Pavement Marking Demonstration Project: State of Alaska and State of Tennessee

REPORT TO CONGRESS

U.S. Department of Transportation
Federal Highway Administration

FHWA-HRT-09-039
APRIL 2010

FOREWORD

This report to the U.S. Congress provides information on four topics related to advanced pavement marking systems: (1) a study on the safety impact of wider edge lines, (2) an evaluation of the durability and cost effectiveness of alternative marking materials, (3) a review of the effects of State procurement processes on the quality of installed markings, and (4) an evaluation of the potential environmental impacts of cost-effective pavement marking system. The intent of this report is to provide decisionmakers with information on materials and methods that will reduce the overall national expenditure on pavement markings while providing improved guidance and enhanced safety for the driving public.

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TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-HRT-09-039	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Pavement Marking Demonstration Project: State of Alaska and State of Tennessee—Report to Congress		5. Report Date April 2010 6. Performing Organization Code
7. Author(s) Paul Carlson, Eun-Sug Park, Carl Andersen, Beverly Kuhn, Adam Pike, Jeffrey Miles, Robert Brydia, Wendy Ealding, and R.J. Porter		8. Performing Organization Report No.
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, TX 77843-3135	Under Contract To: SAIC 1710 SAIC Drive McLean, VA 22102	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-05-D-00025 Task T-06-002
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Safety Research and Development 6300 Georgetown Pike McLean, VA 22101		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
Projects were performed with the cooperation and participation of the Tennessee Department of Transportation and the Alaska Department of Transportation and Public Facilities.

16. Abstract
Under Public Law 109-59, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), the Secretary of the U.S. Department of Transportation was directed to conduct a demonstration project in Alaska and Tennessee to study the safety impacts, environmental impacts, and cost effectiveness of different pavement marking systems and the effect of State bidding and procurement processes on the quality of pavement marking material employed in highway projects.

This report outlines the development of the demonstration projects and the research findings to date. Preliminary findings indicate that States are pursuing alternative procurement strategies to provide high-quality durable markings in a cost-effective manner, often as part of their Strategic Highway Safety Plans, while industry has responded to requirements for more environmentally benign materials. A multistate retrospective analysis suggests that the use of 6-inch edge lines does result in a reduction in several crash types on rural two-lane two-way roads, as compared to 4-inch edge lines. As of the date of this report, pavement markings installed as part of the demonstration project in Tennessee have not yet degraded to the point where comparisons of the cost effectiveness of alternative pavement markings can be made.

17. Key Words Acrylic waterborne paint, Durability, Environmental impacts, Pavement markings, Retroreflectivity, State bidding procedures, Wider edge lines	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service Springfield, VA 22161

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 115	22. Price

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 AND SYMBOLS

Abbreviations

AADT	Annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society of Testing and Materials
Caltrans	California Department of Transportation
CEN	European Committee for Standardization
Cr(VI)	Hexavalent chromium
EB	Eastbound
EPA	Environmental Protection Agency
EPA TCLP	EPA toxicity characteristic leaching procedure
FHWA	Federal Highway Administration
HSIS	Highway Safety Information System
MC	Midpoint of curvature
$mcd/m^2/lux$	Millicandela per square meter per lux
MDOT	Michigan Department of Transportation
mil	One thousandth of an inch
MMA	Methyl methacrylate
MUTCD	*Manual on Uniform Traffic Control Devices*
NTPEP	National Transportation Product Evaluation Program
OSHA	Occupational Safety and Health Administration
PC	Point of curvature
ppm	Parts per million
RRPM	Raised retroreflective pavement marker
RTLTW	Rural two-lane two-way highway
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SAS®	Statistical Analysis Software
SD	Standard deviation
SHSP	Strategic Highway Safety Plan
SPF	Safety performance factor
SR	State route

TDOT	Tennessee Department of Transportation
U	Upstream
USDOT	U.S. Department of Transportation
VOC	Volatile organic compound
W	Location of advance warning sign
WB	Westbound

Symbols

α	Alpha, level of statistical significance
β	Beta, regression coefficient (of a negative binomial model)
χ	Chi, covariate (of a negative binomial model)
c	Combinations, number of factor-level combinations in an interaction
Δ	Delta (upper case), mean difference, in a given factor
δ	Delta (lower case), minimum detectable difference
§	Section (of a document)
σ	Standard deviation
μ	Microgram

EXECUTIVE SUMMARY

Almost $1 billion was spent nationally on pavement markings on State-maintained roads in 2007. When local roads, private roads, and parking areas are included, it was estimated that approximately $2 billion was spent on pavement markings in 2007. Despite the national expenditures on pavement markings, according to a recent American Association of State Highway and Transportation Officials (AASHTO) report, a highway death occurs every 21 minutes as a result of a lane departure. Prevention of roadway departure crashes is one of the Federal Highway Administration's (FHWA) four focus areas for safety. In addition, AASHTO has developed its Strategic Highway Safety Plan (SHSP) that is designed to reduce these crashes. The first objectives of the FHWA focus areas and the SHSP are to keep vehicles in their lanes and on the roadway. Installing and maintaining effective pavement markings is one immediate and obvious way to meet these objectives.

Under Section 1907 of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), the U.S. Congress directed the Secretary of Transportation to conduct demonstration projects in Alaska and Tennessee to study the safety impacts, environmental impacts, and cost effectiveness of different pavement marking systems and the effect of State bidding and procurement processes on the quality of pavement marking material employed in highway projects. The demonstration projects were to include an evaluation of the impacts and effectiveness of increasing the width of pavement marking edge lines from 4 inches to 6 inches and an evaluation of advanced acrylic waterborne pavement markings.

The major findings of the demonstration projects are summarized as follows:

- A field observational study of edge line width on rural two-lane two-way (RTLTW) roads in Tennessee did not indicate a causative relationship between edge line width and safety. This study of driver performance through curves indicated that there were either no real or, at most, only subtle vehicle operational impacts as a result of adding or widening edge line markings—even for narrow two-lane highways—under both day and night conditions. However, an Empirical Bayes (EB) before-after analysis and an independent cross section analysis using historical data from Michigan and Illinois suggest that the installation of wider edge lines results in reductions in many single vehicle road departure crashes. These retrospective analyses are considered more powerful than the observational study, as they incorporate several years of actual crash data rather than a limited number of observations of driver performance. Additional refinements of the retrospective analyses are ongoing and will be presented in a final research report to the FHWA.

- The industry has responded to various Federal and State requirements for pavement marking materials that are environmentally benign and reduce the risk to people from manufacturing to application and removal of materials. While no research has been conducted to date on the amount of airborne lead released when encapsulated lead-pigmented thermoplastic markings are removed from the roadway, the industry has developed lead-free and chromate-free thermoplastic markings, and State agencies are quickly adopting them. An evaluation of the potential environmental and health impacts of heavy metals in glass beads used in pavement markings was beyond the funding limits of this study.

- Preliminary findings indicate that States are pursuing alternative procurement strategies to provide high-quality, durable markings in a cost-effective manner, often as part of their required State SHSPs. While this current study did not conclusively demonstrate that a performance-based specification for pavement markings or a warranty-based contract results in higher quality installations, States are moving to these programs as a means of enforcing minimum standards for pavement marking systems. The effort that State and local agencies expend on the installation and maintenance of pavement markings indicates that these agencies are exercising due diligence in meeting their fiduciary responsibilities for providing a critical public service at the lowest possible cost, and flexibility in State procurement processes should be maintained.

- Differences in traffic volumes, types and patterns, roadway surfaces, installation practices, and environmental conditions interact in ways that make it difficult to formulate general statements regarding the most cost-effective means to provide pavement markings that meet the needs of the driving public during the day and night. While advanced waterborne acrylic markings have performed adequately in the Tennessee demonstration project, they did not survive the winter season in Alaska. In fact, as of this report, all of the alternative pavements marking systems installed as part of the demonstration project in Tennessee are still considered acceptable and require additional exposure to traffic and weather in order to develop recommendations regarding cost effectiveness. The test decks in Tennessee were monitored for pavement marking performance through the 2009–2010 winter, and the results will be included in a final research report to the FHWA.

- Conditions in Alaska prove to be a harsh environment for pavement markings of any type. Most of the markings tested in Alaska were deemed to provide inadequate guidance to drivers after the first winter, even when installed in a recessed groove to minimize plow damage. In order to provide some level of guidance for drivers year round, Alaska has developed a process of using waterborne paint and glass beads to refresh durable markings that lose retroreflectivity but not presence over the winter. This appears to be a viable solution for regions such as mountain pass roads in northern States that experience winter conditions similar to those in Anchorage, AK.

CHAPTER 1. INTRODUCTION

Section 1907 of Public Law 109-59 SAFETEA-LU directs the Secretary of Transportation to:

> "…conduct a demonstration project in the State of Alaska, and a demonstration project in the State of Tennessee, to study the safety impacts, environmental impacts, and cost effectiveness of different pavement marking systems and the effect of State bidding and procurement processes on the quality of pavement marking material employed in highway projects. The demonstration projects shall each include an evaluation of the impacts and effectiveness of increasing the width of pavement marking edge lines from 4 inches to 6 inches and an evaluation of advanced acrylic waterborne pavement markings."(1)

Furthermore, the Secretary is directed to "…submit to Congress a report on the results of the demonstration projects, together with findings and recommendations on methods that will optimize the cost-benefit ratio of the use of Federal funds on pavement marking."(1)

In response, the FHWA established a research project to address the directives described above. The intent of the research was to provide answers to four questions related to the efficacy and safety of pavement markings. To satisfy the requirements of section 1907 and to provide a definitive report on the "methods that will optimize the cost-benefit ratio of the use of Federal funds on pavement marking," the FHWA divided the legislative directive into the following topics:(1)

- **Safety study:** an evaluation of the impacts and effectiveness of increasing the width of pavement marking edge lines from 4 to 6 inches.
- **Durability study:** a study of the cost effectiveness of different pavement marking systems based on maintained retroreflectivity, including advanced acrylic waterborne systems.
- **State bidding and procurement processes study:** a review of the effects of State bidding and procurement processes on the quality of pavement marking material employed in highway projects.
- **Environmental study:** an evaluation of the potential environmental impacts of the cost-effective pavement marking systems identified in the durability study.

The purpose of this report is to describe the work performed to date for the SAFETEA-LU § 1907 Pavement Marking Demonstration Project. The remainder of this report is divided in five main sections—the first four sections provide descriptions of the four studies, and the last section describes the current findings and anticipated recommendations. Supporting appendices are also provided and referenced as appropriate.

This report describes the work performed as of January 2009. Interim reports on literature reviews, experimental plans, and progress reports are not included herein. All of the work conducted under this research project, which is scheduled to terminate in June 2010, will be documented in a final research report provided to the FHWA.

BACKGROUND

Transportation is a major sector of the U.S. economy. It moves people and goods, employs millions of workers, generates revenue, and consumes resources and services produced by other sectors of the economy. In 2005, transportation-related goods and services contributed $1.3 trillion to the $12.5 trillion U.S. gross domestic product (10.4 percent).(2) A large amount of transportation occurs on the Nation's 4 million mile backbone of streets and highways.(2) In general, the safety and quality of these streets and highways are unmatched anywhere else in the world. Many of the highway safety innovations used throughout the world have been developed in the United States.

Pavement markings play an important safety function on U.S. roads. They are widely accepted as being beneficial to drivers because they communicate the intended travel path for short-range operations and the roadway alignment for long-range delineation. To ensure consistent application of pavement markings, their characteristics and warranting criteria are described in the *Manual on Uniform Traffic Control Devices* (MUTCD), setting national standards on their application.(3)

Despite the national pavement marking standards described in MUTCD, according to a recent AASHTO report, a highway death occurs every 21 minutes as a result of a lane departure. In total, that is over 25,000 fatalities per year or almost 60 percent of the Nation's highway fatalities.(4) Because these types of crashes are the Nation's largest safety problem, FHWA promotes a strategic approach to prioritizing and implementing a safety program that includes appropriate countermeasures with roadway departure as one of FHWA's four focus areas for safety. In addition, AASHTO has developed its SHSP that is designed to reduce these numbers.(5) The first objectives of the FHWA focus areas and AASHTO safety plan are to keep vehicles in their lanes and on the roadway. Installing and maintaining effective pavement markings is one immediate and obvious way to meet these objectives.

As called for in SAFETEA-LU, individual States have developed SHSPs.(1) For instance, for the last 3 years, the Missouri Department of Transportation has focused on lane departure countermeasures. It has implemented various countermeasures, including increasing the pavement marking width on all major highways to 6 inches, which has led to a 25 percent reduction in lane departure fatalities from 2005 to 2007.(4)

The science and effort dedicated to effective pavement marking materials and practices can sometimes be overlooked. This may be a function of pavement marking unit costs, typically presented in cents per foot, which are on the order of $0.10/ft to $0.25/ft for installation of conventional markings. However, when each marking on a highway and each mile of a highway are added up, the annual cost of pavement markings in the United States can be surprising. Several sources of State agency information were combined to develop an estimated annual cost of pavement markings, which is based on data from 18 States making up 45 percent of the State-maintained highway miles in the United States.(6) Extrapolating the average cost per mile for the remaining 32 States produced a total annual estimated pavement marking expenditure of $911 million in 2007. This figure is about 1.5 percent of the estimated total capital and maintenance expenditures on State-maintained facilities in the same year (approximately $62 billion).[7]

In addition to State-maintained facilities, pavement markings are also installed on local roads, toll-authority roads, private roads, and other facilities such as parking lots and airports. Local roads account for about 75 percent (2.93 million mi) of the Nation's highways and roads, and 1.65 million mi of that are paved.[8,9] While many of these roads are not marked, there is a substantial proportion that are marked. Historically, approximately 50 percent of fatal crashes occur on local (county, township, and city) roadways.

The task of managing pavement markings falls jointly upon Federal, State, and local transportation agencies (private or semiprivate authorities are also involved in some jurisdictions). These agencies serve as stewards of the public and work within available sources of funding to install and maintain pavement markings in an efficient and effective manner.

The key elements of pavement marking performance are visibility and durability. It is important that drivers can see the pavement markings during the day and night, and it is important that the markings provide a sufficient service life. Paint traditionally has been used for pavement markings because of its availability and low cost; however, the durability of paint is generally less than 1 year, depending to a large degree on traffic volumes, environmental conditions, and the need for plowing operations in snowbelt States. Newer pavement marking materials are constantly being developed to increase visibility and durability but at higher initial costs. These newer materials generally require more sophisticated application equipment and techniques, which are not typically cost effective for transportation agencies to own and operate. Therefore, many of the newer materials are installed by contractor forces rather than agency personnel. This leads to various contracting options, such as performance-based and warranty-based specifications.

Maintaining pavement markings is important for adequate operational performance and safety. Accordingly, maintenance personnel in transportation agencies are charged with managing the visibility and durability of pavement markings. The challenge of maintaining visible markings throughout the year is especially difficult in high-traffic locations and on mountain pass highways as well as for States that allow studded tires or have bare pavement snow removal practices. Many States have found it most efficient to apply waterborne paint pavement markings twice a year because of winter maintenance activities. Even with this level of attention, pavement markings on mountain passes or horizontal curves cannot always be maintained in a cost-effective manner at specific levels.

In addition to testing marking visibility and durability, many agencies are experimenting with advances in pavement markings to reduce crashes. Other factors, such as an emphasis on accommodating older drivers, have inspired States to evaluate their pavement marking programs. States are also experimenting with different bidding and procurement processes in an effort to be more efficient with getting quality pavement markings on the road.

The research topics included in the SAFETEA-LU § 1907 Pavement Marking Demonstration Project are timely and appropriate, as they address many of the ongoing issues that Federal, State, and local transportation agencies face. This report has been prepared to address the topics as described in SAFETEA-LU § 1907.

CHAPTER 2. SAFETY IMPACT ASSESSMENT OF WIDER PAVEMENT MARKINGS

Longitudinal pavement markings provide a continuous amount of information to drivers by enabling them to safely select the appropriate lane and maintain the appropriate lane position. This is true in both day and night conditions. It is believed that increasing marking visibility will better enable drivers to maintain the appropriate lane position, resulting in an improvement in safety. In recent years, the use of wider pavement markings is one method by which transportation engineers have been trying to increase safety, as it is believed that wider pavement markings benefit drivers by increasing the visibility of the pavement markings.

The MUTCD defines the purpose of *longitudinal pavement markings* as the delineation of the vehicle path along the roadway. Variations in longitudinal markings are achieved by altering the color, pattern, and width, which all contribute to identifying the proper path for a driver.(3) It should be noted that while the MUTCD defines standard longitudinal pavement markings as having a width of 4–6 inches, for this report, any pavement markings that are wider than 4 inches are considered wider pavement markings.

Across the United States, the use of 4-inch markings is the basic application, and wider lines are used when deemed necessary. As part of a study conducted by Hawkins and Gates in 2001, the results from a nationwide survey indicated that 58 percent (29 States) used wider pavement markings to some degree.(10) All 50 States responded to this survey, providing a solid baseline for establishing usage. The survey results also indicated that the various States' primary reasons for using markings wider than 4 inches were to improve visibility and thereby improve safety.

The 2001 study also found that there was limited research on the safety effects of using a 6-inch-wide pavement marking versus using the standard 4-inch-wide pavement marking.(10) The existing research did not provide conclusive results on the benefits of wider markings, and the results of various studies often conflicted. Despite these inconclusive findings, a 2007 statewide survey conducted as part of this study shows that the use of wider pavement markings is on the rise.

INTRODUCTION

For this effort, the safety aspect of wider lines was addressed using a dual approach, including a multistate retrospective crash study focusing on pavement marking width and a crash surrogate study conducted in Tennessee.

The retrospective crash study included a national survey of wider marking practices used to identify States that knew where and when they had installed wider markings. Crash data from those States were pooled to conduct a robust statistical analysis of the safety impacts of wider markings.

The crash surrogate study focused on the operational aspects (e.g., change in deceleration profiles approaching and transiting curves, change in mean speed, change in speed variability, mean lateral placement, and lateral placement variability) of vehicles when negotiating horizontal curves on two-lane highways that were marked with 4- and 6-inch pavement marking edge lines. The dual approach provided a comprehensive analysis on the effectiveness of wider lines with the intent of developing conclusive results.

MULTISTATE RETROSPECTIVE ANALYSIS OF WIDER EDGE LINES

This section summarizes the safety analysis efforts associated with various pavement marking widths on rural two-lane highways. A general description of the data collection approach is provided, followed by the results of two analyses of the data. The two analyses are a cross sectional safety comparison between rural two-lane segments with 5- and 4-inch edge lines and a before-after analysis of rural two-lane segments on which the edge line width was changed from 4 to 6 inches.

Data

An electronic survey was distributed to identify States that installed pavement markings wider than 4 inches on all or some of their State-owned highways. It was sent through several media, including the following:

- A list of State transportation agency representatives which was manually developed using rosters for the AASHTO Subcommittee on Safety Management and the Subcommittee on Traffic Engineering, as well as other research team contacts with pavement marking responsibilities.
- A listserv for the AASHTO Subcommittee on Traffic Engineering.
- A listserv for the Institute of Transportation Engineers Traffic Engineering.
- A listserv for the National Committee on Uniform Traffic Control Devices Markings Technical Committee.
- A listserv for the Transportation Research Board Traffic Control Devices Committee.

Several rounds of follow-up telephone calls were made to those States that were identified as having current or previous experience with wider lines. State traffic engineers, district traffic engineers, maintenance engineers, and staff from other safety-related agency branches were contacted to determine the following:

- Whether locations of the wider lines could be determined (by route number and linear reference).
- Whether the use of wider lines was extensive on roadway segments (i.e., not spot treatments).
- Whether approximate dates of wider line installations were known.
- Whether sufficient crash, traffic, and roadway databases existed in formats that could be merged with each other and pavement marking information.

The convergence of affirmative answers in all four areas was rare. Required data were most readily available in Illinois and Michigan.

Illinois

Illinois has varying pavement marking practices across its nine districts. The minimum line width in district 6 is 5 inches. This width includes edge lines on both sides of the traveled way, skip lines, and other types of centerline markings. In district 3, edge lines and centerlines are 4 inches, while white skip lines and yellow skip lines on two-lane highways are 6 inches. The pavement marking practices date back 15+ years before the availability of reliable crash and roadway data for a before-after analysis. A cross sectional analysis approach is possible using more current crash, traffic, and roadway data. Additional detail is provided in the analysis section below.

Illinois is a participating State in the Highway Safety Information System (HSIS). The HSIS is a multistate database managed by the University of North Carolina Highway Safety Research Center and Lendis Corporation, under contract with the FHWA. Participating HSIS States were selected based on their data quality and the ability to merge electronically coded crash-related and highway infrastructure-related files. The HSIS database is often the first data alternative for highway safety research with national sponsorship and geometric design components, including research efforts associated with production of the *Highway Safety Manual* and SafetyAnalyst.(11)

Illinois crash and roadway inventory files were obtained from HSIS from 2001 through 2006. Crashes were located by county, route number, and milepost, while roadway segments were defined by county, route number, beginning milepost, and ending milepost. Crashes were assigned to appropriate roadway segments and counted using a variation of a Statistical Analysis Software® (SAS) code provided by the HSIS lab manager. Over 115 different crash type variations were originally counted. The number was reduced to the following 14 types after a number of preliminary model estimation runs and research team decisions related to the most relevant crash counts for this analysis:

- Total number of crashes.
- Total number of fatal plus injury (F + I) crashes.
- Total number of property damage only (PDO) crashes.
- Total number of day crashes.
- Total number of night crashes.
- Total number of F + I crashes during the day.
- Total number of F + I crashes during the night.
- Total number of wet weather crashes.
- Total number of crashes during wet weather at night.

- Total number of single vehicle crashes.
- Total number of single vehicle crashes in wet weather conditions.
- Total number of crashes with at least one driver 55 years old or older.
- Total number of opposite direction crashes (includes opposite direction sideswipe and head-on collisions).
- Total number of fixed object crashes.

Roadway segments and associated crash counts for rural two-lane highways were identified using area type and roadway classification indicators. Rural two-lane segments coded with presence of traffic signals, stop signs, or yield signs were deleted from the database to minimize the influence of intersection presence on the analysis. Additional segments coded as having extremely short segment lengths or atypical rural two-lane highway features (e.g., medians, auxiliary lanes, etc.) were also eliminated. Finally, segments that showed any change in physical features during the observation period (2001–2006) were deleted to minimize the influence of any major reconstruction project on the analysis results. The final rural two-lane dataset for Illinois consisted of 3,439 segments (1,581.1 mi)—2,810 segments (1,321.4 mi) with 4-inch edge lines and 629 segments (259.7 mi) with 5-inch edge lines. Six years of data (2001–2006) were available for each segment. Descriptive statistics for the primary segment variables considered in the analysis are summarized in table 1 and table 2.

Table 1. Descriptive statistics for continuous Illinois segment variables.

	2,810 Segments with 4-Inch Edge Lines			629 Segments with 5-Inch Edge Lines		
Segment Variable	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Length (mi)	0.12	5.45	0.47	0.12	2.51	0.41
Average daily traffic (vehicles per day)	100	25,900	3,300	100	11,100	2,180
Daily commercial traffic (trucks per day)	0	4,500	390	0	1,000	260
Lane width (ft)	8	16	11.7	9	16	11.5
Shoulder width (ft)	0	14	6.5	0	12	5.9
Paved shoulder width (ft)	0	12	3.7	0	12	4.3

Table 2. Descriptive statistics for categorical Illinois segment variables.

Segment Variable	2,810 Segments with 4-Inch Edge Lines		629 Segments with 5-Inch Edge Lines	
	Frequency	Percent	Frequency	Percent
25 mi/h posted speed	1	< 0.1	1	0.2
30 mi/h posted speed	43	1.5	16	2.5
35 mi/h posted speed	80	2.8	27	4.3
40 mi/h posted speed	72	2.6	14	2.2
45 mi/h posted speed	116	4.1	34	5.4
50 mi/h posted speed	76	2.7	8	1.3
55 mi/h posted speed	2,422	86.2	529	84.1
Presence of horizontal curve sharper than 2.5 degrees	223	7.9	44	7.0

Michigan

Edge lines in Michigan are currently 6 inches wide on all State-owned roadways (except for those with curbs and gutters). The change was made from 4-inch edge lines on almost all of the State-owned systems during 2004. A Michigan Department of Transportation (MDOT) pavement marking engineer estimated that 6-inch lines were installed on 95 percent of applicable mileage in 2004, with the remainder installed in early 2005. A before-after analysis was possible with the timing of the change. The widespread switch from 4- to 6-inch edge lines minimized the concern of selection bias or regression to the mean. However, it also did not allow a before-after analysis using comparison sites within the same State. The research team examined several comparison site alternatives. Additional detail is provided in the analysis section below.

Michigan crash data for 2001–2006 were obtained from the Michigan State Police Traffic Crash Reporting Unit. MDOT provided roadway inventory files for those same years. Crashes were located by county, route number, physical reference number, and milepost. Roadway segments were defined by county, route number, physical reference number, beginning milepost, and ending milepost. Crashes were assigned to appropriate roadway segments and counted using SAS®. Counts for 12 of the 14 crash types available for Illinois were also available for Michigan data analysis. Crash type 14—the total numbers of fixed object crashes—were not available, and for crash type 12—total number of crashes with at least one driver 55 years old or older—the change in number of older drivers from the before to the after period was not known. A count for total number of single vehicle crashes during night was included in the Michigan data, making a total of 13 crash types analyzed for Michigan.

Roadway segments and associated crash counts for rural two-lane highways were identified using an area type indicator and a variable for total number of through lanes. Similar data screening techniques and criteria as those employed for Illinois data were used for Michigan, including those for intersections, atypical rural two-lane highway features, and observed changes in physical features during the observation period. The final rural two-lane dataset for Michigan consisted of 253 segments (851.5 mi). Each segment was observed for 3 years from 2001–2003 with 4-inch lines and for 2 years from 2005–2006 with 6-inch lines. Descriptive statistics for the primary segment variables considered in the analysis are summarized in table 3 and table 4.

Table 3. Descriptive statistics for continuous Michigan segment variables.

Segment Variable	Minimum Segments	Maximum Segments	Average Segments
Length (mi)	0.04	12.69	3.37
Average daily traffic before period	197	17,633	4,497
Average daily traffic after period	299	18,597	4,433
Daily commercial traffic (trucks per day)	20	2,100	360
Lane width (ft)	10	12	11.5
Shoulder width (ft)	3	12	8.1
Paved shoulder width (ft)	0	11	4.2

Table 4. Descriptive statistics for categorical Michigan segment variables.

Segment Variable	Frequency	Percent
25 mi/h posted speed	5	2.0
30 mi/h posted speed	1	0.4
35 mi/h posted speed	4	1.6
40 mi/h posted speed	3	1.2
45 mi/h posted speed	10	4.0
50 mi/h posted speed	4	1.6
55 mi/h posted speed	226	89.3
Level terrain	165	65.2
Rolling terrain	88	34.8

Analysis

Two types of analyses of Illinois and Michigan data were conducted. The first was a cross sectional safety comparison of rural two-lane segments with 5-inch edge lines to similar segments with 4-inch edge lines in Illinois. The second was a before-after analysis of rural two-lane segments in Michigan in which the edge line width was changed from 4 inches to 6 inches in 2004.

Analysis of Illinois Rural Two-Lane Highway Crash Data

In Illinois, data screening reduced the rural two-lane data set to 3,439 segments (1,581.1 mi), consisting of 2,810 segments (1,321.4 mi) with 4-inch edge lines and 629 segments (259.7 mi) with 5-inch edge lines. Crashes occurring at the segments with 4-inch edge lines were compared to crashes occurring at the segments with 5-inch edge lines. The types of crashes analyzed are listed in table 5. The table shows the average crash rates computed as crashes per million vehicle miles of travel averaged over the segments considered in the study for Illinois rural two-lane highways. It is categorized by edge line width.

Table 5. Average crash rate (in million entering vehicles) per 1-mi segment of each roadway type.

