat-line thermoplastic markings was 3.65:1, based on the consistent reduction in nighttime wet-road crashes and estimated with conservative cost and service life assumptions. Applying the sensitivity analysis recommended by the U.S. Department of Transportation (USDOT), this value could range from 2.01:1 to 5.04:1. These results suggest that the treatment—even with conservative assumptions on cost, service life, and the value of a statistical life—can be applied cost effectively despite the relatively small crash reduction effects.

CHAPTER 1. INTRODUCTION

This chapter presents background information on the strategy of using profiled thermoplastic pavement markings, the goals of the study reported here, and a review of the existing literature on the use of profiled thermoplastic pavement markings.

BACKGROUND ON STRATEGY

Although policies have varied by jurisdiction, most roadways with any significant volume of traffic have included 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 treatment of interest is the use of profiled thermoplastic pavement markings. This treatment provides a rumble effect and enhances visibility compared with standard lane markings, particularly at night and during wet conditions. Because snowplowing can destroy this marking, its use is typically limited to locations characterized by warmer climates.

According to the Federal Highway Administration (FHWA), several agencies have used the treatment with good results, but none have conducted a safety effectiveness evaluation.(1)

There are two types of profiled markings—raised and inverted profile patterns—as shown in figure 1 and figure 2.

Figure 1. Photo. Raised profiled thermoplastic marking.(1)

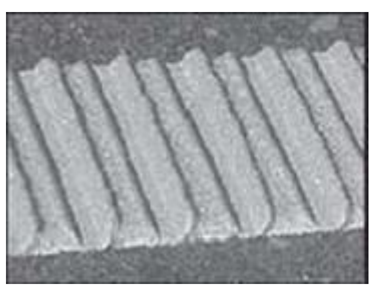

Figure 2. Photo. Inverted profiled thermoplastic marking.(1)

BACKGROUND ON STUDY

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 B/C ratios through research. State transportation departments and other transportation agencies need objective measures for safety effectiveness and benefit–cost (B/C) ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments have provided technical feedback on safety improvements to the DCMF program and have implemented 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.

The use of profiled thermoplastic pavement markings was selected as a strategy to be evaluated as part of this effort.

LITERATURE REVIEW

A literature review found no published research evaluating the effect of profiled thermoplastic pavement markings on crashes. The following discussion of profiled thermoplastic pavement markings is a summary of the information provided in volume 4 of the National Cooperative Highway Research Program *Report 500 Guides*, which focused on center-line applications (in contrast to the States that provided data for this study and applied the profiled markings on edge lines).(2)

Profiled markings provide an audible/tactile effect, although it is less noticeable to drivers of larger vehicles, especially trucks. The effect is similar to that experienced when driving over raised pavement markers with short spacing. While the audible/tactile effect can be advantageous, its principal benefit is improved visibility at night, in particular during wet conditions, compared with standard pavement markings. The treatment would be limited to areas where there is little or no snow because snowplow blades will easily scrape off the markings.

As of the date of this study, the strategy had not been sufficiently evaluated to be considered proven, but there had been no significant findings of negative effects.

Application of profiled thermoplastic markings has been typically recommended under the following conditions for two-lane rural roads:

- Snow removal is not required.
- No-passing zones are relatively long.
- Volume levels and crash experience do not justify more costly treatments.

- Resurfacing or other pavement maintenance activities that would cause removal of the treatment are not scheduled for at least 3 years.

- The areas have higher than normal rainfall.

- These markings can be used as an incremental improvement when more cost-intensive projects are being designed and funded.

There have been no significant obstacles or difficulties in using this treatment, although its use may not be suitable for open-graded or seal-coated surfaces. No adverse effects have been reported for motorcycles.

CHAPTER 2. OBJECTIVE

This research examined the safety impacts of using profiled thermoplastic pavement markings in Florida and South Carolina in comparison with more conventional markings, including a flat-line thermoplastic product. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Intersection-related, snow/slush/ice, and animal 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 (ROR) 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-road crashes (all types and severities combined).
- Nighttime crashes (all types and severities combined).
- Nighttime wet-road crashes (all types and severities combined).

A further objective was to investigate ways in which effects might vary, such as the following:

- By roadway type.
- By level of traffic volumes.
- By posted speed limit.
- By shoulder width.
- By lane width.
- By the site-specific expected crash frequency prior to treatment.
- By the overall effect, measured by the economic costs of crashes by crash type and severity.