Crash Type	4 Inches	5 Inches
Total	1.76	1.86
F + I	0.44	0.33
PDO	1.32	1.53
Daytime	0.74	0.64
Nighttime	0.87	0.98
Daytime F + I	0.26	0.19
Nighttime F + I	0.15	0.13
Wet	0.19	0.14
Wet night	0.10	0.08
Single vehicle	1.31	1.55
Single vehicle wet	0.14	0.12
Single vehicle night	0.79	0.94
Older driver (55 years old or older)	0.40	0.38
Opposite direction	0.04	0.05
Fixed object	0.34	0.30

The crash rates shown in table 5 might be useful if all the segments included in the study are identical except for edge line width, segment length, and annual average daily traffic (AADT) and also if crashes increase linearly with AADT. However, the road segments were different not only in edge line width, segment length, and AADT, but also in other roadway characteristics such as lane width, shoulder width, presence of curves, etc. Also, the relationship between crashes and AADT was not necessarily linear. As a result, the effects of edge line width may not have been estimated correctly by the differences in simple crash rates between 4- and 5-inch edge line segments.

In order to separate out the effect of edge line width from other important roadway characteristics, a negative binomial regression model was developed from the data. The general form of the expected number of crashes in a negative binomial regression model can be given as follows in figure 1:

$$\mu_i = \exp\left(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki}\right)$$

Figure 1. Equation. General form of negative binominal regression.

Where μ_i is the expected number of crashes at segment *i*, $X_{1i}, \ldots, X_{ki}$ are the covariates/predictors corresponding to roadway characteristics of segment *i*, and $\beta_0, \beta_1, \beta_2, \ldots, \beta_k$ are the regression coefficients. A model that included edge line width, lane width, shoulder width, presence of horizontal curve (1: present, 0: not present), and log of AADT as predictors and the log of the segment length as an offset variable provided the closest fit to the Illinois data.

Table 6 shows the estimates of the negative binomial regression model coefficients. The regression coefficient for edge line width was negative and statistically significant at $\alpha = 0.05$, which indicates a positive safety effect of wider edge lines (i.e., a smaller number of crashes is associated with wider edge lines) for the following crash types: F + I (-0.3555), daytime

(-0.1710), daytime F + I (-0.3684), nighttime F + I (-0.2900), wet (-0.2953), single vehicle wet (-0.2560), and fixed object crashes (-0.2808). Note that an $\alpha = 0.05$ indicates that there is a 95 percent probability that the observed differences are not due to chance. It can also be observed that the signs of the coefficients for lane width, shoulder width, log of AADT, and curve presence are consistent with intuition. For example, the negative signs of lane width and shoulder width coefficients imply that crashes tend to decrease as lane width or shoulder width increases, and the positive sign of curve presence implies that crashes tend to increase when there is a curve or curves as compared to when there is no curve.

Table 6. Estimates of regression coefficients of the negative binomial regression model applied to Illinois rural two-lane highway crash data for 6 years (2001–2006).

Crash Type	Intercept	Edge Line Width	Lane Width	Shoulder Width	Log AADT	Curve Presence	Dispersion	Pearson Chi-Square/ Degrees of Freedom
Total	-5.3007	-0.0398	**-0.0675**	**-0.0133**	**0.8645**	**0.2521**	0.4288	1.3101
F + I	-5.9759	**-0.3555**	**-0.0882**	**-0.0417**	**0.9748**	**0.6070**	0.5978	1.2853
PDO	-5.8323	0.0397	**-0.0633**	-0.0066	**0.8458**	0.1260	0.4501	1.2267
Daytime	-7.3511	**-0.1710**	**-0.1026**	**-0.0359**	**1.1449**	**0.2547**	0.5737	1.4866
Nighttime	-4.8929	-0.0239	**-0.0475**	-0.0014	**0.6752**	**0.2945**	0.4196	1.1137
Daytime F + I	-7.5377	**-0.3684**	**-0.0885**	**-0.0471**	**1.1190**	**0.3579**	0.8243	1.3217
Nighttime F + I	-5.7133	**-0.2900**	**-0.0845**	**-0.0369**	**0.7619**	**0.9276**	0.3630	1.0843
Wet	-7.2627	**-0.2953**	**-0.0849**	-0.0212	**0.9853**	**0.3638**	0.7133	1.1082
Wet night	-6.7358	-0.2458	-0.0552	-0.0023	**0.7465**	**0.4562**	0.6720	1.1026
Single vehicle	-3.6780	-0.0196	-0.0403	-0.0076	**0.5624**	**0.3590**	0.4031	1.1220
Single vehicle wet	-5.1418	**-0.2560**	-0.0337	-0.0175	**0.5767**	**0.5359**	0.7081	1.0961
Older-driver (55 years-old or older)	-7.4711	-0.0940	-0.0525	-0.0176	**0.9571**	0.1654	0.5371	1.3095
Opposite direction	**-14.7025**	0.1768*	-0.1019	-0.0051	**1.5046**	**0.6268**	0.3489	1.1148
Fixed object	**-5.0044**	**-0.2808**	-0.0216	**-0.0651**	**0.6937**	**0.6994**	0.5051	1.2885

Note: Significant (at $\alpha = 0.05$) effects are shown in bold. There was an extreme outlier in the opposite direction crash data for a 0.27-mi segment with 5-inch edge lines, which greatly affected an estimate of the edge line width coefficient for opposite direction crashes. When this outlier was removed, the opposite direction coefficient for edge line width changed from 0.3295 to 0.1768 and became insignificant.

For Illinois, raised reflective pavement markers (RRPM) are used statewide, and rumble strips are used on interstates statewide. However, information on additional delineation and guidance measures (other than RRPM and rumble strips) was not available and could not be incorporated into the analysis. Therefore, the above observations are based on the assumption that the effects of the variables not in the database, such as those additional delineation/guidance measures, are the same (or averaged out) for the segments with and without wider edge lines.

Analysis of Michigan Rural Two-Lane Highway Crash Data

In Michigan, changes to 6-inch edge lines occurred in 2004 for about 95 percent of the road segments statewide. Before-after evaluations were conducted with 3 years of before data (2001–2003) and 2 years of after data (2005–2006) obtained from 253 segments corresponding to 851.5 mi of rural two-lane highways. Crashes that occurred during the before period were compared to crashes that occurred during the after period. The types of crashes analyzed can be viewed in table 7, which shows the average crash rates computed as crashes per million vehicle miles of travel averaged over the segments considered in the study for each of the before and after periods.

Table 7. Average crash rate (in million entering vehicles) per 1-mi segment of Michigan rural two-lane highways for each of before (2001–2003) and after (2005–2006) periods.

	Period	
Crash Type	**Before**	**After**
Total	3.06	3.00
F + I	0.44	0.40
PDO	2.63	2.60
Daytime	1.29	1.22
Nighttime	1.41	1.41
Daytime F + I	0.29	0.25
Nighttime F + I	0.12	0.12
Wet	0.28	0.24
Wet night	0.14	0.12
Single vehicle	2.26	2.24
Single vehicle wet	0.21	0.19
Single vehicle night	1.29	1.29
Opposite direction	0.08	0.07

It can be observed from table 7 that crash rates decreased overall. However, this direct comparison of before-after crash rates is valid only when it can be absolutely assured that there have been no changes from before to after periods other than edge line width and traffic volumes and that the relationship between crashes and traffic volumes is linear. Both of these assumptions are often violated when the crash data of multiple years are analyzed. There will almost always be changes over time in weather, vehicle fleet, driver characteristics, economic conditions, etc., and crashes may increase with traffic volume in a nonlinear fashion.

To distinguish the effect of edge line width from the effects of other factors that might have also changed from the before to the after period, an EB approach for safety evaluation was employed.[12,13] The EB method estimated changes in crashes (due to wider edge lines) by comparing the observed number of after period crashes to the predicted number of crashes during the after period that would have occurred had wider edge lines not been installed, rather than to the observed number of before period crashes. Predicted crash frequencies by the EB method were obtained in such a way that they accounted for a potential nonlinear relationship between crashes and traffic volume (through the regression function called the Safety Performance Function (SPF)) as well as changes in general underlying trend caused by extraneous factors such as weather, vehicle fleet, and driver characteristics between the before and after periods. The SPF, which describes the relationship between crashes and traffic volume as well as other roadway characteristic variables such as lane width, shoulder width, and terrain, was derived from the before period from the Michigan data. The changes in general trend would typically have been estimated based on crash counts from road segments on which edge line width remained at 4 inches throughout the study period. Because no such segments remained in Michigan due to statewide installation of 6-inch edge lines during the study period, an alternative approach of deriving the trend factor based on another entity set was taken in which the general trend between the before and after periods was derived from the Illinois F + I crash data obtained from rural two-lane segments with 4-inch edge lines.(13) Using the Illinois data to provide a comparison group yielded results that were comparable to the cross sectional analysis conducted with the Illinois data. Additional analyses are being conducted to further verify this approach.

Table 8 presents the results of EB before-after evaluations based on the crash data in Michigan from 253 segments (851.5 mi) of rural two-lane highways. The observed number of after crashes over the segments, the predicted number of crashes during the after period that would have occurred without installing wider edge lines, and an estimate of the percent change in crashes from the before to the after period are shown in the table. As can be observed from the table, the EB before-after evaluations (using the before period Michigan data to develop the SPFs and the Illinois F + I crash data obtained from segments with 4-inch edge lines to derive a trend between the before and after periods) resulted in the following crash reduction estimates for rural two-lane highways in Michigan:

- Total crashes: 7.1 percent.
- F + I crashes: 17.1 percent.
- PDO crashes: 5.4 percent.
- Daytime crashes: 10.0 percent.
- Nighttime crashes: 2.4 percent.
- Daytime F + I crashes: 18.0 percent.
- Nighttime F + I crashes: 11.7 percent.
- Wet crashes: 24.4 percent.
- Wet night crashes: 22.6 percent.
- Single vehicle crashes: 2.0 percent.
- Single vehicle wet crashes: 20.0 percent.

- Single vehicle night crashes: -0.2 percent.

- Opposite direction crashes: 14.9 percent.

All of these crash reduction estimates, except for nighttime, single-vehicle, and single-vehicle night crashes, were statistically significant at the 95 percent level.

Table 8. Results of EB before-after safety evaluations based on Michigan crash data with 3 years (2001–2003) of before and 2 years (2005–2006) of after data.

Crash Type	Observed After Crashes	Predicted After Crashes with 4-Inch Edge Lines	Percent Reduction in Crashes
Total	6,077	6,541.2	**7.1**
F + I	811	977.5	**17.1**
PDO	5,266	5,563.1	**5.4**
Day	2,231	2,478.6	**10.0**
Night	3,149	3,277.4	2.4
Daytime F + I	498	607.1	**18.0**
Nighttime F + I	257	291.0	**11.7**
Wet	459	607.1	**24.4**
Wet night	243	313.7	**22.6**
Single vehicle	4,862	4,962.86	2.0
Single vehicle wet	353	440.691	**20.0**
Single vehicle night	2,923	2,916.34	-0.2
Opposite direction	165	193.8	**14.9**

Note: Statistically significant results (at 95 percent confidence level) are shown in bold.

CRASH SURROGATE STUDY

The crash surrogate study was designed to detect possible operational impacts of 4-inch versus 6-inch pavement marking edge lines on horizontal curves on RTLTW undivided highways. Three curve site selection criteria (curve radius, posted speed limit, and presence of paved shoulder) were identified through the literature review and team discussions as having the greatest potential impact on the effectiveness of wider edge lines. The crash surrogate study employed a before-and-after technique to reduce site-to-site variability using operational measures of effectiveness as surrogates for crashes. It was assumed that driver-to-driver (or vehicle-to-vehicle) variability would be less than variability caused by installation of wider lines. The literature review, combined with the expert opinion of the research team, led to the decision to study the impacts of wider pavement markings on horizontal curves exclusively. The operational measures of effectiveness that were studied included the following:

- Change in deceleration profiles approaching and negotiating the curve.

- Change in mean speed.

- Change in speed variability.

- Change in mean lateral placement.

- Change in lateral placement variability.

Even with a before-and-after technique, there is the possibility that some uncontrolled extraneous factor may impact the data; hence, the research team chose to have comparison sites. *Comparison sites* are curves that have similar geometric and traffic flow characteristics to the treatment site curves and where the pavement marking width is left unchanged between the before and after periods. Use of comparison sites helped ensure internal validity of the study by reducing confounding between the effect of treatment and the effects of uncontrollable extraneous variables. Examples of uncontrollable extraneous variables in this measure of effectiveness study might have included changes in drivers, driver behavior, and observers between the before and after periods.

Study Site Selection

Based on a review of the literature regarding safety problem areas, all horizontal curve test sites were established on RTLTW highways. Approximately 60 potential sites within Tennessee were visited to assess the geometric and operational characteristics of the candidate curves (see table 9).

Table 9. Safety-related controls for curve study.

Geometric	Operational
• Lane width (10–12 ft). • Grade (≤ 4 percent). • Approach tangent length (≥ 0.25 mi). • Curve length (vehicle time in curve, t ≥ 3 s). • Ambient lighting (none).	• Vehicle headway (≥ 5 s). • On-coming vehicles (none). • Approach speeds (≥ posted speed limit minus 10 mi/h). • Curve speeds (≥ posted advisory speed minus 10 mi/h).

As a result of these site visits, the researchers recommended that a total of 19 horizontal curves should be studied in Tennessee, with 10 treatment sites and 9 comparison sites. The black dots in figure 2 represent the location of the 19 horizontal curve study sites. The researchers verified that no roadway improvements were planned for the 19 study sites for the duration of the study. While efforts were made to select only isolated horizontal curves, two of the horizontal curves were located within winding roadway segments. The speed limit along the winding roadway segments was 35 mi/h, so it was believed that the speed limit had greater influence on the approach speeds than the alignment.

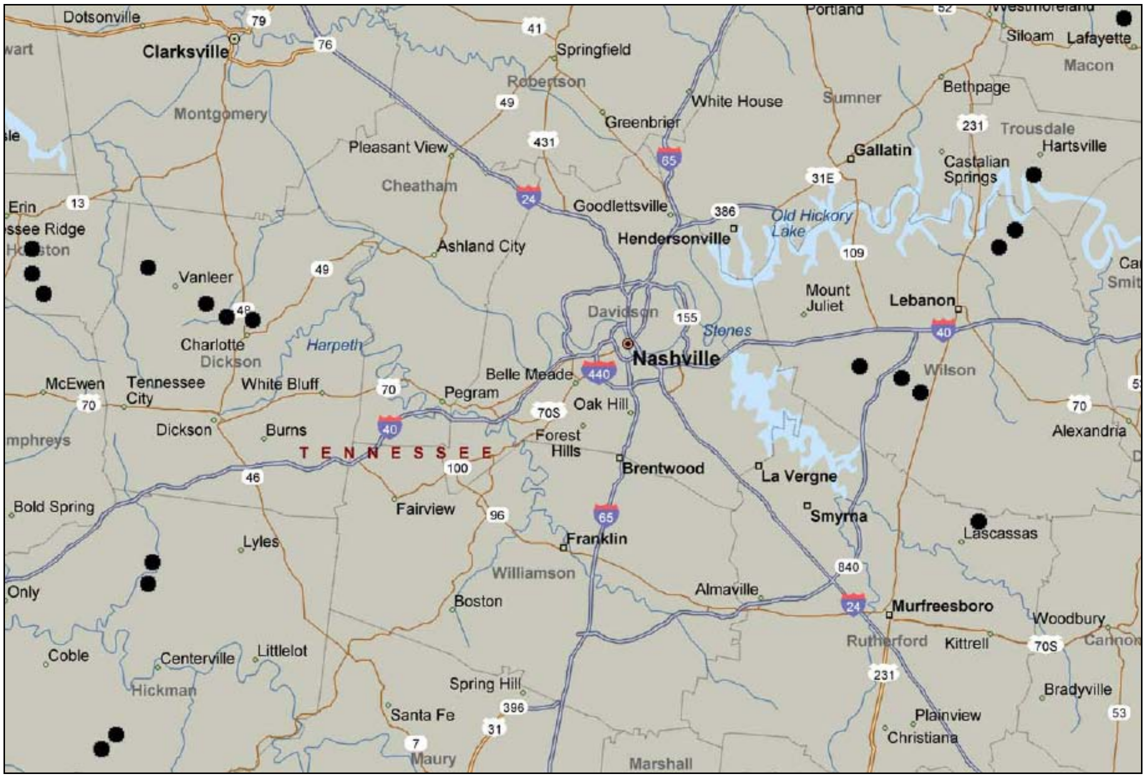

Figure 2. Chart. Map of 19 curve study sites.

The researchers categorized the horizontal curves based on three factors that have been identified through the literature review and team discussions as having the greatest potential impact on the effectiveness of wider edge lines. The sites were selected based on the radius of the curve (two levels), the posted speed limit (two levels), and the presence of a paved shoulder (two levels). The study matrix that includes two by two by two levels of those factors is shown in table 10. The curves were split into the treatment and comparison sites in such a way as to have comparisons for each combination of selection criteria. Note that sites for one of the eight combinations could not be identified.

Table 10. Study site matrix.

	Curve Design Safety Rating[1]			
	Radius ≤ 700 ft (Degree of Curvature ≥ ~8.0)		**Radius ≥ 800 ft (Degree of Curvature ≤ ~7.0)**	
	Presence of Paved Shoulder[2]		**Presence of Paved Shoulder[2]**	
Speed Limit	Yes	No	Yes	No
≥ 55 mi/h	1/1	2/2	2/1	1/1
≤ 50 mi/h	0	2/2	1/1	1/1

[1] 2/1 indicates that there will be at least two treatment sites and one comparison site for each category.

[2] For this project, presence of a paved shoulder exists when there is at least 36 inches of usable pavement beyond the inside edge of the edge line. For this project, absence of a paved shoulder exists when there is less than or equal to 24 inches of usable pavement beyond the inside edge of the edge line.

Data Collection

Data were collected along the 19 rural horizontal curves using traffic classifiers. The before data collection took place over a 5-week period from August to September 2007, and the after data collection took place over a 5-week period from July through August 2008. Traffic classifiers were installed on a Monday and retrieved on a Thursday in the same week by two to four research team members. Approximately 96 hours of data were collected at each study site for the before and after periods.

During the before data collection period, the curves had 4-inch-wide pavement markings. During the after period, the edge lines were restriped with 6-inch-wide pavement markings along the edge lines but not the centerlines—centerlines were restriped with 4-inch-wide markings. Driver eye scanning studies showed that drivers used the adjacent pavement marking edge line to negotiate curves regardless of whether they were in the inside or outside lane.(14)

Every effort was made to minimize differences between the periods of data collection and pavement marking installations. The average retroreflectivity of the edge lines in the before period was 200 mcd/m^2/lx, with none of the sites below 100 mcd/m^2/lx, while the average edge line retroreflectivity for the after period was 288 mcd/m^2/lx. The pavement markings for the after period were installed in late May 2008. After the pavement markings were installed, at least 1 month was provided to allow drivers to acclimate to the new markings.

Equipment Setup

When a vehicle passed through a particular curve, the traffic classifiers recorded the classification of the vehicle (i.e., passenger car or tractor trailer), the lateral position of the vehicle, and the speed of the vehicle. Piezoelectric road sensors were used in conjunction with traffic classifiers. The traffic classifiers enabled the researchers to collect raw data with a time stamp precision of 0.001 s.

Four traffic classifiers were used at each study site to track the movements of the vehicles traveling through the outside of each horizontal curve. These locations are defined as follows and in figure 3:

- **Upstream (U) location:** Positioned approximately 1,000 ft upstream of the curve warning sign location, this location was adjusted to avoid driveways, cross streets, or other factors (i.e., grade, horizontal curvature) that could impact the data collection effort.

- **Advance curve warning sign location:** This location was positioned at the advance curve warning sign (or the location at which a sign would be located when no sign was present). If a wider edge line was installed in the after period, it was started approximately 500 ft in advance of the curve warning sign location.

- **Point of curve (PC) location:** This location was positioned at the PC of the horizontal curve of interest. A second traffic classifier was also installed at this location to ascertain if an opposing vehicle passed through the study curve within ±7 s of a study vehicle traveling in the outside lane.

- **Midpoint of curve (MC) location:** This location was positioned near the MC of interest.

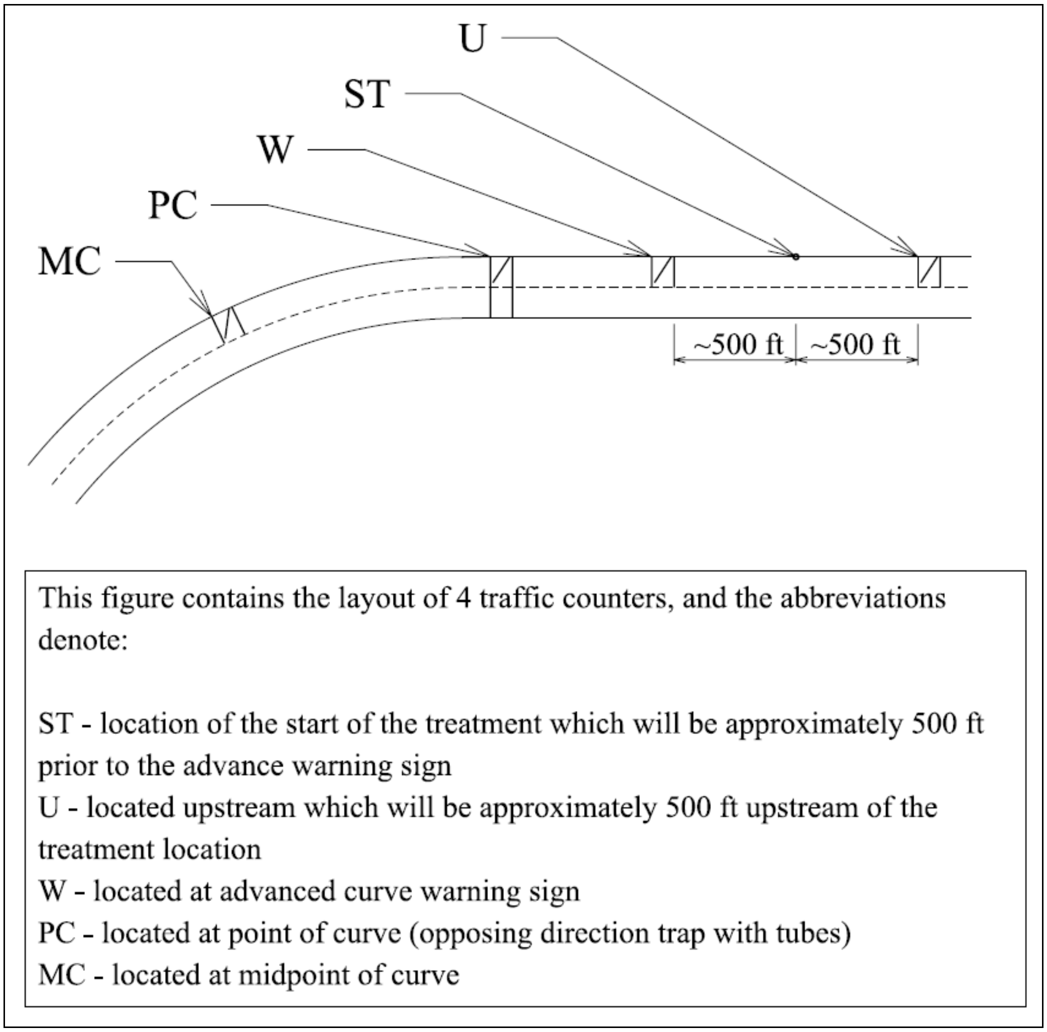

Figure 3. Illustration. Horizontal curve traffic classifier layout.

Sample Size

A power analysis was used to determine the sample size (the number of vehicles, *n*) needed to detect a practically important minimum difference in effects of increasing the pavement marking width and among the interaction effects between the pavement marking width and the day/night factor at each site. The procedures given in Wheeler, Nelson, and Bratcher et al. were used for the sample size calculation.[15–17] Because the necessary sample size varies with the desired significance level (α), the desired power, the standard deviation (SD; σ) of the response variable, and the minimum difference of practical importance (Δ), those values were predetermined before the sample size calculation. By convention, the desired significance level and the desired power were set to 0.05 and 0.90, respectively. Previous research indicates that the approximate SDs in speed and lateral placement in similar curves to those used in this study are 8 mi/h and 20 inches, respectively.[18] The minimum difference of interest before and after installation of wider lines was determined to be 3 mi/h for the mean speeds and 6 inches for the mean lateral placements based on engineering judgment and previous research.(18,19) It is believed that 6 inches is the minimum change in mean lateral position that would be a practically significant change for at least two reasons: (1) field experience has shown that striping installations vary in width as much as ±0.5 inches, and restriping can be misaligned by more than 1 inch, which may result in wide variability between pavement marking installations; and (2) previous research supported 6 inches.(18) The 3 mi/h minimum difference of interest was selected as a value between the values chosen by previous research because it is believed that a change of 3 mi/h would be the minimum change that would influence changing posted speed limits or advisory speeds.(18,19)

The minimum sample size (n_{speed}) necessary for detecting a mean speed difference (Δ) of 3 mi/h, with a σ in speed of 8 mi/h, before and after installation of wider lines at each site is shown in figure 4, where r is the number of levels of a factor.

$$n_{speed} = \left(\frac{3r\sigma}{\Delta}\right)^2 = \left(\frac{3 \text{ x } 2 \text{ x } 8}{3}\right)^2 = 256$$

Figure 4. Equation. Power analysis for sample size to detect a speed difference of 3 mi/h.

The minimum sample size (n_{lp}) necessary for detecting a mean lateral placement difference (Δ) of 6 inches, with a σ of 20 inches, before and after installation of wider lines at each site is shown in figure 5.

$$n_{lp} = \left(\frac{3r\sigma}{\Delta}\right)^2 = \left(\frac{3 \times 2 \times 20}{6}\right)^2 = 400$$

Figure 5. Equation. Power analysis for sample size to detect a lateral placement difference of 6 inches.

The minimum sample size necessary for detecting a mean speed difference of at least 3 mi/h in any two interactions means between pavement marking width and day/night at each site is shown in figure 6. In the figure, v is the number of interaction degrees of freedom, c is the number of factor-level combinations for the factors that are involved in the interaction, k is the number of factors involved in the interaction, and δ is the minimum difference of interest among the interaction effects.

$$n_{speed} = \frac{9\sigma^2(v+1)c}{\delta^2 2^{k-2}}\left(\frac{1}{2}\right) = \frac{9 \text{ x } 8^2(1+1) \text{ x } 4}{3^2 2^{2-2}}\left(\frac{1}{2}\right) = 256$$

Figure 6. Equation. Power analysis for sample size to detect a speed difference of 3 mi/h with two interactions.

The minimum sample size necessary for detecting a mean lateral placement difference of at least 6 inches in any two interactions means between pavement marking width and day/night at each site is shown in figure 7:

$$n_{lp} = \frac{9\sigma^2(\nu+1)c}{\delta^2 2^{k-2}}\left(\frac{1}{2}\right) = \frac{9\times 20^2(1+1)\times 4}{6^2 2^{2-2}}\left(\frac{1}{2}\right) = 400$$

Figure 7. Equation. Power analysis for sample size to detect a lateral placement difference of 6 inches with two interactions.

A sample size of 400 vehicles was selected to assure the power of the tests to be at least 0.90 for both mean speed difference and the mean lateral placement difference. Thus, the desired number of vehicles to be observed for each daytime and nighttime condition and for each before and after installation of wider lines at each site is at least 100 vehicles.

Statistical Analysis Methodology

A field experimental before-after study was conducted to compare 4-inch versus 6-inch pavement marking edge lines along isolated RTLTW roads. The researchers collected continuous quantitative data from traffic classifiers. Two primary treatments were studied: (1) curves marked with 4-inch-wide edge lines and (2) curves marked with 6-inch-wide edge lines. Other factors were the posted speed limit, the curve radius, the shoulder width, and the period of the day. The dependent variables were vehicle speed and vehicle lateral placement. The changes in mean speed, speed variance, 85th percentile speed, mean lateral position, and lateral position variance before and after installation of wider edge lines were the main interests of the study. In addition, the mean differences in the speed and lateral position between the different traffic classifier locations were also investigated, such as between the data collected at the PC and the MC. Evaluation criteria included the following:

- Change in mean speed at each traffic counter location.
- Change in speed variance at each traffic counter location.
- Change in 85th percentile speed at each traffic counter location.
- Change in mean lateral position at each traffic counter location.
- Change in lateral position variance at each traffic counter location.
- Mean difference in speed between traffic counter locations (i.e., between the PC and the MC counter locations).
- Mean difference in lateral placement between traffic counter locations (i.e., between the PC and the MC counter locations).

The statistical analyses included descriptive statistics, graphical analysis, and hypothesis testing. The descriptive statistics calculations included minimums, maximums, ranges, means, medians, quartiles, and 85th percentile values. Boxplots, histograms, scatter plots, and cumulative distributions were used to investigate the distribution of the data and to identify any trends or outliers in the data that would impact the testing methods used to conduct the hypothesis testing. The analysis of variance, specifically a split-plot design analysis, was used to test equality of mean speed and equality of mean lateral position of vehicles before and after the installation of wider edge lines.

Analysis

The descriptive statistics are separated into several tables. Table 11 contains summary statistics with respect to the sample size. While each study site had ample volume to provide 100 vehicles for each condition, some of the sample sizes for the nighttime data were less than desired once the researchers removed all of the unusable data. Unusable data were defined based on the following criteria:

- There was an opposing vehicle present.
- The vehicle in question could not be tracked through the entire system of classifiers.
- The speed data appeared unreasonable (e.g., the upper threshold was set at 100 mi/h because it was believed that vehicles would not be able to achieve that speed or higher within any of the study sites).
- The lateral position data were outside the measureable range of the sensor traps (the measureable range was 9.19 ft).
- The weather was questionable during the period of data collection (only curve 1 in the before condition had weather conditions that warranted the removal of data).

Table 11. Sample size summary.

	Before		After	
Statistic	**Day**	**Night**	**Day**	**Night**
Minimum	279	43	613	56
Mean	1,012	113	901	130
Median	890	84	828	100
Maximum	2,770	354	1,403	274

Table 12 shows summary statistics for the general trends. The values were calculated from the difference in the before and after period means and SD values. A positive value for a change in mean lateral placement would mean that drivers in the after period were driving closer to the centerline, while a negative value for the change in SD in lateral placement would indicate that the drivers were more centrally located within their respective lane of travel. Table 29 through table 32 in appendix A contain the detailed mean and SD values for the speed and lateral position data collected between the before and after periods for all 19 study sites. Other statistics such as range and variance were investigated, but they are not reported herein because they did not enhance the information already provided through the mean and SD. There were no trends that would suggest that the installation of wider edge lines affected a driver's selection of speed, but it appears that the installation of wider edge line markings in rural curves may have impacted a driver's selection of lateral position through horizontal curves (with a slight shift toward the centerline once in the curve). However, there were no mean changes of speed that exceeded 3 mi/h or mean changes in lateral position that exceeded 6 inches, which were established as the practical statistically significant differences during the sample size calculations.

Table 12. Change in speed and lateral position statistics for the treatment sites.

Speed Limit	Change in Statistical Measure	Curve Design Safety Rating: Radius ≤ 700 ft (Degree of Curvature ≥ ~8.0), Presence of Paved Shoulder: Yes, Speed (mi/h)	Lateral Position (inch)	Radius ≤ 700 ft, No: Speed (mi/h)	Lateral Position (inch)	Radius ≥ 800 ft (Degree of Curvature ≤ ~7.0), Presence of Paved Shoulder: Yes, Speed (mi/h)	Lateral Position (inch)	Radius ≥ 800 ft, No: Speed (mi/h)	Lateral Position (inch)
≥ 55 mi/h	Mean	1.6	3.8	-0.1	4.0	0.0	-0.4	0.2	-0.4
	SD	0.1	0.0	0.4	-1.9	0.2	-0.4	-0.1	0.4
≤ 50 mi/h	Mean	0.0	0.0	-0.7	2.1	0.7	-1.5	-1.1	0.0
	SD	0.0	0.0	0.1	1.6	-0.7	-1.1	-0.2	1.1

CHAPTER SUMMARY

The retrospective crash analysis based on Illinois and Michigan rural two-lane highway data shows that there are positive safety effects of wider markings for relevant crashes as follows:

- For Illinois, the negative binomial regression analysis based on the crash data aggregated for 6 years resulted in positive safety effect estimates for F + I, daytime, daytime F + I, nighttime F + I, wet, single vehicle wet, and fixed object crashes.

- For Michigan, an EB before-after evaluation resulted in positive safety effect estimates for total, F + I, PDO, daytime, daytime F + I, nighttime F + I, wet, wet night, single vehicle wet, and opposite direction crashes.

At the same time, the crash surrogate study results support previous findings, which show that there are either no real vehicle operational impacts or, at most, only subtle vehicle operational impacts as a result of adding or widening edge line markings—even for narrow two-lane highways and day and night conditions.

It should be noted that additional work is being completed. For the retrospective crash analysis, researchers are analyzing the impacts of widening interstate highway markings from 4 to 6 inches. For the crash surrogate study, researchers are conducting a more thorough statistical analysis using multivariate analyses techniques.

CHAPTER 3. COST EFFECTIVENESS

As described earlier, the State transportation departments' pavement marking expenditures for 2007 were estimated at approximately $911 million.[7] Finding the most cost-effective pavement marking for a given location could help reduce this figure while providing additional funding for other highway safety and maintenance areas. However, it has proven difficult to determine specific cost effectiveness levels for different pavement marking materials, as there are a plethora of factors that influence the results. One of the best ways to determine the cost effectiveness of pavement markings is to test them under the same conditions for which they are used—on the road.

There are numerous reports documenting pavement marking test deck designs and their results, but there are essentially two main types of on-the-road pavement marking evaluations: (1) transverse test decks and (2) long-line test decks (see appendix B). Transverse test decks are applied perpendicular to the flow of traffic. Long-line test decks are applied in the normal marking locations, consistent with the flow of traffic. Both transverse and long-line test decks may consist of several marking types to allow for comparative analysis. The researchers employed both test deck designs for this study.

INTRODUCTION

Pavement marking test decks were installed in Alaska and Tennessee with cooperation from the local State transportation departments. In 2006, a 12-material test deck was installed near Anchorage, AK, and a 9-material test deck was installed near Nashville, TN. In 2007, a second test deck (also with nine materials) was installed near Tusculum, TN. All three of these test decks included long-line configurations of the right edge line and near lane line. Each section consisted of approximately 0.5 mi of a test material either surface-applied, recessed in a groove, or both. The materials were only installed along tangent sections of highway, free of turning maneuvers and other activities that might have produced biased results. The Anchorage, AK, and Tusculum, TN, test decks also included transverse markings as well as high-build and low-temperature acrylic markings. All three test decks were installed on divided, multilane highways with asphalt pavements in good condition. See appendix C for detailed information about the test deck locations, pavement marking materials, and applications.

During the installation of the test decks, the researchers were present and collected pertinent data for subsequent analysis. Industry representatives were also present to help ensure that the pavement marking materials were installed as per manufacturer recommendations. Samples were taken of all the materials used.

The test decks were evaluated three to four times per year through retroreflectivity and presence measurements. This section of the report describes each test deck, the materials that were installed, and latest results of the monitoring. It also includes an analysis of cost effectiveness based on the current condition of the test deck pavement markings and an average cost for the materials.

ALASKA TEST DECK

In August 2006, a pavement marking test deck was installed on the Glenn Highway (Alaska State Route (SR) 1) northeast of Anchorage, AK. The Glenn Highway is a six-lane divided highway with an AADT of approximately 51,000. The Anchorage, AK, pavement marking test deck area consists of 12 test sections along the Glenn Highway between Boniface Parkway and East Eagle River Loop Road. Table 13 lists the different pavement markings installed on the Alaska test deck.

New markings were installed on the Alaska test deck in both 2007 and 2008 to replace markings that had failed during the previous winter. Throughout the life of the test deck, data were typically collected each year as soon as possible after the winter season, during the summer, and as late as possible prior to the next winter season.

Table 13. Anchorage, AK, test deck edge line and outside lane line pavement markings.

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)
1 AK a	Paint[1]	Spray	Surface, (Shallow), (Deep)	0, 65, 160	12
2 AK a	Paint[1]	Spray	(Shallow), (Deep)	65, 160	30
3 AK a	Methyl methacrylate (MMA)[1]	Extruded	(Shallow), (Deep)	70, 175	100
4 AK a	MMA[1]	Agglomerate	(Shallow), (Deep)	90, 275	200
5 AK a	Tape[1]	Rolled	(Deep)	175	100
5 AK b	Tape[1]	Rolled	(Deep)	175	100
6 AK a	MMA[1]	Extruded	(Shallow), (Deep)	60, 120	100
6 AK b	Modified Urethane[1]	Spray	Surface, (Shallow), (Deep)	0, 70, 120	20
7 AK a	Paint[1]	Spray	Surface, (Shallow), (Deep)	0, 140, 175	12
8 AK a	MMA[1]	Agglomerate	(Shallow), (Deep)	120, 320	200
9 AK a	Paint[1]	Spray	(Shallow), (Deep)	60, 145	30
10 AK a	Polyurea[1]	Spray	(Shallow), (Deep)	65, 155	20
All sections	Paint[2]	Spray	Over existing	Existing	12
1 AK b	Preformed Thermoplastic[3]	Heat in Place	(Deep)	160	125
2 AK b	MMA[4]	Spray	(Shallow), (Deep)	85, 180	60
7 AK b	MMA and Paint[5]	Extruded w/ raised edges, double spray	(Shallow), (Deep)	60, 145	100, 40
9 AK b	MMA and Paint[5]	Extruded w/ raised edges, spray	(Deep)	175	100, 20

[1] August 7, 2006 installation date.
[2] June 21, 2007 installation date.
[3] September 24, 2007 installation date.
[4] October 2, 2007 installation date.
[5] August 5, 2008 installation date.

TENNESSEE TEST DECKS

The researchers installed two test decks in Tennessee: one near Nashville where the central office of the Tennessee Department of Transportation (TDOT) is located and one near Tusculum, a region where snow fall is most likely in Tennessee. These test decks were designed to be similar in several ways to the Alaska test deck so that direct comparisons could be made between materials in Alaska and Tennessee. For instance, the Tusculum, TN, test deck materials were primarily installed with handcarts similar to the Anchorage, AK, test deck. However, there were differences as well. For example, most materials on the Nashville, TN, test deck were installed with long-line trucks. These installation techniques were chosen to assess possible differences between handcart-applied materials and long-line truck applied materials.

Nashville, TN, Test Deck

The Nashville, TN, pavement marking test deck area was installed in October 2006. This test deck has nine sections along SR-840 between I-65 and I-24 with an AADT of approximately 19,000. Table 14 shows the different pavement markings that were installed. Unlike the other test decks, which had 4-inch-wide markings, all markings along the Nashville, TN, test deck were 6 inches wide, as this is the TDOT policy for markings on highways of this functional classification.

In June 2008, the researchers added three lead-free yellow thermoplastic sections to this test deck in order to accomplish two objectives. The first objective was to provide data for the initial and maintained nighttime yellow appearance of the lead-free markings, which is a concern to many State transportation departments considering the switch to a more environmentally benign thermoplastic pavement marking. The second objective was to better understand the environmental impacts of pavement markings, which is further addressed in a subsequent chapter.

Table 14. Nashville, TN, test deck edge line and lane line pavement markings.

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)
1 TN-N	Thermoplastic[1]	Spray	Over rumble strip edge line only	N/A	40
2 TN-N	Thermoplastic[1]	Spray	(Shallow), (Deep)	75, 185	40
3 TN-N	Thermoplastic[1]	Spray	(Shallow), (Deep)	85, 270	90
4 TN-N	Thermoplastic[1]	Extruded	(Shallow), (Deep)	95, 180	120
5 TN-N	Thermoplastic[1]	Inverted Profile	(Shallow)	75	50/225
6 TN-N	Paint[1]	Spray	(Shallow), (Deep)	55, 145	12
7 TN-N	Polyurea[1]	Spray	(Shallow), (Deep)	110, 165	20
8 TN-N	Paint[1]	Spray	(Shallow), (Deep)	135, 175	26
9 TN-N	Paint[1]	Spray	(Shallow), (Deep)	100, 175	25
10 TN-N	Lead-free[2]	Extruded	Surface	0	80
11 TN-N	Lead-free[2]	Extruded	Surface	0	80
12 TN-N	Lead-free[2]	Extruded	Surface	0	85

N/A = Not applicable.
[1] October 16, 2007 installation date.
[2] June 5, 2008 installation date.

Each year, data were typically collected as soon as possible after the winter season, twice during the middle of the year, and as late as possible prior to the next winter season.

Tusculum, TN, Test Deck

The Tusculum, TN, pavement marking test deck area was installed in May 2007. This test deck has nine sections along SR-34 (AADT is approximately 12,000) between SR-107 and SR-75. Table 15 shows the different pavement markings that were installed.

Table 15. Tusculum, TN, test deck edge line and lane line pavement markings.

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)
1 TN-T	Modified epoxy	Spray	(Shallow), (Deep)	100, 125	22
2 TN-T a	MMA	Extruded	(Shallow), (Deep)	100, 170	90
2 TN-T b	MMA	Agglomerate	(Shallow), (Deep)	100, 170	200
3 TN-T	Paint	Spray	(Shallow), (Deep)	50, 110	15
4 TN-T	Paint	Spray	(Shallow), (Deep)	105, 150	24
5 TN-T a	Tape	Rolled	(Shallow), (Deep)	60, 130	100
5 TN-T b	Tape	Rolled	(Shallow), (Deep)	25, 195	100
6 TN-T	Thermoplastic	Extruded	(Shallow), (Deep)	70, 320	90
7 TN-T	Modified urethane	Spray	(Shallow), (Deep)	110, 170	15

DATA COLLECTION TECHNIQUES

The researchers designed a data collection protocol to determine the durability of the pavement markings on the test decks so that when combined with installation costs and indirect costs such as traveler delay, the overall cost effectiveness of the tested pavement markings could be calculated. As part of the data collection protocol, retroreflectivity measurements and photographic images were collected for each pavement marking along the edge line, lane line, and transverse line.

Retroreflectivity Measurements

Retroreflectivity data were collected using a handheld pavement marking retroreflectometer and a mobile retroreflectometer. The handheld retroreflectometer measures only the edge line markings whereas the mobile retroreflectometer measures the edge line and lane line markings. The handheld dataset is used as a way to verify the mobile retroreflectivity dataset. Retroreflectivity measurements were collected in dry conditions only.

The data collection protocol was designed to yield enough data to obtain a statistically valid representation of the pavement markings while keeping the exposure of the data collection team to traffic at a minimum. The data collection protocol for this project was partially modeled after the methodology described in American Society of Testing and Materials (ASTM) D 6359, and all retroreflectivity devices met the criteria set in ASTM E 1710.[20,21] All data collection devices were properly calibrated prior to data collection.

Mobile Measurements

The mobile retroreflectivity data were measured continuously, and an aggregated average was recorded every 52.8 ft (0.01 mi). The value of 0.01 mi is a user-defined measurement length and is near the minimum length allowed by the retroreflectometer software. The first data point at the beginning and last data point at the end of each section were removed from the analysis to ensure that there was no overlap in the data between marking application types or markings not under study.

Handheld Measurements

The handheld retroreflectivity data were measured at specific predetermined points to yield robust and representative data. A sampling plan was developed so that the average value from each set of measurements for each line was within a 95 percent confidence of the true mean for the measured test section.

Photographic Images

Photographic images of each section were taken using a digital camera. These were captured and recorded in order to document their general condition and to ensure their availability to be used later to quantify the presence of the pavement marking materials using a software tool developed by the researchers. A total of 10 images were taken of each marking section in representative locations near where the handheld measurements were taken.

PAVEMENT MARKING DURABILITY

For this project, a pavement marking system was deemed to have remaining service life if it maintained adequate presence as subjectively evaluated in situ and retroreflectivity of at least 100 mcd/m^2/lux. The markings in Alaska experienced severe winter conditions, whereas the markings in Tennessee experienced relatively mild winter conditions. As a result, the durability data between the two regions were vastly different.

It should be noted that the service life of any pavement marking system is quite variable and depends on numerous factors. The only true way to determine the durability of a marking is to monitor the marking's performance throughout its life. Even then, the service life of that particular marking is only applicable to that given set of variables. Traffic volume, roadway surface type, and winter maintenance activities are some of the major influences on the service life of a pavement marking system. Other factors that can influence service life include the percentage of heavy vehicles, application conditions, weather conditions, orientation of the marking, roadway geometry, marking thickness, type of retroreflective optics used, and criteria for determining the end of the service life. Based on the actual conditions at each site, the service life could be longer or shorter than at another site that has the same marking applied. The next sections describe the durability observations from each region of this study. Appendix D includes figures showing the retroreflective degradation of markings that have lasted over 1 year.

Alaska

The winter weather conditions and associated winter maintenance activities experienced on the Alaska test deck proved difficult for many of the pavement marking systems. Some markings failed in either retroreflectivity, presence, or both during the first winter following installation. New materials were applied and tested the following year where materials failed, often with similar results. Table 16 describes the results of the various pavement marking sections along the Alaska test deck. It should be noted that the table only includes the results from the edge line. In all cases but one, the lane line results were similar which is explained as follows.

Table 16 includes results of the in-situ presence ratings as well as the averaged retroreflectivity data by test section. Between April and July 2007, all of the markings were over-coated with standard Alaska Department of Transportation and Public Facilities (DOT&PF) pavement marking paint and beads as initially installed on test section 1 AK a. This material had failed to maintain presence and retroreflectivity through the first winter. The results in table 16 show that the performance of the paint in the second winter was the same. However, using paint to refresh durable markings that lost retroreflectivity but not presence over the winter appeared to be a viable solution for regions that experience winter conditions similar to those in Anchorage, AK.

The paint-based pavement marking systems including the advanced acrylic pavement markings were unable to maintain retroreflectivity and presence past their first winter season. Placing the paint-based pavement marking systems in a groove did not help these systems make it through their first winter. They were the only markings to fail in both durability measures (retroreflectivity and presence) after their first winter.

The only markings that maintained an adequate level of retroreflectivity past their first winter were the tape products installed in sections 5 AK a and 5 AK b. The tape products maintained adequate retroreflectivity past the second winter, although the presence on the lane line was judged as being less than adequate. As shown in table 16, the tape on the edge line continued to provide adequate presence and retroreflectivity through the end of 2008.

The only other pavement marking systems that maintained adequate presence through the first two winters were both applications of extruded MMA. Interestingly, there were no apparent service life differences between surface-applied, shallow groove, and deep groove applications for the individual marking systems in Alaska.

Two new pavement marking systems were installed in August 2008 and were evaluated in spring 2009. The remaining markings were also reevaluated at the same time to determine if they were able to maintain adequate levels of presence or retroreflectivity. The data collection trip that was scheduled for spring 2009 was the researchers' last planned trip to the Alaska test deck. The section of highway including the test decks along the Glenn Highway was scheduled for rehabilitation during summer 2009.

Table 16. Anchorage, AK, edge line pavement marking test deck results.

Test Section	8/28/06		9/25/06		4/23/07		7/16/07		10/2/07		5/13/08		8/5/08		9/28/08	
	P	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**
1 AK a	A	93	A	93	F	N/A	A	135								
1 AK b									A	404	A	80	A	78	A	77
2 AK a	A	294	A	276	F	N/A	A	164								
2 AK b									A	286	A	64	A	74	A	59
3 AK a	A	482	A	452	A	62	A	232	A	182	A	41	A	< 30	A	< 30
4 AK a	A	196	A	209	A	48	A	128	A	64	F	N/A	F	N/A	F	N/A
5 AK a	A	773	A	869	A	236	A	193	A	166	A	193	A	151	A	191
5 AK b	A	526	A	562	A	262	A	185	A	164	A	165	A	181	A	169
6 AK a	A	153	A	173	A	44	A	243	A	133	A	59	A	—	A	54
6 AK b	A	500	A	347	A	40	A	231	A	118	M	44	M	—	M	44
7 AK a	A	358	A	305	F	N/A	A	173	A	107	F	N/A				
7 AK b													A	218	A	210
8 AK a	A	550	A	446	A	108	A	189	A	91	M	107	M	—	M	98
9 AK a	A	436	A	369	F	N/A	A	186	A	106	F	N/A				
9 AK b													A	385	A	337
10 AK a	A	410	A	335	A	40	A	246	A	157	M	53	M	—	M	50

P = Presence rating from in-situ evaluations (A = Adequate, M = Marginal, F = Fail).
R = Average retroreflectivity (mcd/lx/m^2).
Note: Test deck sections with shaded cells indicate a pavement marking failed with a different material to test. Test Sections 1 AK a, 2 AK a, 7 AK a, and 9 AK a were remarked with different materials, and redesignated as 1 AK b, 2 AK b, 7 AK b, and 9 AK b, respectively. The dash (—) indicates missing data.

Tennessee

The pavement marking test sections on the Nashville, TN, test deck have been in service for over 2 years. All marking systems are still showing adequate retroreflectivity and presence. Table 17 and table 18 show the initial and most recent retroreflectivity readings for the edge lines and lane lines, respectively, for each of the different test sections. The data show that not all markings degraded at the same rate. Future retroreflectivity levels can only be accurately determined through continued data collection. The service life of all markings at the Nashville, TN, test deck based on the current data is greater than 2 years. The lead-free thermoplastic installations along the Nashville, TN, test deck were installed in June 2008. All of the installations continued to show adequate presence and retroreflectivity through the end of 2008.

Table 19 shows the initial and most recent retroreflectivity readings for the three lead-free yellow sections. The current retroreflectivity readings are all much higher than the initial retroreflectivity readings. The increase in retroreflectivity is likely due to the fact that the initial measurements were taken the same day that the markings were applied. Initially, the glass beads were slightly over-embedded. As the markings wore, more of the glass beads were exposed, and loose beads were removed, which improved retroreflectivity. Daytime and nighttime color measurements were recorded over time to address concerns that lead-free materials do not provide the same level of a saturated yellow color as do thermoplastic markings with lead chromate as a pigment. Like the retroreflectivity and presence measurements, there is not yet enough information from the color measurements to make an accurate recommendation on these lead-free thermoplastic materials.

Table 17. Nashville, TN, test deck edge line durability information.

Test Section	Edge line Retroreflectivity Levels ($mcd/m^2/lux$)			
	11/8/06 Shallow Groove	10/28/08 Shallow Groove	11/8/06 Deep Groove	10/28/08 Deep Groove
1 TN-N	N/A	N/A	390	172
2 TN-N	433	253	420	306
3 TN-N	398	342	384	435
4 TN-N	721	632	716	727
5 TN-N	732	287	N/A	N/A
6 TN-N	423	339	418	324
7 TN-N	1,217	449	1,413	618
8 TN-N	371	266	409	269
9 TN-N	598	342	599	327

N/A = Not applicable.

Table 18. Nashville, TN, test deck lane line durability information.

Test Section	Lane Line Retroreflectivity Levels ($mcd/m^2/lux$)			
	11/8/06 Shallow Groove	10/28/08 Shallow Groove	11/8/06 Deep Groove	10/28/08 Deep Groove
1 TN-N	N/A	N/A	N/A	N/A
2 TN-N	489	240	450	262
3 TN-N	428	373	389	410
4 TN-N	N/A	N/A	563	619
5 TN-N	659	269	N/A	N/A
6 TN-N	398	281	368	281
7 TN-N	991	410	1021	438
8 TN-N	392	254	416	251
9 TN-N	496	222	495	317

N/A = Not applicable.

Table 19. Nashville, TN, lead-free thermoplastic test deck durability information.

Test Section	Yellow Edge line Retroreflectivity Levels ($mcd/m^2/lux$)	
	6/5/08	10/28/08
10 TN-N	95	312
11 TN-N	152	300
12 TN-N	97	277

The pavement marking test sections at the Tusculum, TN, test deck have been in service for almost 2 years. The marking systems still show adequate retroreflectivity and presence, with the exception of the modified epoxy in section 1 TN-T. The presence of this material has been reduced to less than $^{1}/_{2}$ of the initial installation. The remaining materials still provide retroreflectivity levels significantly higher than 100 mcd/m^2/lux. The pattern of missing and present materials is an indication that the failure of the pavement marking system may be due to an installation problem and not a weakness of the material itself (see figure 8).

Figure 8. Photo. Tusculum, TN, test deck section 1 TN-T presence failure.

Table 20 and table 21 display the initial and most recent retroreflectivity readings for the edge lines and lane lines, respectively, for each of the different test sections. Like the Nashville, TN, test deck, the Tusculum, TN, data clearly show that the markings degraded at different rates. The data only record the degradation of these pavement marking systems during the first 2 years of service. Future retroreflectivity levels can only be accurately determined through continued data collection. Based on the current data, the service lives of all markings at the Tusculum, TN, test deck were greater than 1.5 years.

Table 20. Tusculum, TN, test deck edge line durability information.

Test Section	Edge line Retroreflectivity Levels ($mcd/m^2/lux$)			
	6/5/07 Shallow Groove	10/27/08 Shallow Groove	6/5/07 Deep Groove	10/27/08 Deep Groove
1 TN-T	673	310	686	238
2 TN-T a	510	463	531	350
2 TN-T b	509	187	494	521
3 TN-T	423	199	420	349
4 TN-T	415	380	397	365
5 TN-T a	856	449	945	482
5 TN-T b	1,030	605	966	415
6 TN-T	468	467	464	473
7 TN-T	650	390	695	417

Table 21. Tusculum, TN, test deck lane line durability information.

Test Section	Lane Line Retroreflectivity Levels ($mcd/m^2/lux$)			
	6/5/07 Shallow Groove	10/27/08 Shallow Groove	6/5/07 Deep Groove	10/27/08 Deep Groove
1 TN-T	560	213	496	309
2 TN-T a	549	374	447	304
2 TN-T b	470	245	472	386
3 TN-T	440	214	394	255
4 TN-T	389	319	358	337
5 TN-T a	838	352	780	302
5 TN-T b	908	355	861	214
6 TN-T	477	459	470	463
7 TN-T	505	340	470	357

PAVEMENT MARKING COSTS

The three pavement marking test decks had many different types of pavement markings installed, each of which had a range of expected costs. Geographical location, availability of materials, contract size, application type, material thickness, types of retroreflective optics used, timing of application, surface preparation requirements (e.g., removal of preexisting marking material, preparation of grooves, etc.), and traffic control costs all impact the installation cost of pavement markings. The researchers reviewed information on typical costs for the materials that were installed on the test decks. (See references 22–34.) For materials where costs could not be found in literature, estimated costs were developed based on the cost of similar materials and expected price differences. The pavement marking costs, combined with the pavement marking durability data, were the primary elements needed to determine cost effectiveness levels.
Table 22 displays the pavement marking costs found through a literature search and average bid costs for select States.

Wider pavement markings were found to increase the cost of the marking by varying degrees. Tennessee bid prices for increasing marking width from 4 to 6 inches for thermoplastic showed a 57 percent increase in cost for spray applications and a 50 percent increase in the cost of extruded applications. Other State bid prices indicated a 7 to 28 percent increase for paint and a 50 to 76 percent increase for thermoplastic. A 2002 report by Gates and Hawkins cited an internal memo from the Arizona Department of Transportation which stated, "The main drawback cited to the use of wider markings is the increased cost over 4-inch markings, the magnitude of which depends on the marking width, contract size, materials used and striping procedure. Recent cost estimates by the Arizona DOT [stet] predicted a 38 percent increase in contracted cost for 6-inch thermoplastic markings compared to 4-inch markings."(10)

Grooving the road surface to create an area to recess the markings can be a substantial cost addition to the pavement marking system. In a 2006 report by Lagergren et al., it was reported that groove costs could be $1.05/ft for a 100 mil groove and $0.95/ft for a 60 mil groove.(31) In a 2007 report by Hawkins et al., it was reported that grooves can cost between $0.40/ft and $1.40/ ft.(32) Milled shoulder rumble strips that are used for rumble stripes were found to cost between $0.10/ft and $0.16/ft.(33,34)

Table 22. Pavement marking cost information.