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:

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

- Identifying appropriate untreated reference sites.
- Properly accounting for changes in safety due to changes in traffic volume and other nontreatment factors.
- Pooling data from multiple jurisdictions to improve reliability of the results and to facilitate broader applicability of the products of the research.

CHAPTER 3. METHODOLOGY

The empirical Bayes (EB) methodology for observational before–after studies was used for the evaluation conducted in this study. 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 also used to do the following:

- Overcome the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Account for time trends.
- Reduce the level of uncertainty in the estimates of the safety effects.
- Account for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The methodology derived and documented in detail by Hauer is only summarized here. It also provides a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy.[(3)] The SPFs for roadways without profiled thermoplastic pavement markings can be used with observed crash histories to estimate the number of crashes without treatment, and the crash modification factors (CMFs) developed can be applied to this number to estimate the number of crashes with 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 3.

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

Figure 3. 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 (i.e., 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 is first used to estimate the number of crashes that would be predicted to occur in each year of the before period at reference sites having traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the predicted number of crashes (*m*) before strategy. This estimate of *m* is calculated using the equation in figure 4.

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

Figure 4. Equation. EB estimate of expected crashes.

Where *w* is estimated from the mean and variance of the SPF estimate using the equation in figure 5.

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

Figure 5. Equation. EB weight.

Where *k* is an overdispersion parameter estimated from the SPF calibration.

In specifying the SPF, a negative binomial distributed error structure is assumed, with *k* being the overdispersion parameter of this distribution and that is estimated along with the other parameters of the SPF.

A factor is 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 is 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, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is 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 is also summed over all sites in the strategy group.

The index of effectiveness (θ) is estimated using the equation in figure 6.

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

Figure 6. Equation. Index of effectiveness.[3]

The standard deviation of θ is given by the equation in figure 7.

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

Figure 7. Equation. Standard deviation of index of effectiveness.[(3)]

The percent change in crashes is calculated as $100(1 - \theta)$; thus, a value of $\theta = 0.70$ with a standard error (SE) of 0.12 indicates a 30-percent reduction in crashes with an SE of 12 percent.

CHAPTER 4. DATA COLLECTION

Florida and South Carolina provided data, including the locations and dates of the installation of profiled thermoplastic pavement 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 other than profiled thermoplastic 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.

FLORIDA

This section describes the installation data, reference sites, roadway data, traffic data, crash data, and treatment cost and service life data for Florida sites used in this evaluation.

Installation Data

The Florida Department of Transportation (FDOT) provided a list of installations of profiled thermoplastic markings. FDOT applied the treatment mostly on rural two-lane undivided roads with some use on rural multilane divided roadways. The profiled markings were used for the edge lines. The treatment site data provided include the following installations:

- 27 mi in 2007–2008.
- 138 mi in 2009.
- 292 mi in 2010.
- 58 mi in 2011.
- 119 mi in 2012.

Data from the year of installation were excluded from analysis. No other construction activities were reported at these locations.

Reference Sites

Reference sites were chosen by selecting roadways in the same counties as the treated locations with the same functional class and similar levels of traffic volume and geometrics.

Roadway Data

FDOT provided roadway inventory data that included the following variables:

- Functional class.
- Urban versus rural environment.
- Number of lanes.
- Speed limit.
- Surface width.
- Shoulder width.
- Median type.
- Median width.

Traffic Data

FDOT provided traffic data from 2005 to 2013 in the form of annual average daily traffic (AADT).

Crash Data

FDOT provided crash data from 2005 to 2013, including many variables related to the location, time, and characteristics of each crash.

Treatment Cost and Service Life Data

A range of treatment cost and service life data were provided by FDOT for various contracts. Examination of these data suggested that they were reasonably consistent with the more specific information available for South Carolina, so it was decided to apply the South Carolina Department of Transportation (SCDOT) costs for the economic analysis based on the combined results of the two States.

The information provided by FDOT suggested that a service life of 3 years could be assumed.

SOUTH CAROLINA

This section describes the installation data, reference sites, roadway data, traffic data, crash data, and treatment cost and service life data for South Carolina sites used in this evaluation.

Installation Data

SCDOT provided a list of installations of profiled thermoplastic markings. Most installations were on rural two-lane undivided roads but with some installations on rural multilane divided roadways. The markings were only applied on the edge lines, and application took place in 2011 and 2012. Additional installations in the northern districts of the State had subsequently been removed through snowplowing operations, and these were not included in this study. Data for the installation year were excluded from the analysis. The total length of installations used for this study was 341 mi. The installation information included the route number, mileposts, and construction period.

No other construction activities were reported at these locations.

Reference Sites

Reference sites were chosen by selecting rural two-lane and multilane roadways with characteristics similar to the treated sites and from the same districts as the treated sites.

Roadway Data

SCDOT provided roadway data from 2005 to 2014 that included the following variables:

- Number of lanes.
- Surface width.
- Shoulder width.

- Shoulder type.
- Median type.
- Median width.

Traffic Data

SCDOT provided traffic data from 2005 to 2014 in the form of AADT.

Crash Data

SCDOT provided crash data for 2005 to 2014, including many variables related to the location, time, and characteristics of each crash.

Treatment Cost and Service Life Data

SCDOT provided estimated cost information of $0.50/linear ft for profiled thermoplastic pavement markings. The application cost for edge-line applications was $5,280/mi for two-lane roads and $10,560/mi for four-lane divided roads. The estimated service life is 5 to 7 years.

For flat-line thermoplastic pavement markings typical of the untreated reference sites, SCDOT estimated an installation cost of $0.40/linear ft, with a service life estimated at 5 years.

DATA CHARACTERISTICS AND SUMMARY

Table 1 defines the crash types used for both States. The project team attempted to make the crash type definitions consistent. In both States, intersection-related, snow/slush/ice, and animal crashes were excluded because these crash types were not considered correctable by the treatment under study. Note that sideswipe crashes in Florida were not analyzed because a coding change occurred during the study period; no sideswipe crashes were reported in later years at the treatment sites, and the crash coding for sideswipe crashes was not considered reliable.

Table 1. Definitions of crash types by State.

Crash Type	Florida	South Carolina
Total	Location is coded as not at intersection, and First Harmful Event not animal, and Road Surface Condition not icy.	Junction Type not an intersection type; First Harmful Event not deer or other animal; and Road Surface Condition not snow, slush, or ice.
Injury	Crash resulted in at least one fatality or injury.	Number of fatalities or injuries equal to 1 or more.
ROR	First Harmful Event indicates struck a roadside or off-roadway object.	First Harmful Event Location is roadside or outside trafficway, and crash is not sideswipe-same-direction, sideswipe-opposite-direction, or head-on.
Sideswipe-same-direction	First Harmful Event is sideswipe.	Manner of Collision is sideswipe-same-direction.
Sideswipe-opposite-direction	First Harmful Event is sideswipe.	Manner of Collision is sideswipe-opposite-direction
Head-on	First Harmful Event is head-on.	Manner of Collision is head-on.
Wet-road	Road Surface Condition is wet.	Road Surface Condition is wet.
Nighttime	Light condition is dark with or without lights.	Light Condition is dark with or without lights.
Nighttime wet-road	Crash is defined as both wet-road and nighttime.	Crash is defined as both wet-road and nighttime.

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 or between State comparisons of crashes per mile-year because such comparisons would not account for factors, other than the strategy, that might cause differences in safety between the before and after periods or between States. Such comparisons are properly done with the EB analysis, as presented later.

Table 2. Strategy installation and crash data summary for treatment sites.

Variable	Florida	South Carolina
Number of miles	508.05	341.27
Mile-years before	2,521.40	2,176.19
Mile-years after	1,348.70	788.89
Crashes/mi/year before	1.32	0.97
Crashes/mi/year after	0.80	0.99
Injury crashes/mi/year before	0.73	0.38
Injury crashes/mi/year after	0.44	0.36
ROR crashes/mi/year before	0.32	0.30
ROR crashes/mi/year after	0.13	0.37
Head-on crashes/mi/year before	0.03	0.02
Head-on crashes/mi/year after	0.02	0.02
Sideswipe-same-direction crashes/mi/year before	N/A	0.04
Sideswipe-same-direction crashes/mi/year after	N/A	0.05
Sideswipe-opposite-direction crashes/mi/year before	N/A	0.03
Sideswipe-opposite-direction crashes/mi/year after	N/A	0.04
Wet-road crashes/mi/year before	0.24	0.18
Wet-road crashes/mi/year after	0.15	0.20
Nighttime crashes/mi/year before	0.44	0.31
Nighttime crashes/mi/year after	0.26	0.33
Nighttime wet-road crashes/mi/year before	N/A	0.07
Nighttime wet-road crashes/mi/year after	N/A	0.07

N/A = Not applicable.