Marking Material	Width (inches)	Range of Expected Costs ($/ft)	Expected Cost ($/ft)
Waterborne paint	4	0.05–0.18	0.12
Waterborne paint	6	0.7–0.18	0.15
Thermoplastic spray	4	0.20–0.56	0.30
Thermoplastic spray	6	0.28–0.60	0.50
Thermoplastic extruded	4	0.47–0.58	0.50
Thermoplastic extruded	6	0.70–0.85	0.75
Thermoplastic inverted profile	4	0.62–0.87	0.75
Thermoplastic inverted profile	6	1.05	1.05
MMA spray	4	0.60–1.00	0.90
MMA extrude	4	0.80–1.65	1.10
MMA profiled	4	0.75–2.60	1.50
Tape	4	1.75–3.58	2.50
Polyurea	4	0.68–1.00	0.91
Polyurea	6	0.95–1.40	1.27
Wet reflective high build paint	4	0.19	0.19
Wet reflective high build paint	6	0.24	0.24
Grooving for in-laid markings	N/A	0.40–1.40	0.75
Milled shoulder texturing for rumble stripe	N/A	0.10–0.16	0.15

N/A = Not applicable.

Table 23 through table 25 show the estimated costs for the markings applied at the Anchorage, AK; Nashville, TN; and Tusculum, TN, test decks, respectively. Replications were removed, and materials were ordered from least to most expensive. The costs are displayed for a typical new application on the surface of the road and for an in-laid marking where the cost of the groove is $0.75 per ft. The costs are also on a per linear foot and per mile basis. The Nashville, TN, test deck costs are for 6-inch-wide markings, as this was the only width of marking applied at that test deck.

Table 23. Estimated pavement marking costs for Anchorage, AK, test deck.

Marking Type	Application Type	Surface Applied		In-Laid ($0.75/ft)	
		$/ft	$/mi	$/ft	$/mi
Low volatile organic compound (VOC) paint	Spray	0.12	634	0.87	4,594
Low temperature acrylic	Spray	0.12	634	0.87	4,594
High build acrylic	Spray	0.12	634	0.87	4,594
All weather paint	Spray	0.19	1,003	0.94	4,963
Paint	Double spray	0.30	1,584	1.05	5,544
Modified urethane	Spray	0.91	4,805	1.66	8,765
Polyurea	Spray	0.91	4,805	1.66	8,765
MMA	Spray	0.90	4,752	1.65	8712
MMA	Extruded	1.10	5,808	1.85	9,768
MMA	Agglomerate	1.50	7,920	2.25	11,880
MMA	Extruded w/ raised edges	1.75	9240	2.50	13,200
Tape	Rolled	2.50	13,200	3.25	17,160
Preformed thermoplastic	Heat in place	3.00	15,840	3.75	19,800

Table 24. Estimated 6-inch pavement marking costs for Nashville, TN, test deck.

Marking Type	Application Type	Surface Applied		In-Laid ($0.75/ft)	
		$/ft	$/mi	$/ft	$/mi
Low temperature acrylic	Spray	0.15	792	0.90	4,752
High build acrylic	Spray	0.15	792	0.90	4,752
All weather paint	Spray	0.24	1,267	0.99	5,227
Thermoplastic at 40 mil	Spray	0.30	1,584	1.05	5,544
Thermoplastic at 40 mil	Spray on rumble strip	0.45	2,376	N/A	N/A
Thermoplastic at 90 mil	Spray	0.50	2,640	1.25	6,600
Thermoplastic	Extruded	0.75	3,960	1.50	7,920
Thermoplastic	Inverted profile	1.05	5,544	1.80	9,504
Polyurea	Spray	1.27	6,706	2.02	10,666
Yellow lead-free thermoplastic	Extruded	0.75	3,960	1.50	7,920

N/A = Not applicable.

Table 25. Estimated pavement marking costs for Tusculum, TN, test deck.

Marking Type	Application Type	Surface Applied		In-Laid ($0.75/ft)	
		$/ft	$/mi	$/ft	$/mi
Low temperature acrylic	Spray	0.12	634	0.87	4,594
High build acrylic	Spray	0.12	634	0.87	4,594
Thermoplastic	Extruded	0.50	2,640	1.25	6,600
Modified epoxy	Spray	0.91	4,805	1.66	8,765
Modified urethane	Spray	0.91	4,805	1.66	8,765
MMA	Extruded	1.10	5,808	1.85	9,768
MMA	Agglomerate	1.50	7,920	2.25	11,880
Tape	Rolled	2.50	13,200	3.25	17,160

PAVEMENT MARKING COST EFFECTIVENESS

There are several aspects to achieving the most cost-effective pavement marking. The first and most direct aspect is to compare the net present cost over a given interval using the direct and indirect costs and service life of each candidate material. The researchers designed and implemented an experimental plan that was intended to evaluate the service life of various pavement marking materials under different environmental conditions. However, the data from this project cannot currently be used for calculation of net present cost. The Alaska data are not useful for such a comparison, as the harsh winter conditions caused most of the materials to fail in providing adequate retroreflectivity after only one winter season. Under these conditions, agencies must evaluate the benefits provided by the presence of markings, which include guidance during daytime and a template against which the road can be remarked. The Tennessee data are incomplete in that none of the alternative pavement marking materials have degraded to the point of failure as of the end of 2008.

Indirect costs that must be included in the overall evaluation of cost effectiveness include the delay and safety aspects imposed by striping and restriping activities as well as retroreflectivity measurements activities.[(26)] Another indirect cost that an agency may wish to include is the observed luminance of the pavement markings during wet night conditions. Materials that perform significantly better than average may eliminate the need for augmenting the pavement markings with delineators or RRPMs.

Given the conditions described above, a cost effectiveness calculation cannot be provided at this time. As a result, the research project has been extended through spring 2010 in order to develop additional data on the degradation rates and service lives of the alternative materials. The results of this activity will be documented in a final research report to the FHWA due in June 2010.

ADVANCED ACRYLIC WATERBORNE PAVEMENT MARKINGS FINDINGS

Two types of advanced acrylic waterborne pavement markings (commonly referred to as low temperature and high build) were installed at each of the pavement marking test decks. These markings were designed to provide better performance (high build is considered more durable under typical traffic conditions and allows use of larger optical components for improved retroreflectivity) and greater installation flexibility (low temperature can be applied at reduced ambient and road temperatures) than standard waterborne paint. The cost analysis shows that these paint systems were equivalent in cost to conventional highway paint and much less expensive than other durable pavement markings systems.

The durability of the advanced acrylic paints on the Anchorage, AK, test deck was not acceptable for a durable product (one that would last at least 1 year). Both types of acrylic markings were virtually gone after the first winter season, resulting in less than 1 year of service life.

The durability of the advanced acrylic paints on both Tennessee test decks is acceptable to date. These markings have retained adequate retroreflectivity and presence through the end of 2008. Both advanced acrylic markings are performing comparably to some of the other alternative pavement marking systems as well. As more data are collected at the Tennessee test decks, the durability and resulting cost effectiveness of the advanced acrylic markings will become more evident.

CHAPTER SUMMARY

Three pavement marking test decks were installed to evaluate the durability of various pavement marking materials, including advanced acrylic pavement markings. The goal of these test decks was to obtain the necessary durability data and combine that with cost information to assess the cost effectiveness of the pavement marking systems under evaluation. The test decks were evaluated three to four times per year through measurement of retroreflectivity and presence.

The test deck installed near Anchorage, AK, proved to be in a harsh environment for pavement markings of any type. Most of the markings tested on this test deck were deemed inadequate after their first winter even when installed in a recessed groove to minimize plow damage. The paint-based pavement marking systems, including the advanced acrylic pavement markings, were unable to maintain retroreflectivity and presence past the first winter season. The only markings that maintained adequate presence through the first two winters were the extruded MMA and the tape on the edge line. The tape product did not provide the same level of presence on the lane line as compared to the edge line. It is believed that the added weaving to which lane lines were exposed was responsible for the accelerated degradation of the tape product. The only marking that maintained adequate retroreflectivity through the first two winters was the tape on the edge line. The tape was the most expensive alternative marking installed on the Anchorage, AK, test deck, and it required application in a groove in areas where snow plow operations were expected. If maintained retroreflectivity and presence are deemed to be necessary throughout the winter months and into the spring, then the in-laid tape marking is the only system tested that is able to achieve these performance levels and only for 1 year on the lane lines.

One strategy that the DOT&PF uses is applying a durable MMA marking in a groove and then remarking the MMA with low VOC paint each spring to provide adequate retroreflectivity through the summer and fall. This procedure provides a marking with year-round presence and retroreflectivity from the time the markings are restriped with paint in the spring until the paint wears away during the winter. Without considering the indirect costs of traffic delays and risk of crashes involved with more frequent striping activities, this may be the most cost-effective method for the conditions tested on the Alaska test deck. One option that may be equally effective but reduce the amount of hazardous chemicals is the use of low-temperature advanced acrylic paint in place of the low VOC paint for the spring painting activities.

Two test decks were installed in Tennessee, one near Nashville and another near Tusculum. Essentially, all of the markings being evaluated on the Tennessee test decks continue to provide adequate presence and retroreflectivity. While the markings are not degrading at the same rate, none have reached a point where the retroreflectivity has fallen below the minimum level established for this project of 100 $mcd/m^2/lux$. As a result, the cost effectiveness of the alternative pavement marking systems installed on the Tennessee test decks cannot be determined at this point. These markings continued to be evaluated through the 2009–2010 winter.

CHAPTER 4. STATE BIDDING AND PROCUREMENT PROCESSES

The procurement of pavement markings is often a source of conflicting demands placed on agencies. *Procurement* is not only the simple definition of the purchase of the materials; rather, the term refers to a more holistic view of a contracting mechanism that provides for the purchase and application of pavement marking materials at locations determined by a contracting agency.

As with any contract, the following basic question is asked: How does an agency ensure that it is getting what it has paid for? Typically, this is done by establishing a standard or specification that the contractor must meet. Herein lies the crux of the problem for procuring pavement markings.

While much of the information used to establish the basic standards and specifications are based on previous research and basic scientific principles, there has been an explosion of radically different types of products for pavement marking applications. This growth in product base has outstripped the capability of the research community to adequately and scientifically establish a rigorous basis for what type of pavement marking works best for different applications and locations. While a recent report proposes recommended minimum pavement marking retroreflectivity levels, it does not provide agencies with information on which materials will meet those minimum levels for a given period of time on a specific roadway under typical traffic conditions.[35]

Most State agencies have developed their own standards or specifications to adequately identify pavement marking materials for their specific applications, needs, and regions. Given the vast differences in applications across the country, significant weather differences, differences in vehicle and user populations, and a host of additional factors, the specifications that users have established may be significantly different. In fact, several different types of specifications now exist, including the recipe or component specification, the performance-based specification, and the warranty specification. Complicating the situation even more is that these specifications and the overall performance characteristics change based on the type of pavement marking material (paint, thermoplastic, preformed tapes, etc.).

The following is a root question pertaining to these differing specifications: What are the advantages and disadvantages of any given type? Most importantly, is there evidence to assess the fundamental quality of the pavement markings as a function of the specification used to obtain them? If so, scientific research could be focused on creating a pavement marking specification with potential national applicability which would ensure the desired quality. This in turn could provide better roadway information for drivers, potentially decrease crashes, and save money.

SPECIFICATION TYPES

In the recipe or component specification, the specification defines the materials and application parameters for the components of the pavement marking system. Markings are installed by the contractor using marking materials that meet the specification using procedures defined in the specification. This includes parameters such as the type of paint, the size and amount of retroreflective beads per mile of roadway, the immersion depth of the beads, the temperature of the paint and road, and the ambient weather conditions. The specification can get detailed, which can be a significant advantage because agencies know exactly what they are paying for because the provisions of the materials and placements are all tightly defined.

In direct contrast to the recipe specification, a performance-based specification does not define the specifics of the materials and their placement; rather, it defines the overall goal that must be met by the markings. This goal, which typically seeks a minimum level of retroreflectivity within a prescribed number of days of placement, aims to establish a sufficiently high peak or starting point of the pavement marking material. While the performance is known to degrade over time, establishing a performance peak at the beginning essentially assumes a normal "wear and tear" cycle over the anticipated life of the material. This assumption results in the anticipation that the minimum level of the performance indicator (such as retroreflectivity) will coincide with the physical end-of-life cycle of the material, leading to the material being replaced at exactly the right time. An advantage of this type of specification is that it requires less manpower from the agency to inspect markings at the time of application. However, not enough is known about the marking performance over time in different locations and applications to accurately set initial performance metrics to produce repeatable end-of-life cycles.

The warranty specification is essentially a type of performance specification. However, instead of focusing on an initial metric, the specification focuses on what the performance metric (typically retroreflectivity) should be at the end of the life cycle of the marking. This life cycle may vary greatly depending on the application and type of material. Some warranty specifications are up to 5 years long. If the metric is not met at the end of the service life, the contractor must replace the marking under warranty. The use of this procurement method has obvious implications on contracting timeframes, lengths of contracts, payment schedules, inspection procedures, and other similar items.

SURVEYS ON STATE BIDDING AND PROCUREMENT PROCESSES

As stated previously, the following is a fundamental question: What are the advantages or disadvantages of any given specification mechanism? Additionally, do these advantages provide the capability to assess the quality of the markings procured under any type of specification? Given that the scientific evidence to answer these questions is lacking, most of the available information comes from surveys or workshops.

A 2007 survey performed for the Iowa Department of Transportation (Iowa DOT) Pavement Marking Task Force investigated the use of performance-based specifications across other State transportation departments.(36) Of the 23 responses received, 13 indicated the use of some type of performance-based specification, most typically requiring a minimum initial retroreflectivity. The responses were varied in terms of what types of materials were procured by a performance specification. A number of responses indicated a mix of specification types where paint used a recipe specification but more advanced types of markings such as thermoplastics and tape utilized a performance characteristic. In most cases, the performance metric was initial retroreflectivity. Of the 23 responses, only 5 responses, or 22 percent, used a performance specification across all marking types.

There were no additional follow-up questions relating to the specification type, quality assessments, or any information pertaining to actual or perceived quality of the markings obtained by the different specification mechanisms. Therefore, the only real observation that can be drawn is that while performance specifications are in use in some respect in roughly 50 percent of the States, their wholesale application to all material types is much smaller. Many States are still using the recipe specification, especially for paint, which is the most common pavement marking material.

The National Cooperative Highway Research Program Project 39-13, "Pavement Marking Warranty Specifications," focused on a national survey on State experiences with warranty specifications in 2008. The research team took advantage of this opportunity to request the addition of several questions that were specifically related to the effect of State bidding and procurement processes on the quality of pavement marking material. While the survey had a number of questions, the first question (shown in figure 9) was directly comparable to the 2007 Iowa DOT survey described above.

1. What type of pavement marking procurement process does your agency use for contractor-installed long-line pavement markings?

	Recipe or Component Specification	Performance-Based Specification	Warranty Specification	In-House Marking Application
Paints	☐	☐	☐	☐
Thermoplastics	☐	☐	☐	☐
Multicomponents	☐	☐	☐	☐
Preformed Tapes	☐	☐	☐	☐
Others	☐	☐	☐	☐

Figure 9. Chart. 2008 survey question—procurement process.

Figure 10 shows the graph of the responses for the first question in the 2008 survey. A total of 29 responses were received from agencies, which included State transportation departments and Canadian provinces. While it is evident that the majority of the respondents are still using a recipe specification for the procurement of most types of pavement marking materials, a closer look at the data reveals some interesting facts. In many cases, agencies reported the use of more than one type of specification. For example, for the procurement of paint markings, 6 of the 29 respondents indicated the use of both recipe- and performance-based specifications. Four respondents indicated that they used overlap for thermoplastics, four respondents indicated that they used multicomposite, and seven indicated that they used preformed tapes. These results demonstrate that agencies are not limiting themselves to a single procurement mechanism for a specific marking material. It may also show that agencies are using composite specifications such as a recipe specification with some performance requirements (e.g., initial retroreflectivity). Because these results were somewhat unexpected, there is insufficient detail in the later questions to explore this issue in more depth.

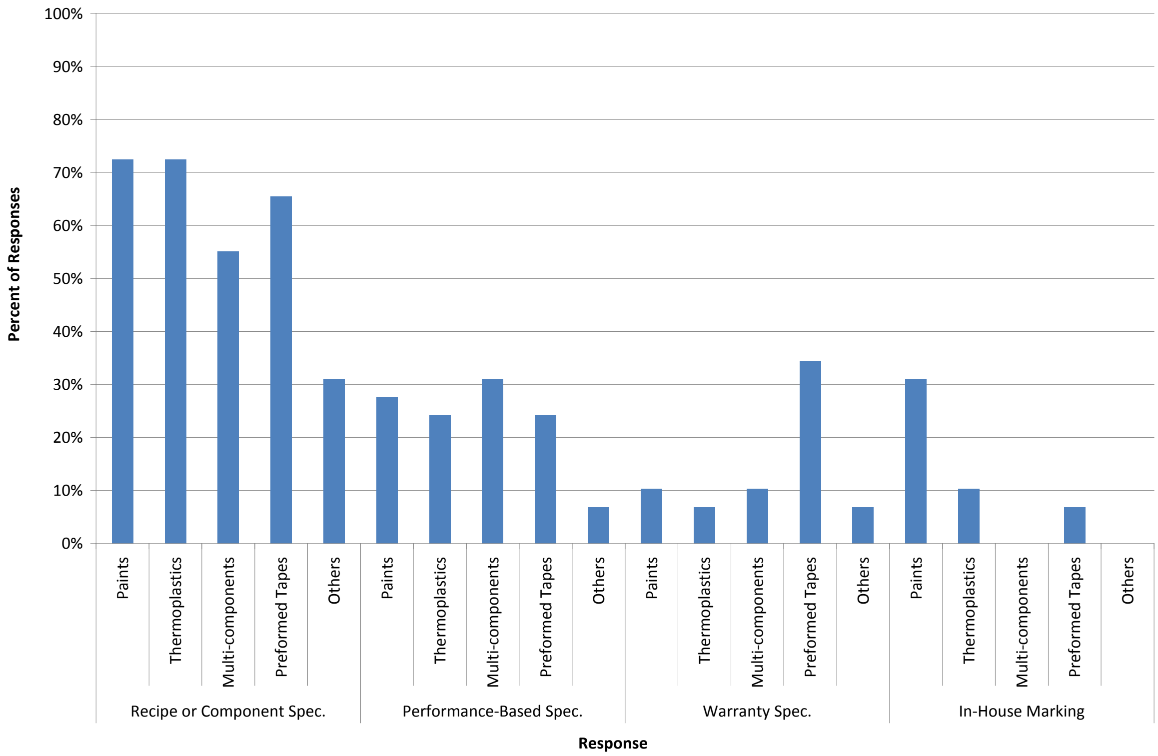

Figure 10. Graph. 2008 survey response—type of specification versus material.

A comparison of the responses by agencies that participated in both the 2007 and 2008 surveys is also interesting. There were 12 agencies that responded to both surveys. Of these, seven reported the same results in both surveys. One agency that reported the use of performance-based specifications in 2008 did not report that same use in 2007. Four agencies which had reported the use of performance-based specifications in 2007 did not indicate the use of such specifications in 2008. However, the second question of the 2008 survey (shown in figure 11) which addressed the issue of changes in the specification type used to procure pavement markings, indicates that agencies did not actually revert back to a recipe specification after using a performance specification. Therefore, differences in responses between 2007 and 2008 may be due to differences in how the questions were asked and how the answers were tabulated.

2. Has your agency's pavement marking procurement process changed from a recipe specification to a performance-based specification or a warranty specification or a combination of the above (for any or all pavement marking systems used by your agency)?

☐ Yes – *Please answer questions 3 - 6.*
☐ No – *Please explain why not, and particularly if your agency has tried a different type of specification only to go back to a recipe specification.*

Figure 11. Chart. 2008 survey question—procurement process change.

Fourteen respondents answered "yes" to the question in figure 11, while 15 respondents answered "no." There was no timeframe mentioned with regard to the change in specification, so there were no direct comparisions available to the 2007 survey. The list of responses from the 15 agencies stating "no" includes the following:

- "We have implemented a performance-based spec for temporary markings in one of our regions. All permanent markings and temporary markings in the other regions use recipe/ component specifications. Performance specifications have not been implemented due to funding issues for conducting the retroreflectivity testing."

- "Neither performance-based nor warranty-based specifications are used because we do not want to keep contracts open when monitoring pavement marking performance. In-house application only."

- "We are considering changing to performance-based but haven't had time to pursue it yet."

- "Always relied on performance evaluations."

- "Performance-based specifications seem to be of greater benefit in more northern climates where the striping cycle is shorter and subject to more harsh conditions. To date, we have not identified a definite benefit of performance-based contracts. Also, we may not have sufficient manpower to correctly monitor the condition of markings over a lengthy contract."

- "We supply the product (paint and glass bead) which we procure using a component specification. Placement by private contractors is performance-based (most placement is done by our own department forces). We work with paint suppliers to develop the specification for the materials and this collaborative approach is working well. As a result, there are no plans to change the process."

- "We have better control with the recipe. We tried one warranty but it was painful. The supplier eventually honored the warranty, but it was like pulling teeth."

- "We have had success with this type of specification."

- "We only approve pavement markings that are placed on our NTPEP (National Transportation Product Evaluation Program) Test Deck."

Questions 3–6 of the 2008 survey focused on ascertaining the reasons for the change as well as any benefits or consequences.

Question 3 listed several common reasons for changing from a recipe to a performance-based specification and asked respondents to identify all those reasons which were applicable (see figure 12).

3. What were the underlying reasons for the change?

- ☐ Lack of State forces for inspection
- ☐ Lack of quality / durability
- ☐ Initial costs
- ☐ Life-cycle
- ☐ Reported benefits
- ☐ Research findings
- ☐ State regulations
- ☐ Others:

Figure 12. Chart. 2008 survey question—reasons for process change.

Many agencies responded with more than one reason, so the total number of responses represented in figure 13 is significantly greater than the number of agencies (14) that indicated a switch in their specifications.

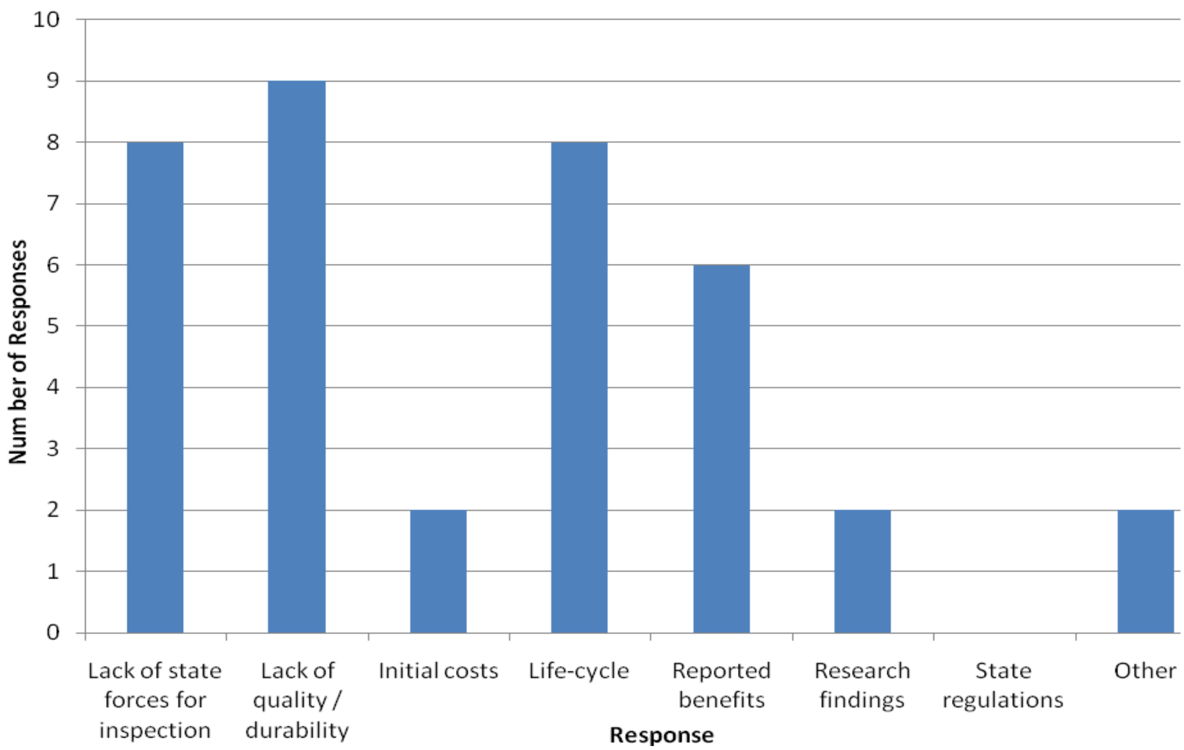

Figure 13. Graph. 2008 survey response—reasons for switching to performance-based specification.

The four most common answers were the following:

- Lack of State forces for inspection.
- Lack of quality/durability.
- Life-cycle costs.
- Reported benefits.

The lack of State forces for inspection is a significant answer because it points to a particular onus or disadvantage of the recipe specification. In a recipe specification, because individual components are detailed, a significant amount of checking or inspection may be required to assess if the contractor is applying the materials in accordance with the specification. By comparison, in a performance-based specification, the inspection needs are typically reduced since a reduced number of performance indicators such as retroreflectivity are inspected.

The answer for a lack of quality or durability indicates that a significant number of the respondents are trying to increase the quality of their pavement markings and are using performance-based specifications as one avenue to achieve that goal.

Question 4 of the 2008 survey asked respondents to identify the benefits of the move to a performance- or warranty-based specification (see figure 14). Although the format of the question provided no mechanism to differentiate between expected and realized benefits, respondents were asked to check all the answers that applied. Because of this, the tally of the number of responses to the individual items in question 4 is larger than the number of respondents answering "yes" to question 2.

4. What were the expected and realized benefits (please provide examples if available)?

- ☐ Lower initial costs
- ☐ Higher initial costs
- ☐ Lower life-cycle costs
- ☐ Higher life-cycle costs
- ☐ More durable markings
- ☐ Less durable markings
- ☐ Innovative products or application techniques
- ☐ Industry teaming / innovation
- ☐ Others:

Figure 14. Chart. 2008 survey question—expected and realized benefits.

Figure 15 shows that the highest number of responses were associated with a desire to lower the life-cycle costs and obtain more durable markings. This indicates that agencies use or are at least investigate the use of performance- or warranty-based specifications to improve the quality of the pavement markings.