Table 3 and table 4 provide summary information for the volume and roadway data for the treatment sites, and table 5 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 mi and traffic volumes were not considered.

Table 3. Volume and roadway data summary for Florida sites.

Variable	Treatment			Reference		
	Average	Minimum	Maximum	Average	Minimum	Maximum
AADT before	9,830	120	133,762	13,422	472	110,056
AADT after	9,657	120	132,500	N/A	N/A	N/A
Average outside shoulder width (ft)	5.00	2.00	18.00	4.97	1.00	23.00
Average inside shoulder width (ft)	3.00	2.00	10.00	2.52	1.00	11.00
Number of lanes	3.00	2.00	10.00	2.00	2.00	10.00
Posted speed limit (mi/h)	54.00	25.00	70.00	51.28	25.00	70.00
Surface width (ft)	20.00	20.00	120.00	35,015	18.00	120.00
Median width (ft)	13.00	0.00	236.00	18.36	0.00	106.00

N/A = Not applicable.

Table 4. Volume and roadway data summary for South Carolina sites.

Variable	Treatment			Reference		
	Average	Minimum	Maximum	Average	Minimum	Maximum
AADT before	5,881	120	23,371	7,094	450	37,644
AADT after	5,549	120	23,050	N/A	N/A	N/A
Average outside shoulder width (ft)	6.21	0.00	12.00	5.57	0.00	12.00
Average inside shoulder width (ft)	0.33	0.00	10.00	0.07	0.00	4.00
Number of lanes	2.41	2.00	4.00	2.78	2.00	6.00
Posted speed limit (mi/h)	N/A	N/A	N/A	N/A	N/A	N/A
Surface width (ft)	29.79	20.00	66.00	34.09	18.00	78.00
Median width (ft)	9.17	0.00	99.00	12.08	0.00	106.00

N/A = Not applicable.

Table 5. Data summary for reference sites.

Variable	Florida	South Carolina
Number of miles	982.89	142.70
Mile-years	8,845.98	1,427.0
Crashes/mi/year	1.25	2.09
Injury crashes/mi/year	0.70	0.69
ROR crashes/mi/year	0.21	0.45
Head-on crashes/mi/year	0.02	0.06
Sideswipe-same-direction crashes/mi/year	N/A	0.17
Sideswipe-opposite-direction crashes/mi/year	N/A	0.03
Wet-road crashes/mi/year	0.21	0.41
Nighttime crashes/mi/year	0.37	0.61
Nighttime wet-road crashes/mi/year	0.07	0.13

N/A = Not applicable.

CHAPTER 5. DEVELOPMENT OF SPFs

This chapter presents the SPFs developed for each State. The SPFs were used in the EB methodology to estimate the safety effectiveness of this strategy.[(3)] 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, used in the EB calculations, was estimated iteratively from the model and the data. For a given dataset, smaller values of k indicate relatively better models. Estimates of k are provided, along with other model parameters.

SPFs were calibrated separately for Florida and South Carolina using the corresponding reference sites from each State. The SPFs developed are presented by State in the following sections.

FLORIDA

Figure 8 presents the form of the SPFs for Florida, which are presented in table 6 for two-lane roads and in table 7 for multilane roads.

$$\frac{\text{Crashes}}{\text{mile} - \text{year}} = exp^{a} AADT^{b} exp^{c*urbrur\ +d*lanes\ +e*outs\,hldwid}$$

Figure 8. Equation. Form of SPFs for Florida.

Where:
AADT = Annual average daily traffic volume.
urbrur = Urban or rural indicator (1 if rural; 0 if urban).
lanes = Number of lanes indicator (1 if two-lane road; 0 if multilane road).
outshldwid = Total width of outside shoulder in ft.
a, b, c, d, e = Parameters estimated in the SPF calibration process.

Table 6. Parameter estimates and SEs for SPFs for Florida two-lane roads.

Crash Type	*a (SE)*	*b (SE)*	*c (SE)*	*d (SE)*	*e (SE)*	*k (SE)*
Total	−6.1605 (0.8484)	0.7494 (0.0801)	−0.2376 (0.1281)	−0.7743 (0.3066)	—	0.9997 (0.0961)
Injury	−6.6533 (0.8948)	0.7324 (0.0850)	−0.2019 (0.1351)	−0.7081 (0.3151)	—	0.8710 (0.1087)
ROR	−4.7588 (0.7815)	0.3733 (0.0875)	—	—	−0.0724 (0.0374)	1.0195 (0.1496)
Wet-road	−7.8781 (0.8857)	0.6753 (0.0998)	—	—	−0.0983 (0.0478)	0.7622 (0.1895)
Nighttime	−8.9148 (0.7447)	0.8750 (0.0844)	—	—	−0.0724 (0.0374)	1.0195 (0.1496)
Nighttime wet-road	−9.5244 (1.4369)	0.6709 (0.1647)	—	—	—	1.5210 (0.6474)

For the head-on crash type, the total crash SPFs were used with a multiplier of 2.5 percent.
k is the estimated overdispersion parameter of the SPF.
— Indicates the variable associated with this parameter was not included in the SPF.

Table 7. Parameter estimates and SEs for SPFs for Florida multilane roads.

Crash Type	*a (SE)*	*b (SE)*	*c (SE)*	*d (SE)*	*e (SE)*	*k (SE)*
Total	−10.4061 (0.4791)	1.1516 (0.0493)	—	—	—	0.9346 (0.0564)
Injury	−10.0352 (0.5059)	1.0494 (0.0518)	—	—	—	0.8486 (0.0613)
ROR	−6.6828 (0.6114)	0.5621 (0.0626)	—	—	—	1.0824 (0.1165)
Wet-road	−13.1037 (0.7157)	1.2323 (0.0724)	—	—	—	1.0926 (0.1116)
Nighttime	−10.1507 (0.5544)	0.9945 (0.0566)	—	—	—	0.7552 (0.0677)
Nighttime wet-road	−12.8712 (0.9752)	1.0912 (0.0982)	—	—	—	1.1884 (0.2054)

For the head-on crash type, the total crash SPF was used with a multiplier of 1.5 percent.
k is the estimated overdispersion parameter of the SPF.
— Indicates the variable associated with this parameter was not included in the SPF.

SOUTH CAROLINA

The form of the SPFs for South Carolina, which are presented in table 8 and table 9, is shown in figure 9.

$$\frac{\text{Crashes}}{\text{year}} = exp^{a} AADT^{b} Length^{c} exp^{d*WIDTH}$$

Figure 9. Equation. Form of SPFs for South Carolina.

Where:

Length = segment length in mi.
WIDTH = total lane width in ft.

Table 8. Parameter estimates and SEs for SPFs for South Carolina two-lane roads.

Crash Type	*a (SE)*	*b (SE)*	*c (SE)*	*d (SE)*	*k (SE)*
Total	−4.6715 (1.0491)	0.8865 (0.1326)	0.6618 (0.0754)	−0.0902 (0.0310)	0.5065 (0.1121)
Injury	−4.1584 (1.1961)	0.7081 (0.1483)	0.7489 (0.0870)	−0.0968 (0.0418)	0.4419 (0.1385)
ROR	−2.4670 (1.1849)	0.5305 (0.1474)	0.8336 (0.0904)	−0.1153 (0.0463)	0.3736 (0.1187)
Head-on + sideswipe-opposite-direction	−8.5087 (1.7023)	0.7328 (0.2087)	0.9831 (0.1650)	—	0.3830 (0.3248)
Sideswipe-same-direction	−10.6206 (2.3048)	0.9467 (0.2800)	0.5159 (0.1520)	—	0.5231 (0.4623)
Wet-road	−5.7593 (1.1402)	0.8714 (0.1348)	0.7403 (0.0892)	−0.1146 (0.0453)	0.1601 (0.0917)
Nighttime	−4.3691 (1.0210)	0.6535 (0.1248)	0.7327 (0.0764)	−0.0660 (0.0335)	0.2625 (0.0916)

For the nighttime wet-road crash type, the total crash SPF was used with a multiplier of 8 percent.
k is the estimated overdispersion parameter of the SPF.
— Indicates the variable associated with this parameter was not included in the SPF.

Table 9. Parameter estimates and SEs for SPFs for South Carolina multilane roads.