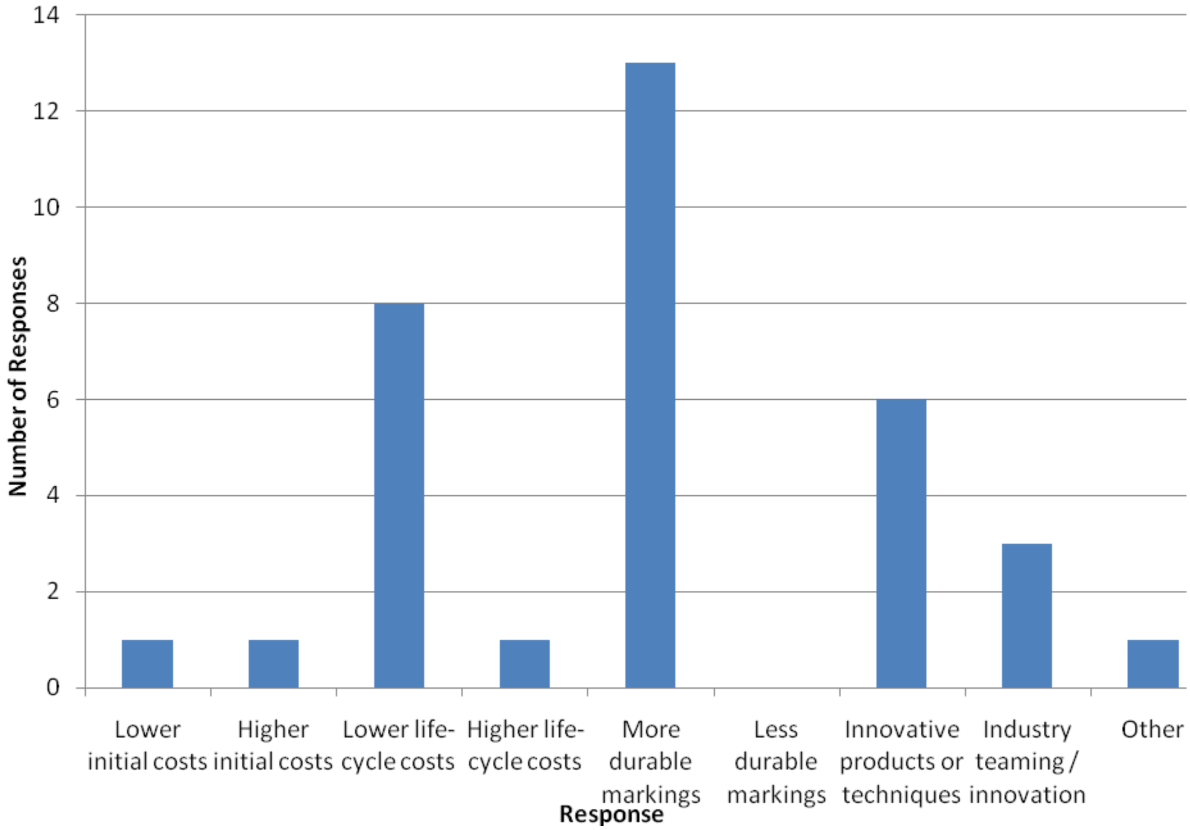

Figure 15. Graph. 2008 survey response—benefits of switching to a performance-based or warranty-based specification.

Question 5 of the 2008 survey investigated whether there were any unintended circumstances of the switch in specification type (see figure 16). Respondents were once again asked to check all the answers that applied. Because of this, the tally of the number of responses to the individual items in question 5 was larger than the number of respondents, indicating a switch in their specifications.

5. Were there any unintended consequences?

- ☐ Reduced number of contractors
- ☐ Disputes between owner and contractor regarding retroreflectivity
- ☐ Responsibility of retroreflectivity reporting
- ☐ Additional administration burdens
- ☐ Others:

Figure 16. Chart. 2008 survey question—unintended consequences.

Figure 17 shows a fairly even distribution across all the responses. The expectation therefore is that a switch to a performance- or warranty-based specification should hold no hidden trouble spots.

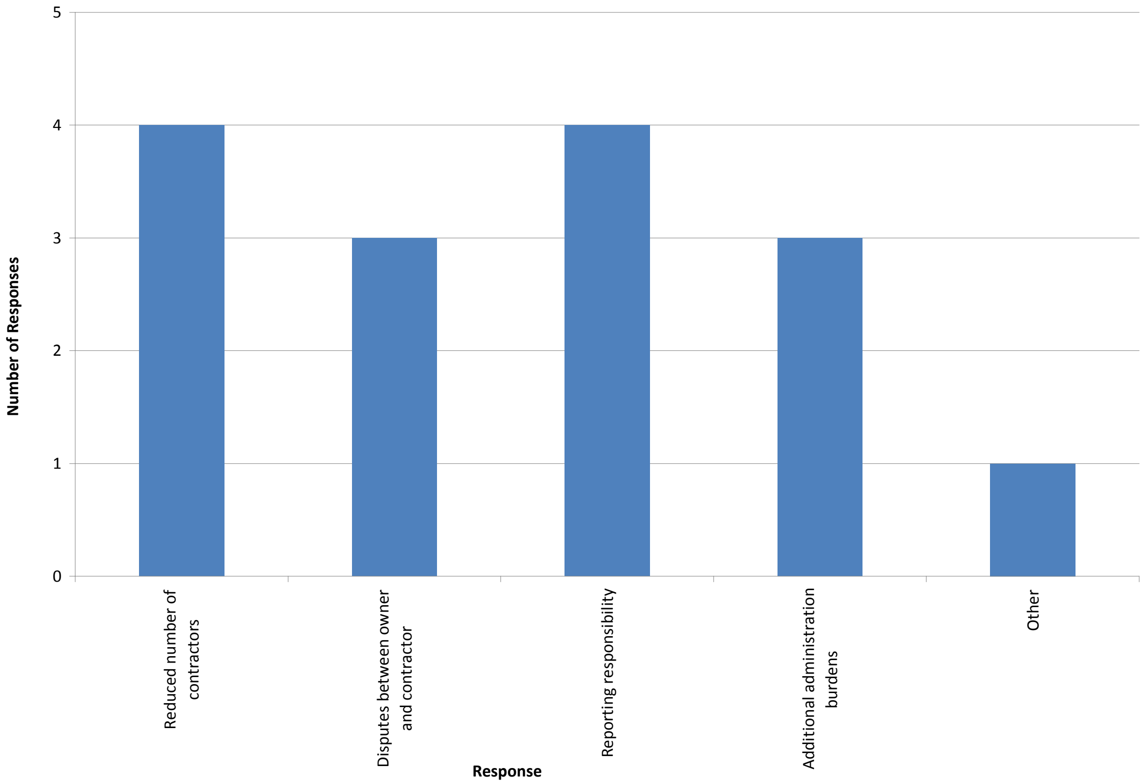

Figure 17. Graph. 2008 survey response—unintended consequences of switching to a performance-based or warranty-based specification.

The final question in the 2008 survey was an open-ended question asking respondents to describe how the change in specification in use has affected the quality of the markings. The following responses were received:

- "It's too early to tell. We've only been using the warranty specification for a couple of years, and it's still undergoing revisions now."
- "There are many reasons, but the primary reasons are that our State forces did not prioritize in placing pavement markings. Many times the pavement markings were placed repetitively, or not placed at all within a timely manner. Reduced staff, increased maintenance, costs of inspections with materials and placing of markings was very burdensome to our agency."
- "The quality of the markings has improved dramatically. With the institution of initial performance retro requirements, the quality of our lines has improved. Prior to performance specs, we had no standards for initial readings and lots of complaints about poor quality work."
- "The changes have made our State have longer lasting more durable markings and better wet reflective markings at night."
- "With the existing contract it is near impossible to measure the mil thickness of material

going down. Industry has complained that in order to achieve the retro values that they had to use less paint. In the proposed contract, we are specifying a minimum mil thickness that they will have to verify by onboard computer, and still maintain the retro values (200 and 150)."

- "The retroreflectivity of the temporary markings (that used paint) has improved."

- "Almost all pavement marking is done with State maintenance crews. In the past, we used Contractor applied markings in high traffic areas using epoxy. However, we had persistent problems in getting the work done in a timely manner, and in getting acceptable initial retroreflectivity values. This program was abandoned, and our State maintenance crews began applying high-build waterborne paint in high traffic areas. We feel we are getting acceptable quality using waterborne paint that is applied with State crews."

- "We are using more durable products (thermoplastic, MMA, and epoxy) at high traffic locations."

- "Overall, the quality of the markings is good, and if not, they will be addressed by the warranty process."

- "Better, longer lasting markings."

- "We use a combination Recipe Spec and Performance-based Spec. This spec pertains only to our annual restriping with maintenance materials: waterborne paint and sprayable thermoplastic. Attached is a copy of our special provision for adjusted payment. This spec, or variations of it, has been used for approximately 10 years. We have seen retro readings increase as the contractors have taken responsibility for the marking quality. We have an independent retro contractor take readings on our maintenance markings, which are placed between May 1 and August 31. These measurements are taken between September 15 and October 31, depending on the location in the State. Maintenance type markings on construction projects are not measured. There are inspectors on construction projects. With our durables (multicomponent and tape products) we expect the contractor/manufacturer to right any problem. Most problems with durables are installation related. Any material can be removed from the qualified products list if the performance is not as we expect."

- "Performance-based specifications put more responsibility on the contractor to provide a quality product."

- "We generally feel that with the performance-based specification for epoxy resin pavement markings (the type of pavement marking material used throughout the State for permanent marking applications), we are receiving new markings with better retroreflectivity than before when only component specifications were used. Regarding warranty specifications (as defined in this survey), we have used only for "job-specific" preformed patterned tape markings, which we use for broken lane lines on freeways and expressways on only a limited basis. However, quality has been an issue with these types of markings even though we used a warranty specification, as we have experienced several disputes between contractor/material vendor regarding responsibilities for repair/replacement of inlaid tape markings deemed unacceptable."

- "Improved life-cycle cost on major roadways."

CHAPTER SUMMARY

There is no research that conclusively demonstrates that a move to performance- or warranty-based specifications for the procurement of pavement markings will result in higher quality installations. In fact, as evidenced by reviewing recent surveys of State agencies, there is a wide disparity in how agencies are procuring pavement markings. This is perhaps influenced by the lack of a national standard for basic pavement marking performance, such as retroreflectivity.

The surveys cited in this report show some important trends and information. First, many States are implementing or at least experimenting with performance- or warranty-based specifications. It is reasonable to assume that in a time of significant fiscal constraints, this trend represents an underlying belief that the pavement marking procurement process can be improved by moving to a different type of specification. Furthermore, responses from the surveys indicate that many of the agencies investigating these types of specifications are doing so to obtain higher quality, longer life cycles, increased durability, and a reduction in administrative costs such as inspections.

The scope of these responses goes beyond one or two agencies and is largely similar across different surveys performed at different times. Not only does this provide some degree of verification to each survey effort, but it also indicates a widespread national interest in improving the quality of pavement markings. The procurement process is certainly one area that appears reasonable to have an impact on that quality by moving to a mechanism that prescribes expected results regardless of the makeup of the materials.

The effort that State and local agencies expend on the installation and maintenance of pavement markings, as indicated through the surveys and the direct and supportive participation in the demonstration projects, indicates that these agencies are exercising due diligence in meeting their fiduciary responsibilities for providing a critical public service at the lowest possible cost.

CHAPTER 5. ENVIRONMENTAL AND SAFETY ISSUES

The objective of this part of the study was to conduct an evaluation of the potential health and environmental impacts of the alternative pavement marking systems that were included in the demonstration projects and the specific materials used in those systems. Prior to 1990, solvent-borne paint was used by many agencies for pavement marking binder material. In the early 1990s, practically all transportation agencies in the United States reduced the use of solvent-borne paint primarily due to Environmental Protection Agency (EPA) requirements on dangers due to solvents. Waterborne and latex paint have replaced the solvent-borne paints of earlier years. In addition, some new durable materials have been introduced, all of which meet the EPA requirements. However, some of the new more durable materials have specific issues associated with cleaning tanks and spray guns and with disposal of the debris resulting from grinding or hydroblasting old and worn marking materials from the roadway. If these types of products are found to be effective in terms of their durability and performance, as evaluated in the demonstration projects, then the research team will identify the environmental issues associated with their use. The most knowledgeable source of this information is the industry. Therefore, the research team plans to work with the appropriate industry representatives to identify the environmental concerns and issues, including storage of materials, proper cleaning of equipment, and proper handling of debris from marking removal efforts.

GENERAL INFORMATION

The environmental and health and safety impacts of pavement marking systems need to be considered in light of the various regulatory requirements. The following lists show where additional information can be found concerning those impacts:

Environmental

- Hazardous Waste (EPA)—see http://www.epa.gov/epawaste/laws-regs/index.htm.
- Clean Air Act (EPA)—primarily VOC emissions. See http://www.epa.gov/air/caa.
- Clean Water Act (EPA)—pertains to discharge into waterways, e.g., from spills. See http://www.epa.gov/regulations/laws/cwa.html.
- Federal Hazardous Materials Transportation Law (USDOT Pipeline and Hazardous Materials Safety Administration)—impacts manufacturers and striping crews transporting pavement marking materials. See http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/Hazmat%20Law%20Overview.pdf.
- National Air Quality Standards for Lead (EPA)—recently strengthened and impacts manufacturers. See http://www.epa.gov/air/lead/actions.html.

Health and Safety

- Hazard Communication Standard (Occupational Safety and Health Administration (OSHA))—applies to products as supplied, it does not address worker exposure during eradication. See http://www.osha.gov/SLTC/hazardcommunications/index.html.

- Lead Standard (OSHA)—affects manufacturers, striping and eradication crews. See http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10641.

- Hexavalent Chromium Standard (OSHA)—see http://www.osha.gov/SLTC/hexavalent chromium/index.html.

HEAVY METALS IN GLASS BEADS

The U.S. manufacturers of glass beads used in pavement markings have recently expressed concern about the importation of glass beads from Third World countries, particularly China. Overseas producers have considerably lower production costs, and U.S. producers have become concerned about competition and erosion of their markets. They have raised concerns about foreign glass beads containing significant levels of heavy metals, which could be a potential safety and environmental concern to users in the United States.

The primary elements of concern appear to be lead, arsenic, and antimony. Some glass manufacturers deliberately add lead and arsenic to glass (particularly optical glass) to impart clarity and control bubbles. Glass recycled from television sets and computer monitors are another potential source of all three elements. Many electronics recycling programs send their products overseas to be dismantled, which may be a way that these elements enter the manufacturing process. As a precaution, a number of agencies worldwide are beginning to implement specifications that limit the total heavy metal content of glass beads (see table 26).

Table 26. Specifications for heavy metal content of glass beads (ppm).

Agency	Arsenic	Lead	Antimony	Barium	Cadmium	Chromium	Selenium	Silver	Mercury
Washington State Department of Transportation [37]	20.0	50.0	No limit	100.0	1.0	5.0	1.0	5.0	0.2
California Department of Transportation 2008 [38,39]	200	200	200	10,000[a]	100	500[b]	100	500	20
CA proposed legislation 2008 [40]	75								
UK Highways Agency [41]	750[c]	200	1,000						
CEN 1423 proposed [42]	nd–1,000[d]	nd–1,000	nd–1,000						
ÖNORM (Austria) [43]	200								
Main Roads Western Australia [44]	50[e]	50[e]	50[e]						

[a] Excluding barium sulfate.
[b] As Cr(VI).
[c] Equivalent to 1,000 ppm arsenic trioxide cited in the standard, converted to elemental arsenic for comparison in this table.
[d] nd = not detectable (detection limit not specified, as it depends on the test method, actual regulatory limit depends on the application).
[e] Also being considered as the Australia/New Zealand standard.[45]
Note: Blank cells indicate missing data.

As can be seen, the limits vary widely, and some of these standards may be hard to achieve. Most beads are made from waste glass from recycling programs, and restrictions on heavy metals may impact the environmental benefit of recycling. There is also the potential that overly restrictive limits on heavy metals may impact optical performance of beads by reducing clarity.

The magnitude of environmental and safety hazards of heavy metals in glass beads is somewhat uncertain. Heavy metals in glass beads do not appear to be leachable under the conditions of the EPA Toxicity Characteristic Leaching Procedure (TCLP) test, which defines toxicity under current hazardous waste regulations. In fact, vitrification appears to be an acceptable method of disposing of heavy metal wastes.[46] An ongoing project at Rowan University studies the total heavy metal levels in various batches of domestic and foreign sourced beads and leaching under a variety of conditions including the presence of snow and ice control chemicals.[47] This project will be completed in June 2010.

RECENT ENVIRONMENTAL REGULATIONS IMPACTING PAVEMENT MARKINGS

In 1994, FHWA released a memorandum describing the impact of a new EPA regulation on the use of pavement marking material. The regulation was developed to reduce architectural and industrial maintenance coating emissions by 40 percent by 2004. It led to the establishment of a 1.25 lb/gal limit by 2000 and a 0.83 lb/gal limit by 2004 on VOC content for pavement marking materials. Over the past 10 years, transportation agencies in the United States have gradually replaced conventional solvent paints with waterborne paints (that have low VOC contents) and other newer pavement marking materials.

Waterborne traffic paints are the most widely used and least expensive pavement marking materials available. *Waterborne paints* are single-component paints that are ready for application and do not require additional ingredients. They are environmentally friendly and much easier to handle than conventional solvent paints. They greatly decrease the safety hazard for workers given their low VOC content (typically less than 1.25 lb/gal of VOC). This reason, coupled with the low cost, are the major advantages of waterborne paints.

On February 28, 2006, OSHA published the final hexavalent chromium Cr(VI) standard. The new permissible exposure limit for Cr(VI) is 5 $\mu g/m^3$. In the pavement marking arena, this is primarily an issue for agencies using thermoplastic binders. Most States have moved to lead and chromate-free specifications for thermoplastic, which is the most commonly used durable pavement marking system in the United States. New regulations make it difficult for the industry to handle lead chromate in the dry form in the manufacturing plant. Thermoplastic manufacturers are pushing for lead-free and chromium-free specifications. Some States are concerned and are specifying resin-encapsulated lead chromate pigments, which will meet the new regulations but push the problem further upstream. This means the encapsulated process is usually outsourced from the United States to avoid environmental concerns. There is still the issue of line removal when encapsulated specifications are used. The researchers are testing lead-free thermoplastics in Tennessee; the main issue is the maintained nighttime yellow color.

On October 15, 2008, the EPA strengthened the national ambient air quality standards for lead. The revised standards are 10 times more stringent than the previous standards and will improve health protection for at-risk groups, especially children. The EPA has revised the level of the primary (health-based) standard from 1.5 $\mu g/m^3$ to 0.15 $\mu g/m^3$, measured as total suspended particles. This change is mostly going to impact the requirements for removal of thermoplastic, as it is usually done with a grinding mechanism, creating significant quantities of dust. Grinding operators and bystanders will most likely be exposed to levels above the new EPA regulations unless proper respiratory gear is used. Waterblasting may be a technique that could be used to reduce the exposure, but it may still violate the new EPA regulations. No research has been conducted in this area; however, as manufacturers push for lead-free and chromate-free thermoplastic specifications, there will soon be lead-free and chromate-free markings. However, there are currently thousands of miles of thermoplastic markings on the roads that will be removed by grinding and/or waterblasting. The removal of these lines and the environmental concerns inherently associated with the removal process will be the largest challenge related to thermoplastic markings.

CHAPTER SUMMARY

State agencies are changing to lead-free and chromate-free thermoplastic markings, thereby satisfying the most recent environmental regulations. The latest EPA airborne lead regulation may cause a concern for agencies that try to remove lead-pigmented thermoplastic pavement markings. No research has been conducted to date to determine the amount of airborne lead released when encapsulated lead-pigmented thermoplastic is removed (by grinding or waterblasting).

Some multicomponent materials tested on the Alaska and Tennessee test decks are qualified as hazardous materials. Depending on the results of the Tennessee durability information and the final recommendations made from that information, there may be other environmental concerns resulting from this effort. However, the durability test decks in Tennessee are not yet old enough to make recommendations concerning specific pavement marking materials.

An evaluation of the potential environmental and health impacts of heavy metals in glass beads used in pavement markings was beyond the scope of this study. The magnitude of environmental and safety hazards of heavy metals in glass beads is somewhat uncertain. Heavy metals in glass beads do not appear to be leachable under the conditions of the EPA TCLP test which defines toxicity under current hazardous waste regulations. In fact, vitrification is an acceptable method of disposing heavy metal wastes. An ongoing project at Rowan University is studying total heavy metal levels in various batches of domestic and foreign sourced beads and leaching under a variety of conditions, including the presence of snow and ice control chemicals. This project will be completed in June 2010.

CHAPTER 6. CONCLUSIONS

This report, prepared in response to requirements in SAFETEA-LU § 1907, provides a summary of findings regarding a pavement marking demonstration project carried out in Alaska and Tennessee.

IMPACTS OF WIDER PAVEMENT MARKINGS

Earlier crash studies conducted on wider pavement markings have been inconclusive, showing no particular benefit. The research summarized herein is based on two independent analyses of the potential benefit of wider pavement markings on rural two-lane highways—one using an EB before-after analysis and the second using a cross sectional analysis based on a binomial regression model.

- An EB before-after evaluation of crash data in Michigan resulted in positive safety effect estimates for total, F + I, PDO, daytime, daytime F + I, nighttime F + I, wet, wet night, single vehicle wet, and opposite direction crashes.

- A negative binomial regression analysis based on crash data in Illinois aggregated for 6 years resulted in positive safety effect estimates for F + I, daytime, daytime F + I, nighttime F + I, wet, single vehicle wet, and fixed object crashes.

The crash surrogate study results support previous findings, which show that there are either no real vehicle operational impacts or, at most, only subtle vehicle operational impacts as a result of adding or widening edge line markings, even for narrow two-lane highways and day and night conditions.

COST EFFECTIVENESS OF PAVEMENT MARKINGS

The Anchorage, AK, test deck proved to be a harsh environment for pavement markings of any type. Most of the markings tested on this test deck were deemed inadequate after the first winter, even when installed in a recessed groove to minimize plow damage. Paint-based pavement marking systems, including the advanced acrylic pavement markings, were unable to maintain retroreflectivity and presence past the first winter season. The only markings that maintained adequate presence through the first two winters were extruded MMA and tape. The tape product did not provide the same level of presence on the lane line as compared to the edge line. It is believed that the added weaving to which lane lines are exposed was responsible for the accelerated degradation of the tape product. The only marking that maintained adequate retroreflectivity through the first two winters was the tape on the edge line. The tape was the most expensive alternative marking installed on the Anchorage, AK, test deck and required application in a groove in areas where snow plow operations were expected. If maintained retroreflectivity and presence are deemed to be necessary throughout the winter months and into the spring, then the in-laid tape marking is the only tested system that was able to achieve these performance levels for only 1 year on the lane lines.

One strategy that the DOT&PF uses is applying a durable MMA marking in a groove and remarking the MMA with low VOC paint each spring to provide adequate retroreflectivity through the summer and fall. This procedure provides a marking with year-round presence and retroreflectivity from the time the markings are restriped with paint in the spring until the paint wears away during the winter. Without considering the indirect costs of traffic delays and the risk of crashes involved with more frequent striping activities, this may be the most cost-effective method for the conditions tested on the Alaska test deck. One option that may be equally effective and reduce potential environmental concerns is the use of low-temperature advanced acrylic paint in place of the low VOC paint for the spring painting activities.

Two test decks were installed in Tennessee, one near Nashville and another near Tusculum. Essentially all of the markings evaluated on the Tennessee test decks continue to provide adequate presence and retroreflectivity. While the markings have not degraded at the same rate, none have reached a point where the retroreflectivity has fallen below the minimum level of 100 $mcd/m^2/lux$ established for this project. As a result, the cost effectiveness of the alternative pavement marking systems installed on the Tennessee test decks cannot be determined at this point. These markings continued to be evaluated through the 2009–2010 winter.

STATE PROCUREMENT AND BIDDING PRACTICES

In a review of State transportation department practices, it was discovered that there is a wide disparity in how the agencies procure pavement markings. There is no research that conclusively demonstrates that a move to performance- or warranty-based specifications for the procurement of pavement markings result in higher quality installations.

State agencies are moving to performance- or warranty-based specifications to obtain higher quality, longer lasting, and more effective pavement markings.

ENVIRONMENTAL CONCERNS

State agencies are changing to lead-free and chromate-free thermoplastic markings, thereby satisfying the most recent environmental regulations. The latest EPA airborne lead regulation may cause a concern for agencies that try to remove lead-pigmented thermoplastic pavement markings. No research has been conducted to determine the amount of airborne lead released when encapsulated lead-pigmented thermoplastic is removed (by grinding or waterblasting).

Some multicomponent materials tested on the Alaska and Tennessee test decks are qualified as hazardous materials. Depending on the results of the Tennessee durability information and the final recommendations made from that information, there may be other environmental concerns resulting from this effort. However, the durability test decks in Tennessee are not yet old enough to make recommendations concerning specific pavement marking materials.

An evaluation of the potential environmental and health impacts of heavy metals in glass beads used in pavement markings was beyond the scope of this study. The magnitude of environmental and safety hazards of heavy metals in glass beads is somewhat uncertain. Heavy metals in glass beads do not appear to be leachable under the conditions of the EPA TCLP test which defines toxicity under current hazardous waste regulations. In fact, vitrification appears to be an acceptable method of disposing of heavy metal wastes. An ongoing project at Rowan

University is studying total heavy metal levels in various batches of domestic and foreign sourced beads as well as leaching under a variety of conditions, including the presence of snow and ice control chemicals. This project will be completed in June 2010.

APPENDIX A. CRASH SURROGATE STUDY RESULTS

Table 27 provides a coded study site matrix to be used a key for subsequent tables.

Table 27. Coded study site matrix.

Speed Limit (mi/h)	**Curve Radius**			
	Radius ≤ 700 ft (Degree of Curvature ≥ ~8.0)		**Radius ≥ 800 ft (Degree of Curvature ≤ ~7.0)**	
	Presence of Paved Shoulder		**Presence of Paved Shoulder**	
	Yes	**No**	**Yes**	**No**
≥ 55	1	2	3	4
≤ 50	5	6	7	8

Table 28 provides the sample size for the crash surrogate study. Table 29 through table 32 provide the speed data by location, change in speed data by location, lateral position data by location, and change in lateral position data by location, respectively, for the study.

Table 28. Sample size of crash surrogate study.

Curve	Code	Comparison (C)/ Treatment (T)	Speed (mi/h)		Radius (ft)	Shoulder (Y/N)	Time of Day	Observations	
			Limit	Advisory				Before	After
1	1	T	55	30	318	N	Day	849	752
							Night	86	82
2	1	T	55	35	539	N	Day	388	613
							Night	44	84
3	1	C	55	35	649	N	Day	804	828
							Night	75	83
4	1	C	55	40	663	N	Day	492	674
							Night	66	135
5	2	T	55	30	314	Y	Day	298	810
							Night	76	100
6	2	C	55	35	613	Y	Day	2,770	1,031
							Night	199	274
7	3	T	55	30	881	N	Day	871	916
							Night	83	56
8	3	C	55	40	1,857	N	Day	408	770
							Night	43	99
9	4	T	55	N	1,171	Y	Day	904	735
							Night	84	86
10	4	T	55	45	1,250	Y	Day	890	1,050
							Night	60	97
11	4	C	55	N	1,425	Y	Day	923	790
							Night	83	94
12	5	T	35	30	406	N	Day	891	914
							Night	72	98
13	5	T	50	40	672	N	Day	1,340	1,224
							Night	117	102
14	5	C	45	30	460	N	Day	1,291	686
							Night	95	193
15	5	C	35	30	511	N	Day	1,801	1,403
							Night	116	261
16	7	T	50	40	1,193	N	Day	279	1,083
							Night	113	104
17	7	C	45	30	860	N	Day	626	846
							Night	354	211
18	8	T	45	N	1,161	Y	Day	2,065	772
							Night	247	143
19	8	C	35	N	1,650	Y	Day	1,337	1,222
							Night	129	169

Table 29. Speed data by location.

Curve	Code	Statistic	Speed by Location (ft/s)							
			U		W		PC		MC	
			Before	After	Before	After	Before	After	Before	After
1	1	Mean	71.6	71.5	71.9	75.4	67.4	67.6	60.2	60.1
		SD	8.4	8.8	12.5	9.6	7.7	7.7	5.9	6.5
2	1*	Mean	69.7	69.8	69.9			69.1	62.8	64.5
		SD	10.1	9.4	8.6			7.9	8.7	8.8
3	2	Mean	73.7	73.8	70.8	70.9	66.4	65.9	55.9	56.3
		SD	8.1	8.2	8.1	8.2	7.6	7.4	6.0	5.8
4	2	Mean	73.1	72.1	78.8	77.1	78.3	76.1	74.9	73.7
		SD	7.7	9.2	8.7	9.1	8.5	8.8	8.0	8.5
5	2*	Mean	75.0	73.3	73.3		68.0		65.0	65.7
		SD	10.6	10.7	9.9		9.8		8.5	8.6
6	2*	Mean	75.4	74.2	76.5	76.4	75.2	75.7	72.8	72.8
		SD	12.5	12.5	9.5	9.7	9.2	9.3	9.2	8.9
7	3	Mean	84.4	83.5	83.5	83.2	82.7	82.3	81.0	81.7
		SD	7.2	7.2	7.3	7.2	7.5	7.4	7.7	7.4
8	3	Mean	75.9	74.3		82.1	82.0	81.5	80.7	80.6
		SD	17.9	17.7		9.9	9.6	9.1	9.3	9.0
9	3*	Mean	88.2	87.0	86.6	86.7	84.6	84.4	84.9	84.7
		SD	7.6	7.6	7.6	7.8	7.8	8.0	7.5	7.4
10	4	Mean	69.1	69.2	69.2	68.8	68.9	68.5	68.1	68.0
		SD	7.5	7.4	8.2	8.4	8.2	8.4	8.4	8.7
11	4*	Mean	77.8	76.1	83.1	81.7	80.4	80.6	82.3	
		SD	11.3	12.7	9.8	10.6	9.2	9.8	8.8	
12	6	Mean	62.4		64.5	64.8	61.4	54.7	55.0	54.2
		SD	9.3		8.0	9.1	7.4	6.8	5.9	6.1
13	6	Mean	75.3	74.9	77.8	77.9	74.3	76.0	72.7	72.6
		SD	12.0	14.0	9.5	9.3	9.0	10.1	9.1	8.8
14	6*	Mean	75.4	76.1	72.3	76.2	71.3	73.2	64.3	65.7
		SD	8.7	8.9	7.8	7.9	6.6	6.8	6.3	6.4
15	6*	Mean	73.1	72.5	69.9	69.4		63.5	60.5	59.4
		SD	8.6	9.1	8.3	8.6		8.3	7.7	8.5
16	7	Mean	79.3	77.0	80.1	77.9	80.2	78.0	73.8	72.3
		SD	8.6	8.7	9.0	8.7	9.0	8.6	8.5	8.1
17	7*	Mean	60.6	60.8	72.3	71.3	70.3	70.2	68.3	
		SD	20.4	20.0	9.7	8.9	9.3	9.2	8.7	
18	8	Mean	73.1	77.1	78.5	79.6	76.0	76.7	74.6	75.6
		SD	8.8	8.9	9.7	8.8	9.5	8.7	9.2	8.1
19	8*	Mean	74.7	74.8	76.4	75.9	72.3	71.9	70.7	70.4
		SD	7.2	7.7	7.9	7.8	7.0	6.9	6.8	6.7

* Indicates a comparison study site.
Note: Blank cells indicate missing data.

Table 30. Change in speed data by location.

Curve	Code	Statistic	Change in Speed by Location (ft/s)					
			W-U		PC-W		MC-PC	
			Before	After	Before	After	Before	After
1	1	Mean	-1.1	3.9	-4.9	-7.8	-7.2	-7.6
		SD	9.2	5.9	12.0	5.8	4.5	4.9
2	1*	Mean	.2					-4.6
		SD	6.7					5.0
3	2	Mean	-2.9	-2.9	-4.4	-5.0	-10.5	-9.6
		SD	4.1	4.3	2.1	2.3	4.4	4.8
4	2	Mean	5.7	5.0	-.5	-1.0	-3.4	-2.5
		SD	3.1	5.3	2.0	2.1	2.6	2.5
5	2*	Mean	-1.7		-5.3		-2.9	
		SD	7.3		5.2		6.4	
6	2*	Mean	1.1	2.3	-1.2	-.7	-2.5	-2.9
		SD	7.9	15.8	3.5	13.2	3.3	12.0
7	3	Mean	-.9	-.3	-.8	-.9	-1.6	-.5
		SD	2.8	3.1	2.5	2.7	2.3	2.1
8	3	Mean		8.0		-.8	-1.0	-.9
		SD		13.1		3.4	2.9	2.3
9	3*	Mean	-1.6	-.3	-2.0	-2.3	.2	.2
		SD	3.2	3.7	3.1	3.7	2.2	3.0
10	4	Mean	.1	-.4	-.4	-.3	-.8	-.5
		SD	5.3	4.9	2.3	2.1	3.2	2.2
11	4*	Mean	5.4	5.6	-2.7	-1.1	1.9	
		SD	7.3	8.0	3.9	3.7	3.5	
12	6	Mean	2.1		-3.1	-10.0	-6.4	-.5
		SD	10.6		3.2	8.0	8.7	3.3
13	6	Mean	2.5	3.1	-3.6	-3.7	-1.5	-.8
		SD	7.7	10.2	2.8	2.5	1.8	1.7
14	6*	Mean	-3.2	.1	-.9	-2.9	-7.0	-7.5
		SD	6.5	5.5	3.5	3.0	4.4	4.5
15	6*	Mean	-3.3	-3.0		-5.9		-4.0
		SD	4.1	8.4		9.6		8.5
16	7	Mean	.8	.9	.1	.1	-6.4	-5.9
		SD	4.9	4.9	2.8	2.6	4.3	3.6
17	7*	Mean	11.8	10.5	-2.0	-1.2	-2.1	
		SD	18.3	17.5	3.5	3.6	3.2	
18	8	Mean	4.3	2.6	-2.7	-3.0	-1.3	-1.2
		SD	4.8	4.6	3.7	3.6	3.9	3.1
19	8*	Mean	1.6	1.1	-4.1	-4.1	-1.6	-1.5
		SD	3.6	4.6	4.1	3.8	2.1	2.2

* Indicates a comparison study site.
Note: Blank cells indicate missing data.

Table 31. Lateral position data by location.

Curve	Code	Statistic	Lateral Position by Location (inches)							
			U		W		PC		MC	
			Before	After	Before	After	Before	After	Before	After
1	1	Mean	42.2	40.4	34.5	32.5	22.1	30.1	46.2	50.2
		SD	13.5	13.9	16.5	9.5	10.9	9.2	17.4	15.5
2	1*	Mean	27.7	27.4	24.7			26.5	47.6	48.3
		SD	10.3	11.1	9.5			12.0	13.8	14.1
3	2	Mean	35.8	43.4	28.1	26.1	22.3	21.7	36.2	39.1
		SD	13.6	11.5	10.1	9.2	10.5	9.1	14.5	13.4
4	2	Mean	23.7		25.1	27.6	30.9	32.9	40.5	44.2
		SD	12.3		11.4	11.3	10.9	11.8	14.9	15.7
5	2*	Mean	40.7	38.8	30.2		30.7		53.7	55.2
		SD	11.3	11.7	9.8		11.7		16.0	15.6
6	2*	Mean	33.4		27.5	25.4	17.1	20.5	34.0	34.3
		SD	13.2		11.6	10.9	10.9	12.0	15.0	15.3
7	3	Mean	31.1	31.0	39.6	35.9	37.3	38.9	43.6	43.0
		SD	13.3	13.6	11.4	11.6	13.0	13.9	13.9	14.2
8	3	Mean	30.7	30.1		40.6	46.7	41.5	56.2	54.6
		SD	13.5	13.0		11.0	14.6	13.6	15.5	16.2
9	3*	Mean	43.3	41.1	42.9		37.5	34.6	49.2	45.2
		SD	10.8	10.9	11.4		11.8	13.2	13.7	14.2
10	4	Mean	31.6	30.5	28.9		28.1	25.8	29.3	28.9
		SD	12.0	13.1	11.1		10.7	12.3	13.3	12.9
11	4*	Mean	37.9	36.4	33.9	30.2	26.5	32.9	34.1	
		SD	13.8	15.2	10.8	11.9	11.2	12.2	12.0	
12	6	Mean	37.5		39.3	35.2	18.0	26.0	43.5	51.7
		SD	11.2		11.1	11.7	5.2	11.1	16.5	16.3
13	6	Mean	34.8	41.6	32.0	30.0	30.8	30.6	40.3	37.7
		SD	12.7	15.2	10.8	11.4	11.9	11.8	12.8	13.1
14	6*	Mean	29.7	29.6	44.1	37.5	39.1	38.0	53.8	52.4
		SD	9.0	8.9	10.5	10.9	10.3	10.8	16.0	17.2
15	6*	Mean	32.0	6.6	45.1	23.5		41.6	38.6	43.2
		SD	12.1	11.6	14.9	13.2		12.3	13.1	15.6
16	7	Mean	38.0	37.5	31.2	34.1	23.7	23.0	38.8	38.8
		SD	13.2	12.7	12.7	11.9	11.1	10.9	12.6	13.8
17	7*	Mean	40.6	39.0	23.6	24.7	28.9	30.2	34.6	
		SD	16.9	16.0	10.5	10.1	12.2	10.7	16.8	
18	8	Mean	57.7	33.9	30.7	29.7	24.8	22.3	38.1	36.6
		SD	22.5	11.3	11.7	9.7	11.1	9.7	13.1	12.0
19	8*	Mean	31.8	39.4	38.7	38.3	32.1	34.1	51.6	53.9
		SD	11.4	10.0	10.2	11.1	10.8	10.3	13.6	14.8

* Indicates a comparison study site.
Note: Blank cells indicate missing data.

Table 32. Change in lateral position data by location.

Curve	Code	Statistic	Change in Lateral Position by Location (inches)					
			W-U		PC-W		MC-PC	
			Before	After	Before	After	Before	After
1	1	Mean	-5.8	-7.9	-10.2	-2.4	24.2	20.1
		SD	20.4	14.5	16.8	10.9	17.5	15.6
2	1*	Mean	-3.0					21.9
		SD	11.7					15.1
3	2	Mean	-7.7	-17.3	-5.8	-4.4	13.9	17.3
		SD	14.1	12.1	6.8	6.3	14.4	13.5
4	2	Mean	1.4		5.9	5.3	9.6	11.3
		SD	12.7		10.7	11.2	13.3	14.4
5	2*	Mean	-10.5		.5		23.1	
		SD	12.6		10.9		15.7	
6	2*	Mean	-5.9		-10.4	-5.0	16.9	13.8
		SD	14.4		12.8	15.6	13.2	18.6
7	3	Mean	8.5	4.9	-2.3	3.0	6.3	4.0
		SD	14.1	13.6	12.8	13.6	13.3	14.1
8	3	Mean		10.4		1.0	9.4	13.2
		SD		14.1		12.5	17.3	16.7
9	3*	Mean	-.3		-5.5		11.7	10.5
		SD	11.5		11.8		13.2	14.8
10	4	Mean	-2.7		-.8		1.2	3.2
		SD	15.0		8.9		12.4	12.3
11	4*	Mean	-4.0	-6.2	-7.4	2.7	7.6	
		SD	14.5	16.0	11.1	11.7	12.3	
12	6	Mean	1.8		-21.3	-9.2	25.5	25.8
		SD	14.6		9.8	13.3	17.5	16.1
13	6	Mean	-2.9	-11.5	-1.2	-2.0	9.5	11.2
		SD	13.6	16.8	10.5	9.5	10.8	11.6
14	6*	Mean	14.3	7.9	-5.0	.6	14.7	14.5
		SD	11.9	11.3	12.4	12.3	15.8	16.4
15	6*	Mean	13.0	17.4		18.1		1.6
		SD	15.9	15.3		16.3		17.8
16	7	Mean	-6.7	-3.5	-7.6	-11.1	15.1	15.8
		SD	15.5	14.6	11.8	12.2	14.0	14.1
17	7*	Mean	-17.0	-14.4	5.3	5.5	5.8	
		SD	17.3	15.3	12.2	9.7	16.0	
18	8	Mean	-27.5	-4.2	-6.0	-7.4	13.4	14.3
		SD	21.5	11.7	12.0	10.1	13.4	12.8
19	8*	Mean	6.8	-1.1	-6.6	-4.3	19.6	19.9
		SD	15.1	10.8	14.9	11.1	13.0	13.9

* Indicates a comparison study site.
Note: Blank cells indicate missing data.

APPENDIX B. PAVEMENT MARKING TEST DECK DESIGNS

TRANSVERSE TEST DECKS

Transverse test decks are the field method used by NTPEP. NTPEP test decks are located around the country, and the data are pooled to be used by any transportation agency. The procedures for conducting a test deck are based on the ASTM D 713 standard. This procedure calls for the site to have the following characteristics: (See references 48–50.)

- An AADT greater than 5,000 vehicles per day.
- Free rolling with no grades, curves, intersections, or close access points to minimize turning and braking movements.
- Four-lane divided highway.
- Full exposure to the sun with good drainage.
- Roadway must have been in operation for at least 1 year.

Transverse test decks are installed using the protocol established in ASTM D 713 and by the NTPEP standards and best practices.[48] This protocol indicates the design of the test deck, appropriate installation conditions, and when and how to collect data after installation. An example of an NTPEP transverse test deck is given in figure 18 (photograph courtesy of the Pennsylvania Department of Transportation), and an example of a transverse test deck in Alaska is given in figure 19 (photograph courtesy of the Alaska Department of Transportation and Public Facilities).

LONG-LINE TEST DECKS

Long-line test decks are installed in the same location and direction as standard pavement markings. This allows the markings to be placed under typical circumstances, and they are subjected to normal traffic conditions. Long-line test decks give realistic installation and wear conditions to the markings. These conditions provide an environment where durability can be accurately measured and monitored.

Long-line test decks do not have a protocol for test location, installation conditions, or data collection procedures. This can lead to variations in design from one test deck to another, which may lead to variations in results between studies. These variations are typical when normal pavement markings are applied to roadways.

Figure 18. Photo. Typical transverse test deck.

Figure 19. Photo. Transverse test deck in Alaska.

As part of this research, a standalone paper comparing the results of the transverse and longitudinal test decks will be produced. A summary of the advantages and disadvantages of each test desk design can be found in table 33 and table 34.

Test Deck Summary

Both transverse and long-line test decks have advantages and disadvantages. Each method of pavement marking testing can provide useful information depending on the information being sought after.

Table 33. Advantages and disadvantages of transverse test decks.

Advantages	Disadvantages
• Most common form of on-the-road testing. • They are used by the AASHTO-NTPEP program. • Markings can be placed close together in a relatively short length of roadway, which can help to minimize biases and provide reasonable uniform wear. • The close proximity of the materials on a transverse deck allows for quick data collection. • Materials in wheel track receive more hits than long lines and therefore act as an accelerated test deck. • Transverse decks are easier to organize and implement than long-line decks. • Conditions and applications of materials can be closely controlled.	• The results may be good for comparing products to each other, but they are not representative of how the materials will perform in the field. • The criteria used to evaluate the markings are not the same as the criteria used to evaluate long lines, especially the criterion used to assess nighttime visibility. • Retroreflectometers cannot measure the retroreflectivity of the lines in the direction that they are worn and as drivers would view them at night. A subjective rating is used to indicate the performance of the line in the direction of travel. • Transverse decks require a lane closure to place the material and to evaluate the material. • Correlation between test decks is difficult due to traffic and environmental conditions and the subjective measures used to judge durability. • Markings are applied with handheld applicators, which do not provide the same consistency and quality of large trucks that are normally used to apply markings on roadways.

Table 34. Advantages and disadvantages of long-line test decks.

Advantages	Disadvantages
• Marking materials are placed on the test deck with the same equipment that is used regularly to install markings. • Markings can be evaluated under real climate and traffic conditions. • Markings allow for the measurement of retroreflectivity in the direction of wear as well as the visual inspection of performance and durability in the direction of wear. • The results provide the best indication as to how a marking will perform in the field under similar conditions. • Retroreflectivity can be measured with mobile devices, increasing the safety to technicians and minimizing the impact on traffic.	• There is not an established protocol for long-line testing like there is for transverse decks. • Evaluation with handheld retroreflectometers and/or colorimeters requires lane closures with a best-case scenario using a mobile operation. • Environmental conditions vary not only from State to State but within the State and on the test deck. • Location selection may prove to be difficult. Road sections need to be long and similar to provide similar weather and traffic conditions for all material to be tested. • Coordinating successful long-line test decks is a significant undertaking requiring a major commitment of those involved. • The long-line test decks may require a long evaluation period in order to determine differences between materials.

APPENDIX C. DURABILITY TEST DECK INFORMATION

Since one of the primary goals of this task was to compare the durability performance of different pavement marking materials measured over time, the markings needed to be subjected to similar traffic conditions. Furthermore, a reasonably high traffic volume was desired in order to illustrate the differences between materials in the short time available for the study. It was important to consider roadway design features, traffic characteristics, and local environmental conditions when selecting the test deck locations. Together with each State transportation department, the study sites were carefully selected so that they were representative and similar. The sites were also chosen based on pavements that would not need major maintenance during the life of the study. All of the test decks were installed on asphalt pavements in good condition; all materials were installed along the edge line and right-most lane line of multilane highways; and all test sections were applied along tangent sections.

PAVEMENT MARKING PREPARATION FOR IN-LAID MARKINGS

The intended goal of the placement of the pavement markings was to place half the length of the marking section on the surface of the road and half in a groove (in-laid). This required that within each test section, half of the section needed the current markings to be eradicated, leaving a clean new surface for installation. The second half of the test section needed to be grooved to an adequate depth so that the marking would be in-laid below the road surface. The specific parameters of the grooving for the in-laid products were based on providing a consistent difference between the height of the final pavement marking system and the height of the roadway. The goal was to have the pavement marking system, including the optics of the pavement marking system, slightly depressed in the roadway to provide protection from the wintertime plowing and studded tires.

The eradication process was not always consistent and ended up leaving a shallow groove in the road surface. A similar problem occurred when trying to create the groove for the in-laid marking section. The grooving machines were typically deeper than specified. To account for these discrepancies in eradication and groove depths, areas where the markings were eradicated were considered to be placed in a shallow groove, and areas where the road was fully grooved (marking system below the road surface) were considered a deep groove. In some cases, markings were also applied over the preexisting markings and were considered a surface application. The various placements of the markings all occurred within the 0.5-mi test section. Markings that only had two placement types were each installed for approximately 0.25 mi.

ANCHORAGE, AK, PAVEMENT MARKING TEST DECK AREA

Figure 20. Photo. Glenn Highway SR-1.

Figure 21. Photo. Proposed pavement marking installation sites.

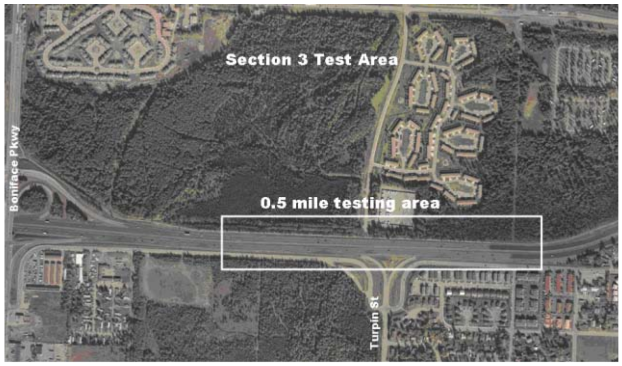

Figure 22. Photo. Test section 3.

Figure 23. Photo. Test section 5.

Figure 24. Photo. Test section 6.

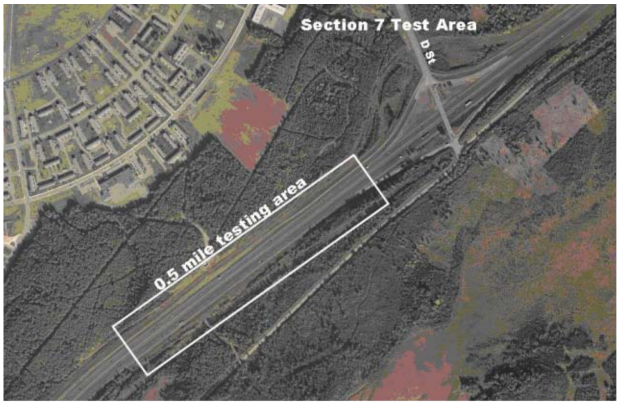

Figure 25. Photo. Test section 7.

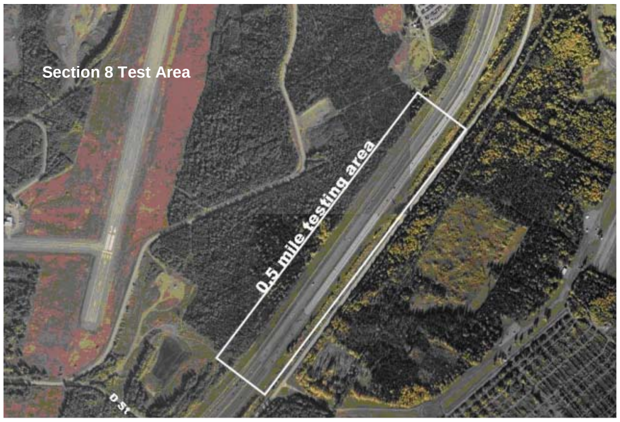

Figure 26. Photo. Test section 8.

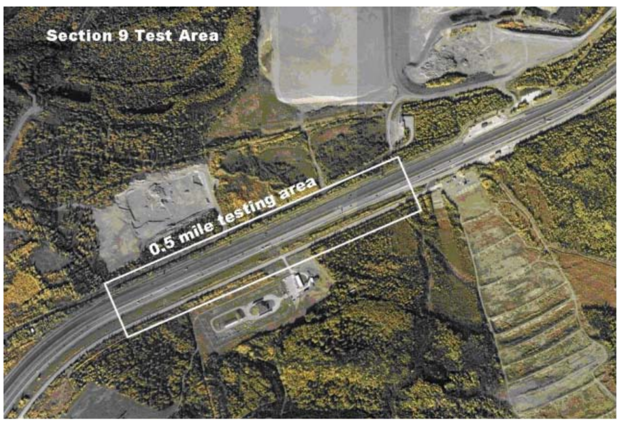

Figure 27. Photo. Test sections 9.

ANCHORAGE, AK, PAVEMENT MARKINGS

Table 35. Initially installed edge line and outside lane line pavement markings (8/7/06).

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type
1 AK a	Alaska DOT&PF low VOC paint	Spray	Surface, (Shallow), (Deep)	0, 65, 160	12	AASHTO M247
2 AK a	3M all weather paint	Spray	(Shallow), (Deep)	65, 160	30	Swarco type 2 and 3M elements
3 AK a	MMA 98:2 (Stirling Lloyd)	Extruded	(Shallow), (Deep)	70, 175	100	Type 2
4 AK a	MMA 98:2 (Stirling Lloyd)	Agglomerate	(Shallow), (Deep)	90, 275	200	Type 2
5 AK a	3M pavement marking tape 380IES	Rolled	(Deep)	175	100	N/A
5 AK b	3M pavement marking tape 380WR	Rolled	(Deep)	175	100	N/A
6 AK a	MMA 4:1 (Ennis)	Extruded	(Shallow), (Deep)	60, 120	100	30/50 Mesh Swarco Megalux T13 coated
6 AK b	Modified urethane (IPS)	Spray	Surface, (Shallow), (Deep)	0, 70, 120	20	Potters Type 1 AC110 coating and type 4 Visibead plus 2
7 AK a	Low temperature acrylic waterborne paint (Ennis)	Spray	Surface, (Shallow), (Deep)	0, 140, 175	12	Swarco AASHTO M247
8 AK a	MMA 4:1 (Degussa–Pathfinder™)	Agglomerate	(Shallow), (Deep)	120, 320	200	Swarco AASHTO M247
9 AK a	High build acrylic waterborne paint (Ennis)	Spray	(Shallow), (Deep)	60, 145	30	Swarco Megalux Type 3
10 AK a	Polyurea (IPS)	Spray	(Shallow), (Deep)	65, 155	20	Potters type 1 AC110 coating and type 4 Visibead plus 2

N/A = Not applicable.
Note: Section 1 AK a was applied with long-line striping equipment; all other sections were hand cart applied.

Table 36. Pavement markings installed after the first winter in Anchorage, AK.

Date	Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type
6/21/07	All	Alaska DOT low VOC paint	Spray	Over existing	Existing	12	AASHTO M247
9/24/07	1 AK b	Flint trading premark preformed thermoplastic	Heat in place	(Deep)	160	125	N/A
10/2/07	2 AK b	Standard Alaska DOT&PF MMA	Spray	(Shallow), (Deep)	85, 180	60	AASHTO M247

N/A = Not applicable.

Note: Paint and MMA were applied with long-line striping equipment; preformed thermoplastic was hand cart applied.

Table 37. Pavement markings installed after the second winter in Anchorage, AK.

Date	Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type
8/5/08	9 AK b	MMA (Ennis), paint (Pervo)	Extruded with raised edges, double spray	(Shallow), (Shallow and Deep)	60, 60 and 145	100, 40	30/50 Mesh, 30–30–40 Swarco mega blend
8/5/08	7 AK b	MMA (Ennis), paint (Pervo)	Extruded with raised edges, spray	(Deep)	175	100, 20	30/50 Mesh, 30–30–40 Swarco mega blend

Note: Paint was applied with long-line striping equipment; MMA was hand cart applied.

NASHVILLE, TN, PAVEMENT MARKING TEST DECK AREA

Figure 28. Photo. SR-840.

Figure 29. Illustration. Proposed pavement marking installation sites.

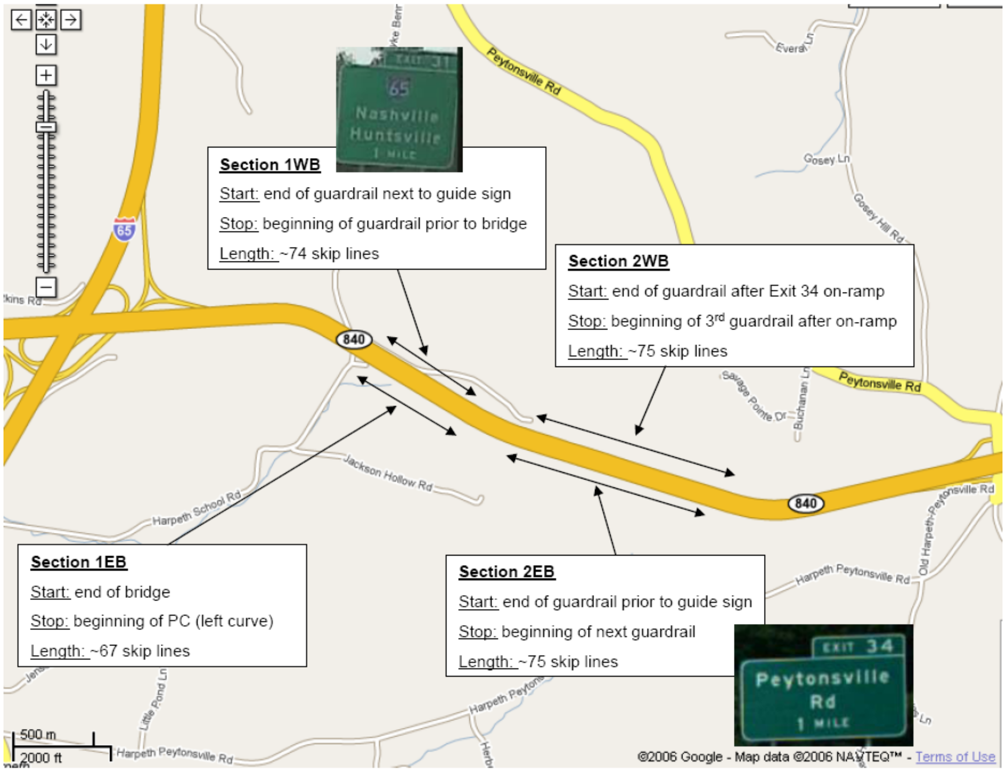

Figure 30. Illustration. Test sections 1 and 2.

Figure 31. Illustration. Test section 3.