Crash Type	*a (SE)*	*b (SE)*	*c (SE)*	*d (SE)*	*k (SE)*
Total	−18.2646 (1.4823)	2.0712 (0.1578)	0.7742 (0.0717)	—	0.2524 (0.0884)
Injury	−15.7429 (1.5549)	1.6966 (0.1635)	0.7458 (0.0758)	—	0.5953 (0.2394)
ROR	−6.0470 (3.0778)	0.5845 (0.3276)	1.0229 (0.1434)	—	0.5953 (0.2394)
Head-on + sideswipe-same-direction	−20.5081 (3.3853)	1.9528 (0.3442)	0.8685 (0.1508)	—	0.1024 (0.1716)
Sideswipe-same-direction	−17.9590 (2.0064)	1.8196 (0.2068)	0.8101 (0.0943)	—	0.1228 (0.1131)
Wet-road	−18.8293 (2.1940)	1.9640 (0.2296)	0.7955 (0.1072)	—	0.3254 (0.1529)
Nighttime	−17.4415 (1.6741)	1.8433 (0.1750)	0.8167 (0.0824)	—	0.1581 (0.0786)

For the nighttime wet-road crash type, the total crash SPF was used with a multiplier of 8 percent.
k is the estimated overdispersion parameter of the SPF.
— Indicates the variable associated with this parameter was not included in the SPF.

CHAPTER 6. BEFORE–AFTER EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 10 details the Florida results, and table 11 details the South Carolina results. These results include the estimates of predicted crashes in the after period without treatment, the observed crashes in the after period, and the estimated CMF and its SE for all crash types considered. The results were consistent between the two States in that no CMF results were statistically significantly different from 1.0. Both States also indicated a modest reduction in total crashes and a reduction in nighttime wet-road crashes of approximately 10 percent, although these were not statistically significant at the 95-percent confidence level.

Table 10. Results for Florida.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	1,136.28	1,085	0.954	0.035
Injury	582.48	590	1.012	0.049
ROR	182.59	172	0.941	0.080
Head-on	19.47	24	1.229	0.259
Wet-road	204.13	201	0.983	0.078
Nighttime	348.31	352	1.010	0.062
Nighttime wet-road	63.52	58	0.910	0.129

Table 11. Results for South Carolina.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE Error of Estimate of CMF
Total	789.81	779	0.986	0.041
Injury	312.59	281	0.898	0.060
ROR	254.45	292	1.146	0.078
Head-on + sideswipe-opposite-direction	49.09	44	0.894	0.143
Sideswipe-same-direction	35.57	36	1.009	0.177
Wet-road	152.73	157	1.027	0.089
Nighttime	281.57	261	0.926	0.064
Nighttime wet-road	60.76	55	0.903	0.131

Table 12 provides the results for the combined Florida and South Carolina data for the crash types analyzed in both States. Even with the combined data, none of the estimated CMFs were statistically significant at the 95-percent confidence level.

Table 12. Combined results for Florida and South Carolina.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	1,926.09	1,864	0.968	0.027
Injury	895.07	871	0.973	0.038
ROR	437.04	464	1.061	0.056
Wet-road	356.86	358	1.003	0.059
Nighttime	629.87	613	0.973	0.045
Nighttime wet-road	124.28	113	0.908	0.092

DISAGGREGATE ANALYSIS

An attempt was made to further analyze the combined dataset for nighttime wet-road crashes to identify site characteristics for which the safety benefits might be greatest. Only nighttime wet-road crashes were considered because this was a key target crash type and the only one that showed some consistency and sizable effect for both States; however, the CMF estimates were still not statistically significant at the 95-percent confidence level.

The following variables were investigated:

- Number of lanes.
- Surface width.
- Average shoulder width.
- Median width.
- AADT.
- Expected nighttime wet-road crash frequency per mi prior to treatment.

The project team saw no differences or clear trends in the estimated CMF for any of the geometric variables or AADT. Therefore, for this dataset, the expected effect of this strategy on nighttime wet-road crashes was the same, regardless of differences in these aspects of the roadway environment.

There were some indications that the CMF for nighttime wet-road crashes might be smaller (a larger benefit) for sites with higher expected nighttime wet-road crash frequency per mi prior to treatment. However, the sample was too small for a robust conclusion in this regard.

CHAPTER 7. ECONOMIC ANALYSIS

The project team conducted an economic analysis to determine the estimated B/C ratio for this strategy. Nighttime wet-road crashes, which were reduced, were considered for this analysis. The observed benefit—a CMF of 0.908—was not unexpected because this was the principal target crash type. Although the estimated CMF was based on a small sample of crashes and was not statistically significant at the 95-percent confidence level, it was consistent between the two States, which suggests that it was justified to use it for this purpose.

On the cost side, specific costs and information provided by SCDOT were used because these were reasonably consistent with the range of costs provided by FDOT for various contracts. It was conservatively assumed that the base condition that characterized the reference group of untreated sites consisted of flat-line thermoplastic pavement markings with a cost of $0.40/linear ft. The cost provided for profiled thermoplastic markings was $0.50/linear ft, so the relative cost of $0.10/linear ft was used as the unit treatment cost for the analysis. With these assumptions, the estimated treatment cost for the two States combined was $524,691.

Although service lives of between 3 and 5 years were provided by the two transportation departments, the analysis assumed, conservatively, a useful service life for safety benefits of 2.5 years, the average after-period length at the treatment sites.

Based on information from the Office of Management and Budget's *Circular A-4*, the project team used a real discount rate of 7 percent to calculate the annual cost of the treatment based on the 2.5-year service life.(4) With this information, the installation costs converted to annual costs of $125,926.

For the benefit calculations, the most recent FHWA mean comprehensive crash costs were used as a base.(5) Council et al. developed these costs based on 2001 crash costs and found that the unit costs (in 2001 U.S. dollars (USD)) for property damage only and fatal plus injury crashes for all speed limits combined were $7,428 and $158,177, respectively.(5) These were updated to 2015 USD by applying the ratio of the U.S. Department of Transportation's (USDOT's) 2015 value of a statistical life of $9.4 million to the 2001 value of $3.8 million.(6) By applying this ratio of 2.47 to the unit costs for property damage only and fatal plus injury crashes and then weighting by the frequencies of these two crash types in the after period (from table 12), the aggregate 2015 unit cost for total crashes was obtained as shown in figure 10.

$$2.47*(7,428*(993/1,864)+158,177*(871/1,864)) = \$192,337$$

Figure 10. Equation. Aggregate 2015 unit cost for total crashes calculation.

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

The project team calculated the crash reduction by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented (based on table 12). The number of nighttime wet-road crashes saved per year was 4.48, which the project team obtained by dividing the crash reduction of 11.28 by the average number of after-period years per site (2.52).

The annual benefit (i.e., crash savings) of $862,033 was the product of the crash reduction per year (4.48) and the aggregate costs of a crash, with all severities combined ($192,337). The B/C ratio of 3.65:1 was calculated as the ratio of the annual benefit to the annual cost. USDOT recommends conducting a sensitivity analysis by assuming values of a statistical life 0.55 and 1.38 times the recommended 2015 value.(6) These factors can be applied directly to the estimated B/C ratio to obtain a range of 2.01:1 to 5.04:1. 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 despite the relatively small crash reduction effects.

CHAPTER 8. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness of profiled thermoplastic pavement markings applied to edge lines as measured by crash frequency. The study used data from two-lane and multilane roads in two States—Florida and South Carolina—to examine the effects for specific crash types, including total, fatal plus injury, ROR, head-on, sideswipe-opposite-direction, sideswipe-same-direction, wet-road, nighttime, and nighttime wet-road crashes. Only nighttime wet-road crashes, the principal target crash type, exhibited a material change, yielding a CMF of 0.908, which was not unexpected because this was the primary target crash type. Although the estimated CMF was based on a small sample of crashes and was not statistically significant at the 95-percent confidence level, it was consistent between the two States, which suggests its use may be justifiable.

Based on the consistent reduction in nighttime wet-road crashes and estimated with conservative cost and service life assumptions, the B/C ratio relative to flat-line thermoplastic markings was 3.65:1. Applying the sensitivity analysis recommended by USDOT, this value could range from 2.01:1 to 5.04:1. 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 or for which a CMF was insignificant where recommended, as well as more informative analyses to develop disaggregate CMFs that reflect different application circumstances.

APPENDIX A. ADDITIONAL INSTALLATION DETAILS FROM FLORIDA

This appendix presents additional details provided by FDOT regarding its installations of profiled thermoplastic pavement markings.

1. Can you provide average installation costs per line-mile and the estimated service life of the products used?

   > Average cost for a 6-inch 100 mil above-surface thickness extruded with bump material could average somewhere between $3,275 to $3,900 [per] gross lane mile. Service life as required by specification is 3 years.