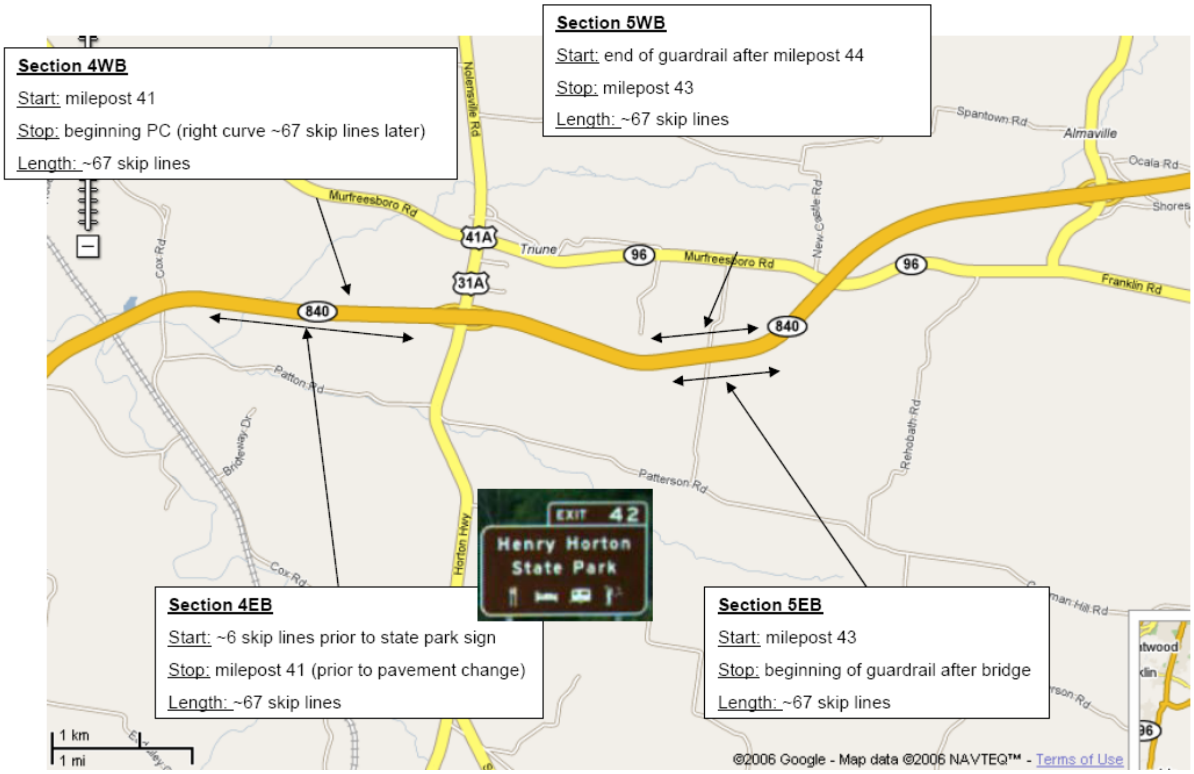

Figure 32. Illustration. Test sections 4 and 5.

NASHVILLE, TN, PAVEMENT MARKINGS

Table 38. Initially installed edge line and lane line pavement markings in Nashville, TN.

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type	Bead Rate
1 TN-N	Thermoplastic (Ennis)	Spray	Over rumble strip edge line only	N/A	40	Potters type 1 AC110 coating	8 lb/100 ft^2
2 TN-N	Thermoplastic (Ennis)	Spray	(Shallow), (Deep)	75, 185	40	Potters type 1 AC110 coating	8 lb/100 ft^2
3 TN-N	Thermoplastic (Ennis)	Spray	(Shallow), (Deep)	85, 270	90	Potters type 1 AC110 coating	8 lb/100 ft^2
4 TN-N	Thermoplastic (Ennis)	Extruded	(Shallow), (Deep)	95, 180	120	Potters type 1 AC110 coating and type 4 Visibead plus 2	6 lb type 1 and 10 lb Type 4 per 100 ft^2
5 TN-N	Thermoplastic (Gulfline)	Inverted Profile	(Shallow)	75	50/225	Potters type 1 AC110 coating and type 4 Visibead plus 2	6 lb Type 1 and 10 lb Type 4 per 100 ft^2
6 TN-N	Low temperature acrylic waterborne paint (Ennis)	Spray	(Shallow), (Deep)	55, 145	12	Potters Type 1 AC110 coating	8 lb/100 ft^2
7 TN-N	Polyurea (Epoplex)	Spray	(Shallow), (Deep)	110, 165	20	Prismo high index cluster and Potters type 4 Visibead plus 2	8 lb cluster and 10 lb Type 4 per gallon
8 TN-N	3M all weather paint	Spray	(Shallow), (Deep)	135, 175	26	Swarco type 2 and 3M elements	18 grams type 2 and 7.5 grams elements per linear foot
9 TN-N	High build acrylic waterborne paint (Ennis)	Spray	(Shallow), (Deep)	100, 175	25	Swarco type 3 virgin glass	10-12 lb/100 ft^2

Note: All pavement markings were installed with long-line striping equipment.

Table 39. Lead-free thermoplastic pavement markings installed 6/5/08 in Nashville, TN.

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type	Bead Rate
10 TN-N	Ennis lead-free thermoplastic	Extruded	Surface	0	80	AASHOT M247 with AC110 coating	8–10 lb/100 ft^2
11 TN-N	Swarco lead-free thermoplastic	Extruded	Surface	0	80	AASHOT M247 with AC110 coating	8–10 lb/100 ft^2
12 TN-N	Dobco lead-free thermoplastic	Extruded	Surface	0	85	AASHOT M247 with AC110 coating	8–10 lb/100 ft^2

Note: All pavement markings were installed with long-line striping equipment.

TUSCULUM, TN, PAVEMENT MARKING TEST DECK AREA

Figure 33. Photo. SR-34.

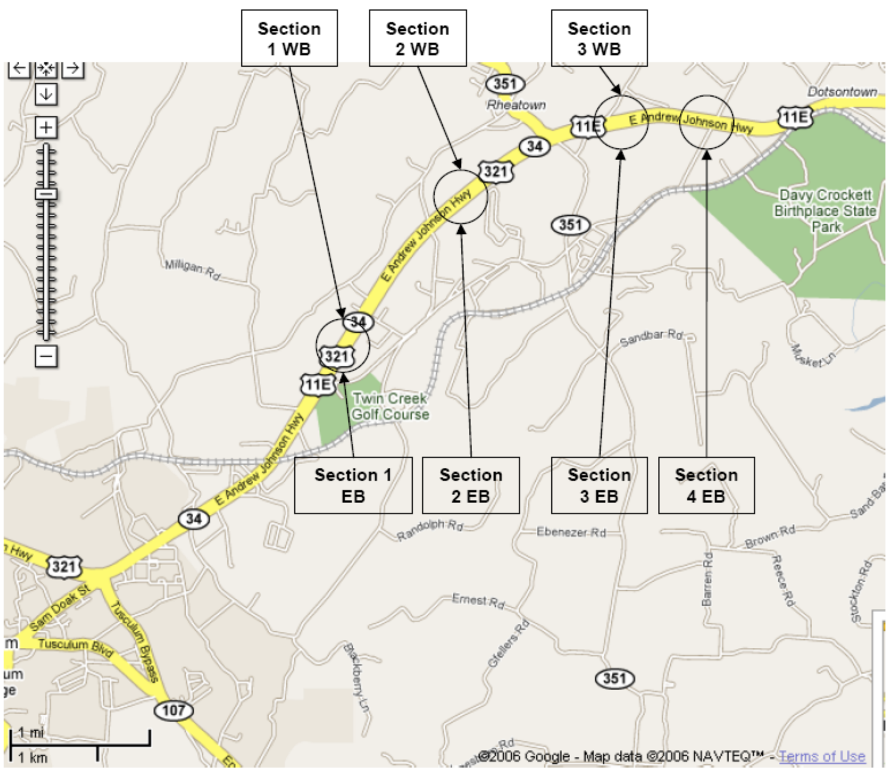

Figure 34. Illustration. Proposed pavement marking installation sites.

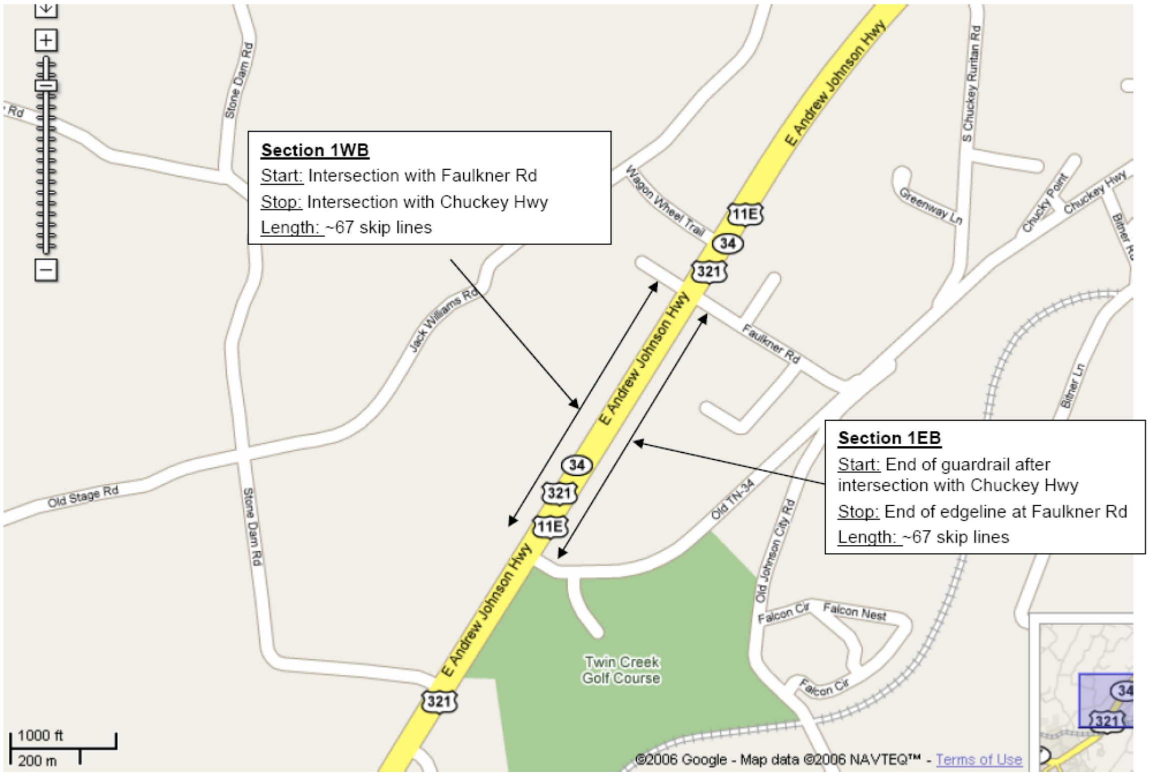

Figure 35. Illustration. Test section 1.

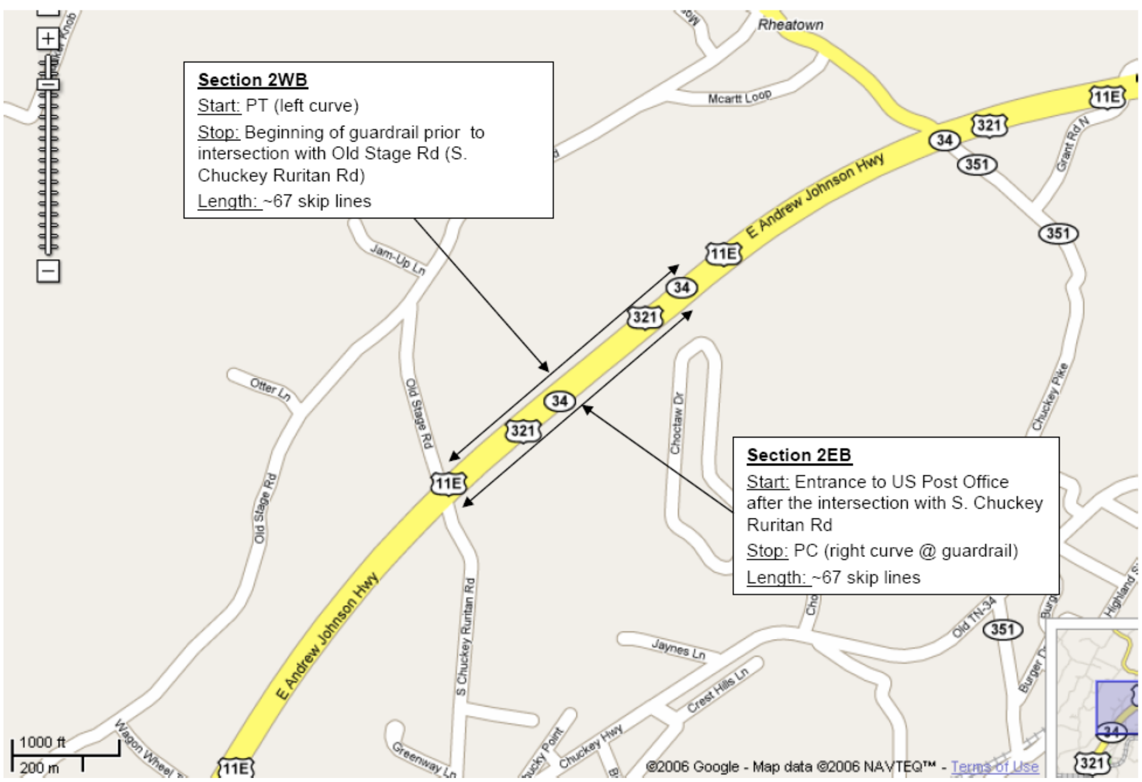

Figure 36. Illustration. Test section 2.

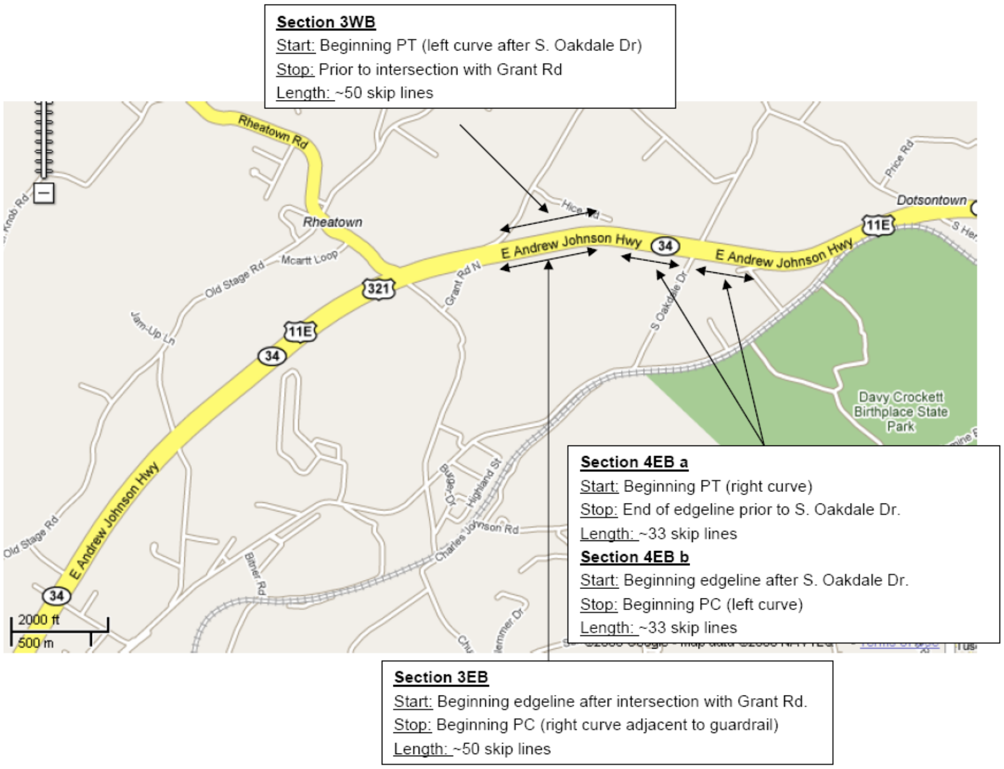

Figure 37. Illustration. Test section 3 and 4.

TUSCULUM, TN, PAVEMENT MARKINGS

Table 40. Initially installed edge line and lane line markings on 5/14/07.

Test Section	Marking Type	Application Type	Placement (In-Laid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type	Bead Rate
1 TN-T	Modified epoxy (Epoplex)	Spray	(Shallow), (Deep)	100, 125	22	Type 4 Visibead Plus II=E16, type 1 MNDOT spec	10-lb type 4 and 6-lb type 1 per 100 ft^2
2 TN-T a	MMA (Degussa)	Extruded	(Shallow), (Deep)	100, 170	90	Swarco AASHTO M247	8–10 lb/100 ft^2
2 TN-T b	MMA (Degussa–Pathfinder™)	Agglomerate	(Shallow), (Deep)	100, 170	200	Swarco AASHTO M247	8–10 lb/100 ft^2
3 TN-T	Low-temperature acrylic waterborne paint (Ennis)	Spray	(Shallow), (Deep)	50, 110	15	AASHTO M247	8 lb/100 ft^2
4 TN-T	High-build acrylic waterborne paint (Ennis)	Spray	(Shallow), (Deep)	105, 150	24	Potters type 4 Visibead Plus II	12 lb/100 ft^2
5 TN-T a	ATM pavement marking tape 300	Rolled	(Shallow), (Deep)	60, 130	100	N/A	N/A
5 TN-T b	ATM pavement marking tape 400	Rolled	(Shallow), (Deep)	25, 195	100	N/A	N/A
6 TN-T	TN standard thermoplastic (superior)	Extruded	(Shallow), (Deep)	70, 320	90	Swarco AASHTO M247	8–10 lb/100 ft^2
7 TN-T	Modified urethane (IPS)	Spray	(Shallow), (Deep)	110, 170	15	Type 4 Visibead Plus II=E16, type 1 MNDOT spec	10-lb type 4 and 8-lb type 1 per 100 ft^2

N/A = Not applicable.
Note: Sections 1 TN-T and 6 TN-T were applied with long-line striping equipment; all other sections were hand cart applied.

APPENDIX D. PAVEMENT MARKING RETROREFLECTIVITY DEGREDATION GRAPHS

This appendix contains graphs showing the retroreflectivity degradation of each test section that lasted at least 1 year. The y-axes on the graphs represent retroreflectivity (mcd/m^2/lux), and the x-axes represent the age of the markings in days since application. For more specific marking information, refer to appendix C. Note that the y-axes vary in scale for the different graphs.

ALASKA TEST DECK

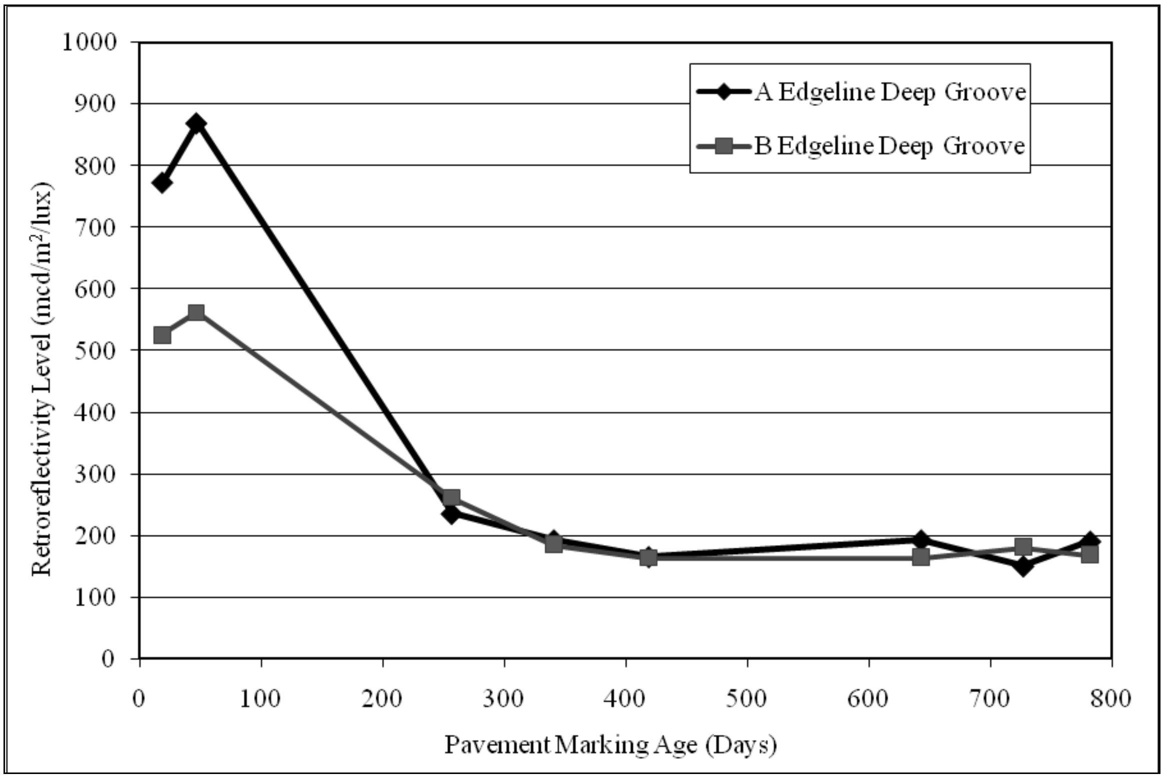

Figure 38. Graph. Retroreflectivity degradation sections 5 AK a and 5 AK b.

NASHVILLE, TN, TEST DECK

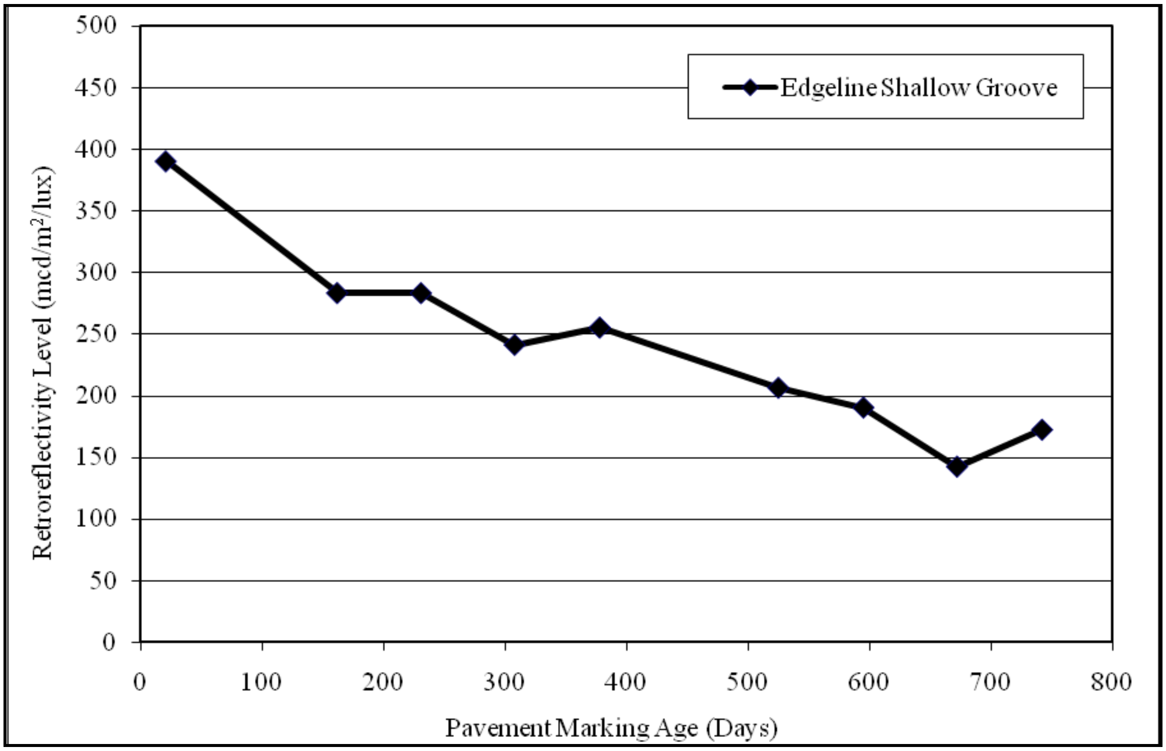

Figure 39. Graph. Retroreflectivity degradation section 1 TN-N.

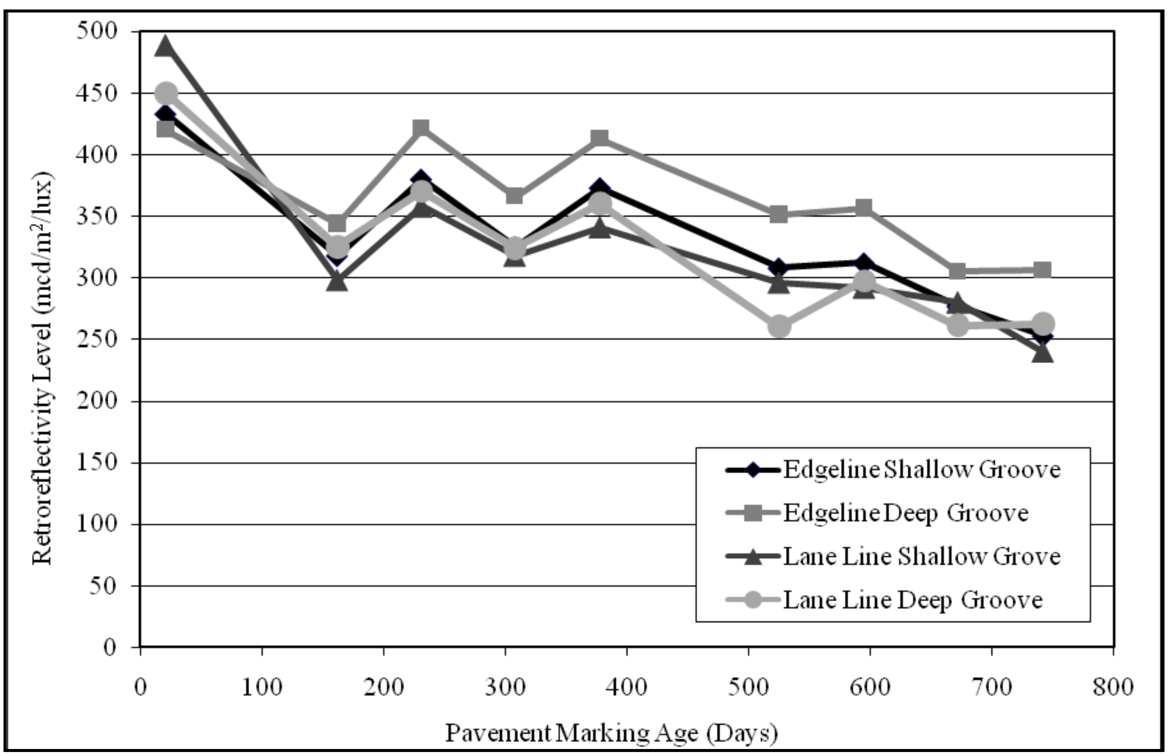

Figure 40. Graph. Retroreflectivity degradation section 2 TN-N.