2. Are raised or inverted profile patterns applied?

   > Raised patterns are used; inverted profile is no longer allowed by specification.

3. On which of edge lines, center lines, and lane lines are profiled thermoplastic markings applied?

   > Yellow and white edge lines are specified; center line has to have a documented history of crossover accidents to be warranted.

4. Can you provide any installation guidelines for the markings (e.g., width, spacing, pavement types on which the markings are not suitable)?

   > Our requirements for Specification 701 in Florida is [a] 6-inch line, audible bump is spaced at approximately [a] 30-inch spacing, [and] materials are allowed on both asphalt and concrete surfaces by Specification 701.
   >
   > Specification 701 is available at the following link: http://www.dot.state.fl.us/programmanagement/Implemented/SpecBooks/January2016/Files/701-116.pdf.

5. Are there any criteria for deciding which roads receive the profiled thermoplastic markings (e.g., a certain level of AADT or critical crash rate)?

   > As of January 21, 2015, policy is to use profiled thermoplastic on concrete pavements for edge lines and center lines on all rural, two-lane and multi-lane, flush shoulder, non-limited access facilities, where posted speed is 50 mi/h or greater.
   >
   > http://www.dot.state.fl.us/rddesign/Bulletin/RDB15-02.pdf

6. Were any other safety countermeasures installed at the treatment sites evaluated by this study in conjunction with the profiled thermoplastic markings?

   > None reported.

7. Please describe any notable challenges related to the <u>installation</u> of the markings and how you overcame them.

None reported.

8. Please describe any notable challenges related to the maintenance of the markings and how you overcame them.

   None reported.

9. What lessons learned or recommendations would you share with another agency interested in the widespread application of profiled thermoplastic markings?

   None reported.

APPENDIX B. ADDITIONAL INSTALLATION DETAILS FROM SOUTH CAROLINA

This appendix presents additional details provided by SCDOT regarding its installations of profiled thermoplastic pavement markings.

1. Can you provide average installation costs per line-mile and the estimated service life of the products used?

   An average cost would be $0.50/linear ft. Service life of 5 years.

2. Are raised or inverted profile patterns applied?

   Primarily, raised profiles are used, and the thermoplastic is preferred to the disc but both are allowed.

3. On which of edge lines, center lines, and lane lines are profiled thermoplastic markings applied?

   Typically, the edge line only is treated.

4. Can you provide any installation guidelines for the markings (e.g., width, spacing, pavement types on which the markings are not suitable)?

   Criteria for rumble strips including profiled thermoplastic markings [are] available at: http://info.scdot.org/Construction_D/Engineering%20Directive%20Memorandums/EDM53.pdf.

   Specifications [are] available at: http://www.scdot.org/doing/technicalpdfs/supspecs/profile_marking_system.pdf.

5. Are there any criteria for deciding which roads receive the profiled thermoplastic markings (e.g., a certain level of AADT or critical crash rate)?

   Rumble strips shall be placed on shoulders or edge lines of all partial and non-controlled access roadways, subject to the following criteria:

   a. Roadway is classified as rural.
   b. ADT [average daily traffic] is 500 vehicles per day or greater.
   c. Posted speed limit is 45 mi/h or greater.
   d. Existing roadway width is 20 ft or greater.

   Thermoplastic profiled markings are an acceptable alternative only if rumble stripes are not feasible due to structural insufficiencies of a paved shoulder where milled in rumble strips may damage the surface/shoulders.

6. Were any other safety countermeasures installed at the treatment sites evaluated by this study in conjunction with the profiled thermoplastic markings?

A select few projects may have been through resurfacing efforts but is minimal.

7. Please describe any notable challenges related to the installation of the markings and how you overcame them.

   Not aware of any challenges.

8. Please describe any notable challenges related to the maintenance of the markings and how you overcame them.

   Their use is limited due to the short lifecycle and comparable cost to milled in rumble strips. We are not necessarily a snow State, but any snow removal or shoulder leveling would practically remove the markings.

9. What lessons learned or recommendations would you share with another agency interested in the widespread application of profiled thermoplastic markings?

   Obviously, use of the profile should be in a State with limited snow activity. One should also consider that when shoulders are leveled that the profiled marking will likely be removed. Where possible, milled-in rumble strips should be the preferred method based on cost and longevity.

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