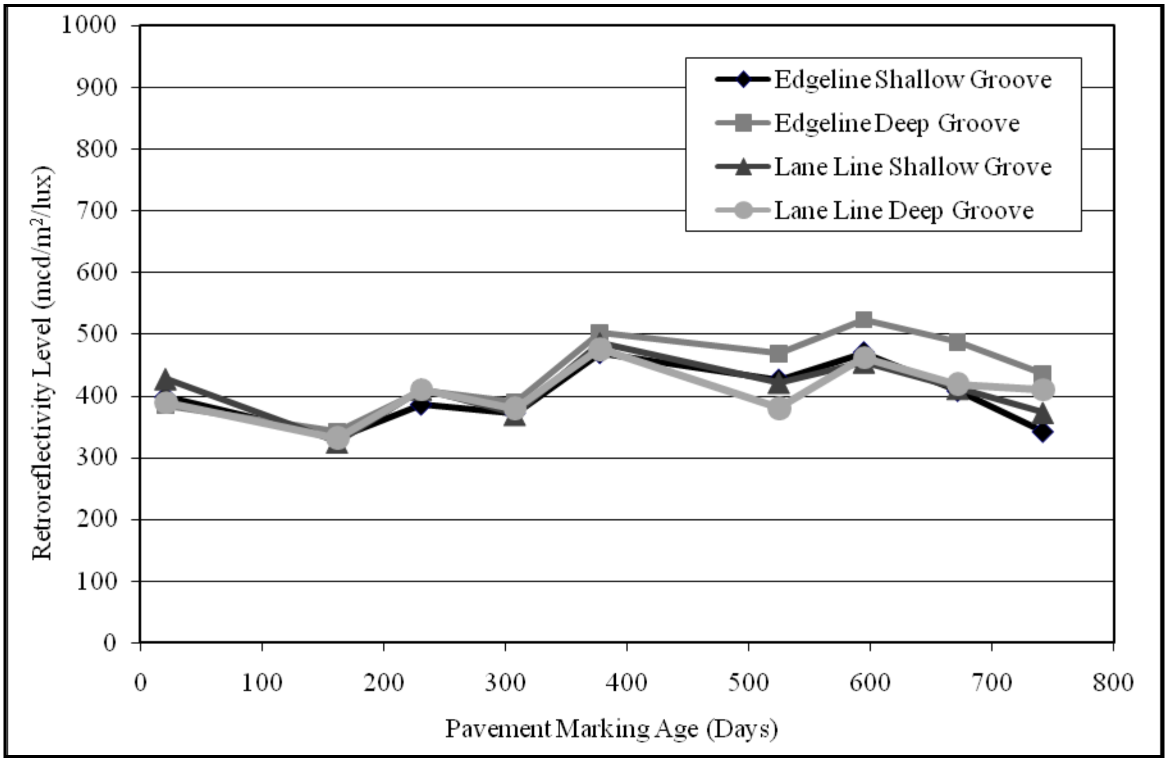

Figure 41. Graph. Retroreflectivity degradation section 3 TN-N.

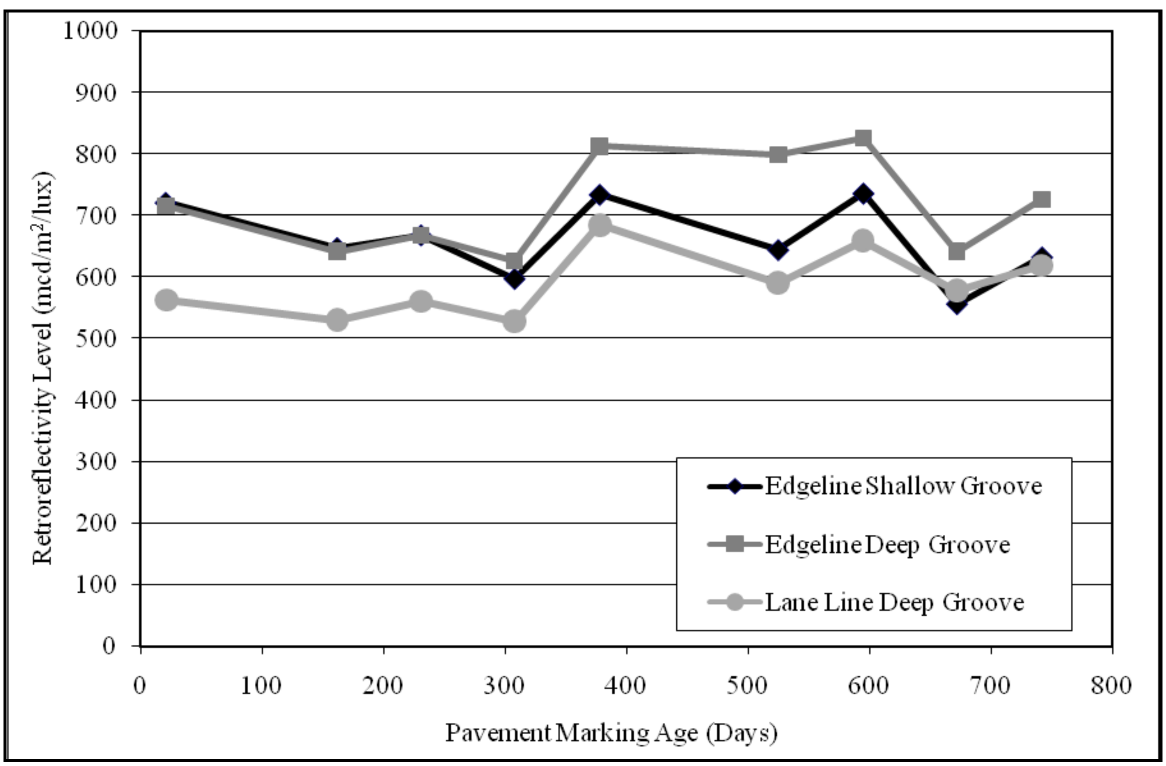

Figure 42. Graph. Retroreflectivity degradation section 4 TN-N.

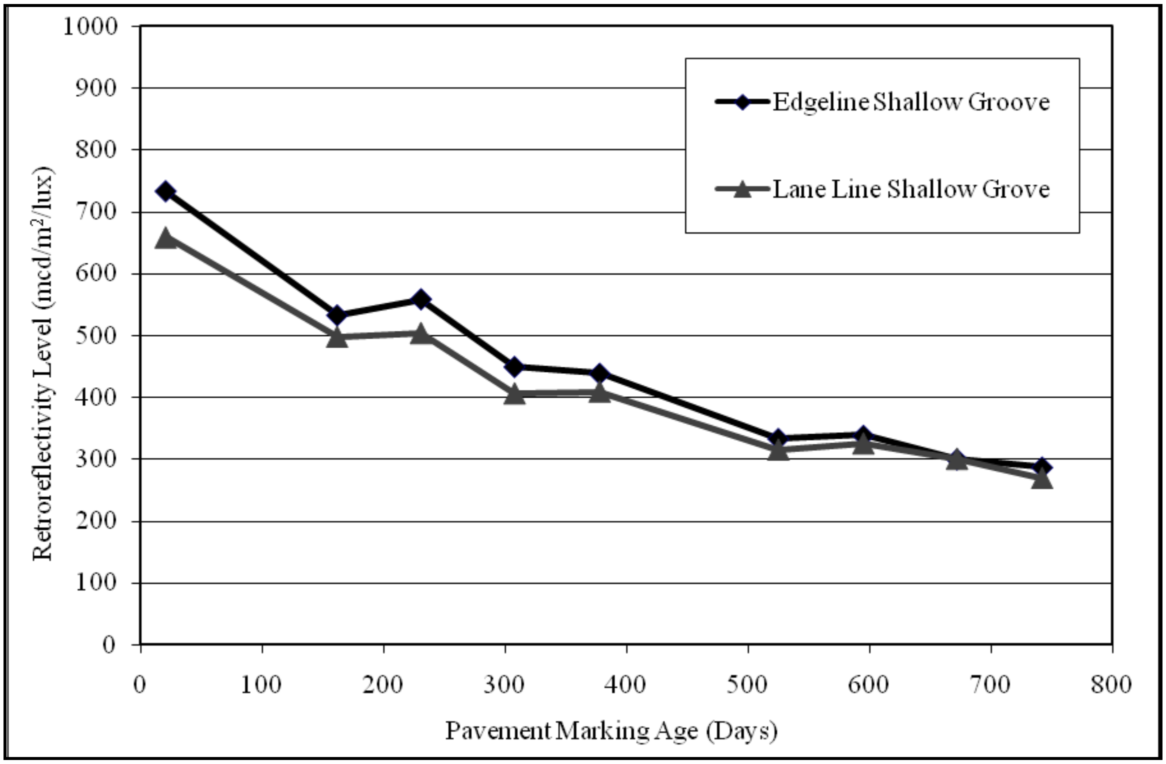

Figure 43. Graph. Retroreflectivity degradation section 5 TN-N.

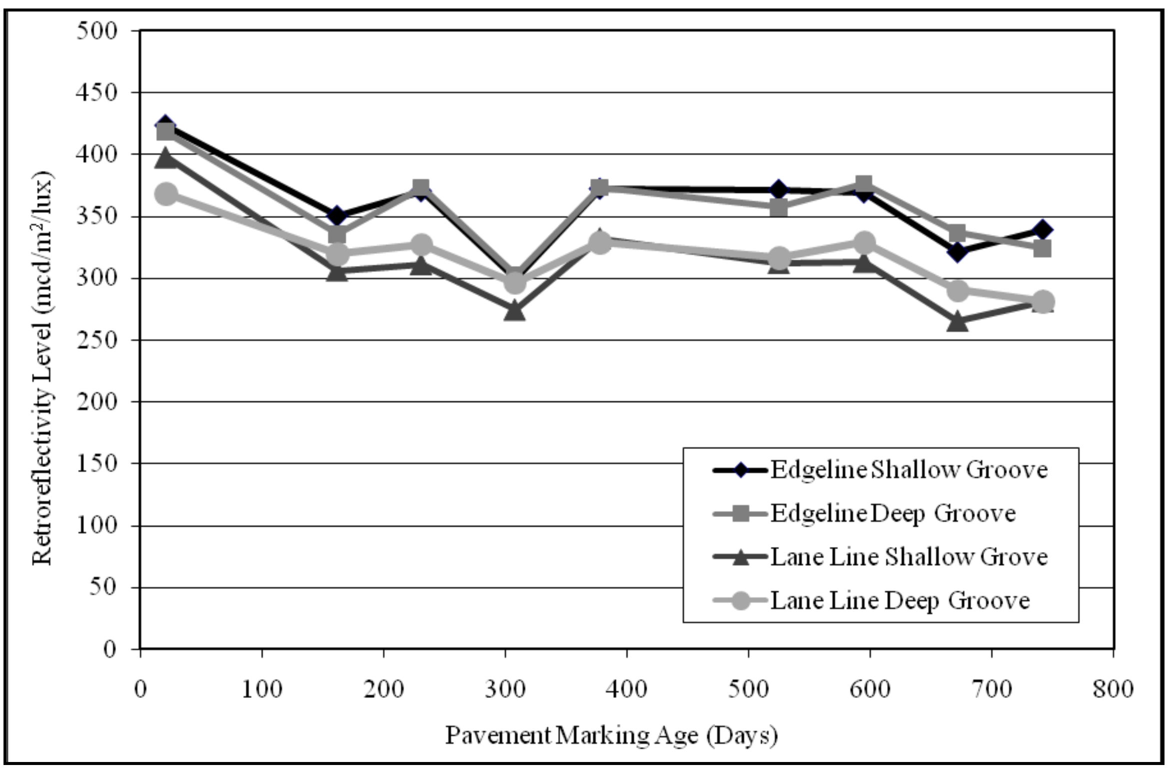

Figure 44. Graph. Retroreflectivity degradation section 6 TN-N.

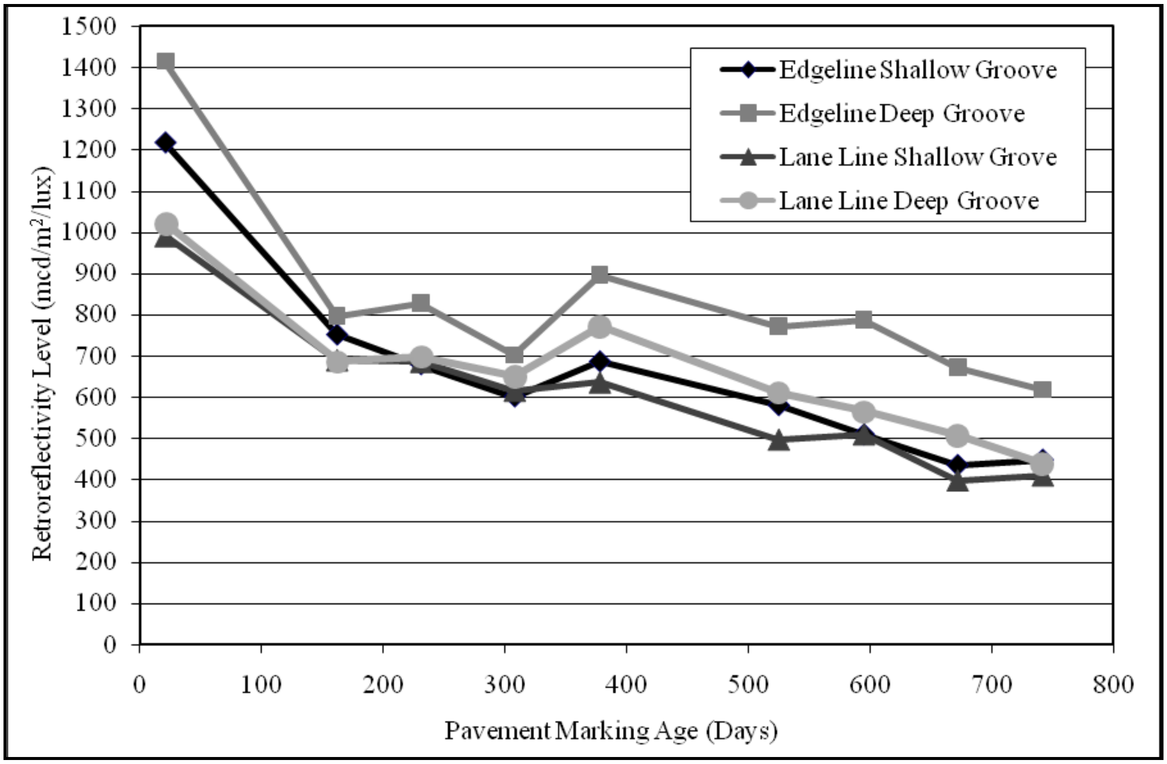

Figure 45. Graph. Retroreflectivity degradation section 7 TN-N.

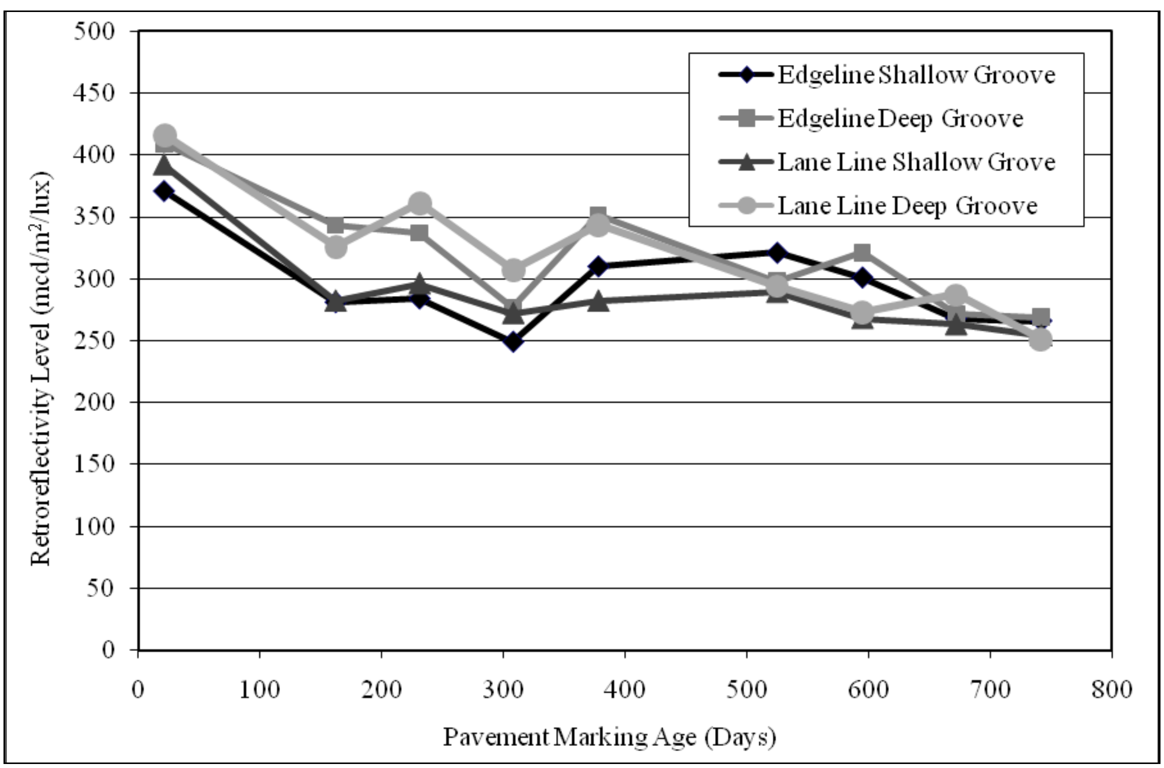

Figure 46. Graph. Retroreflectivity degradation section 8 TN-N.

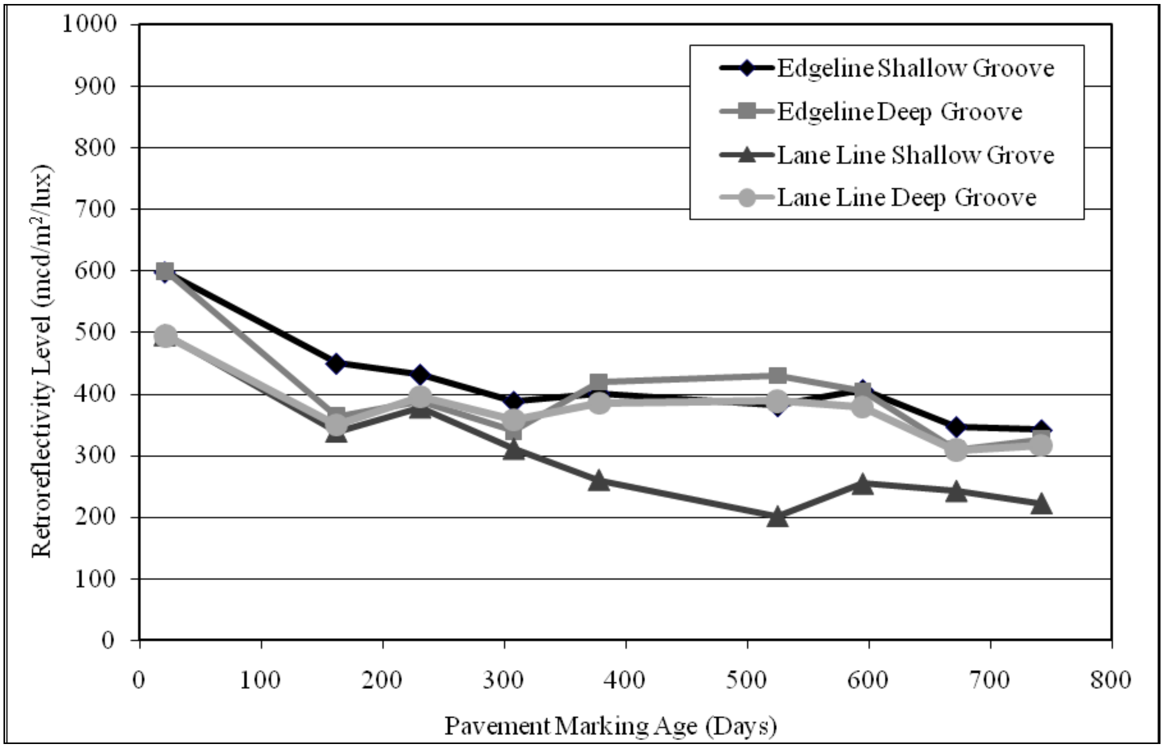

Figure 47. Graph. Retroreflectivity degradation section 9 TN-N.

TUSCULUM, TN, TEST DECK

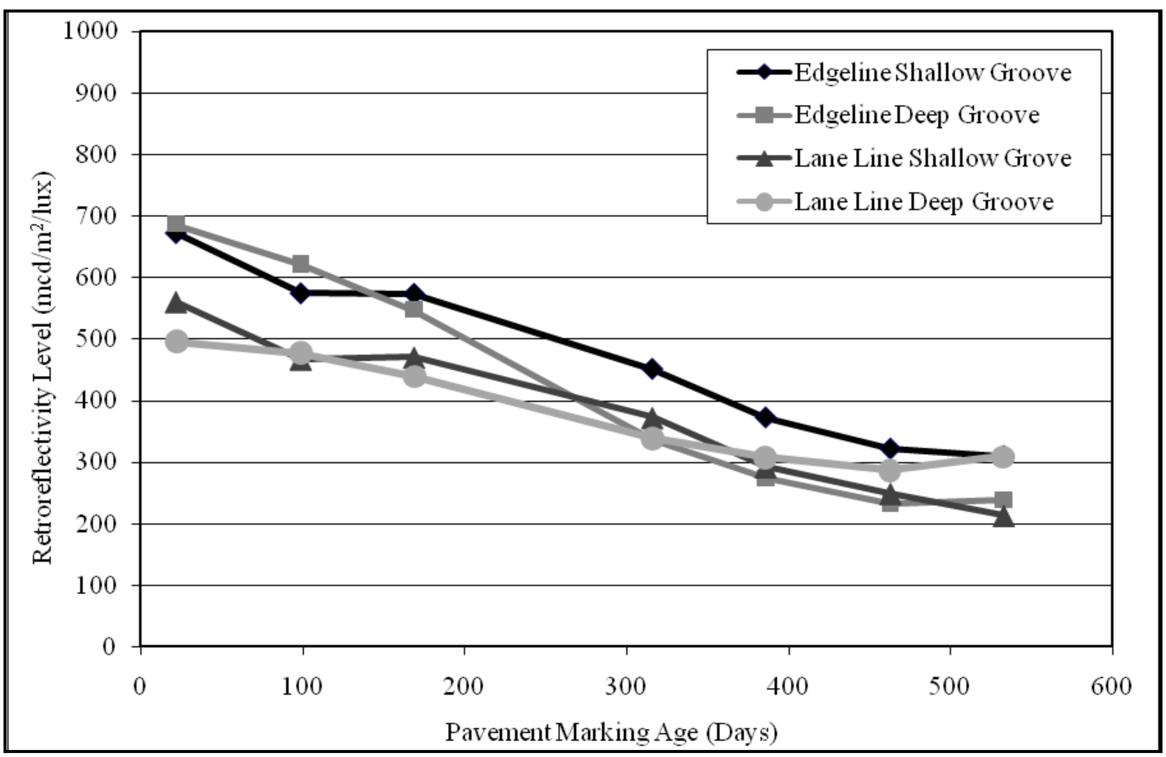

Figure 48. Graph. Retroreflectivity degradation section 1 TN-T.

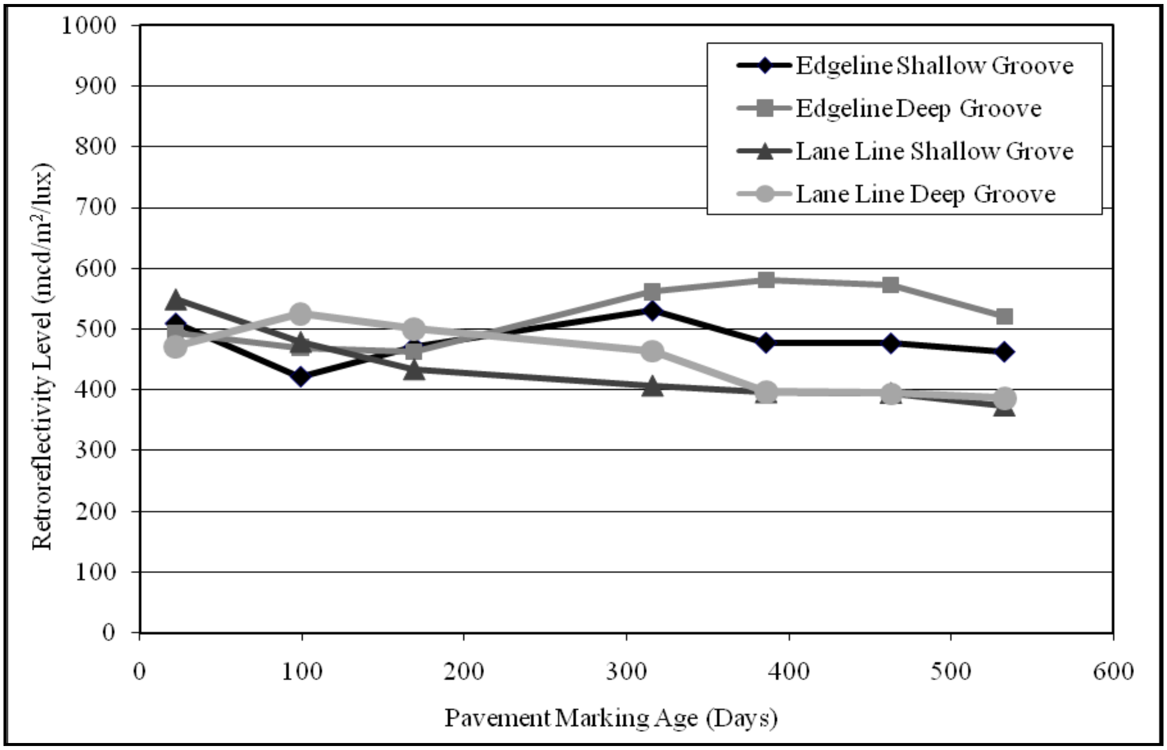

Figure 49. Graph. Retroreflectivity degradation section 2 TN-T a.

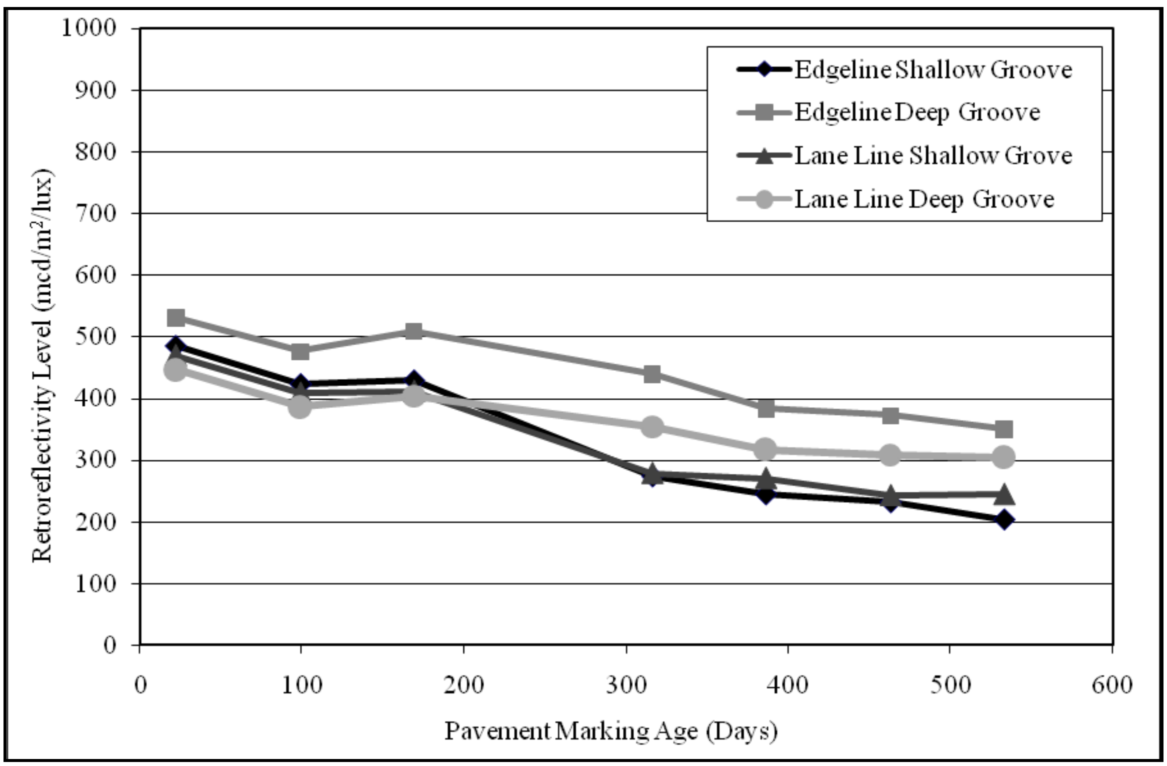

Figure 50. Graph. Retroreflectivity degradation section 2 TN-T b.

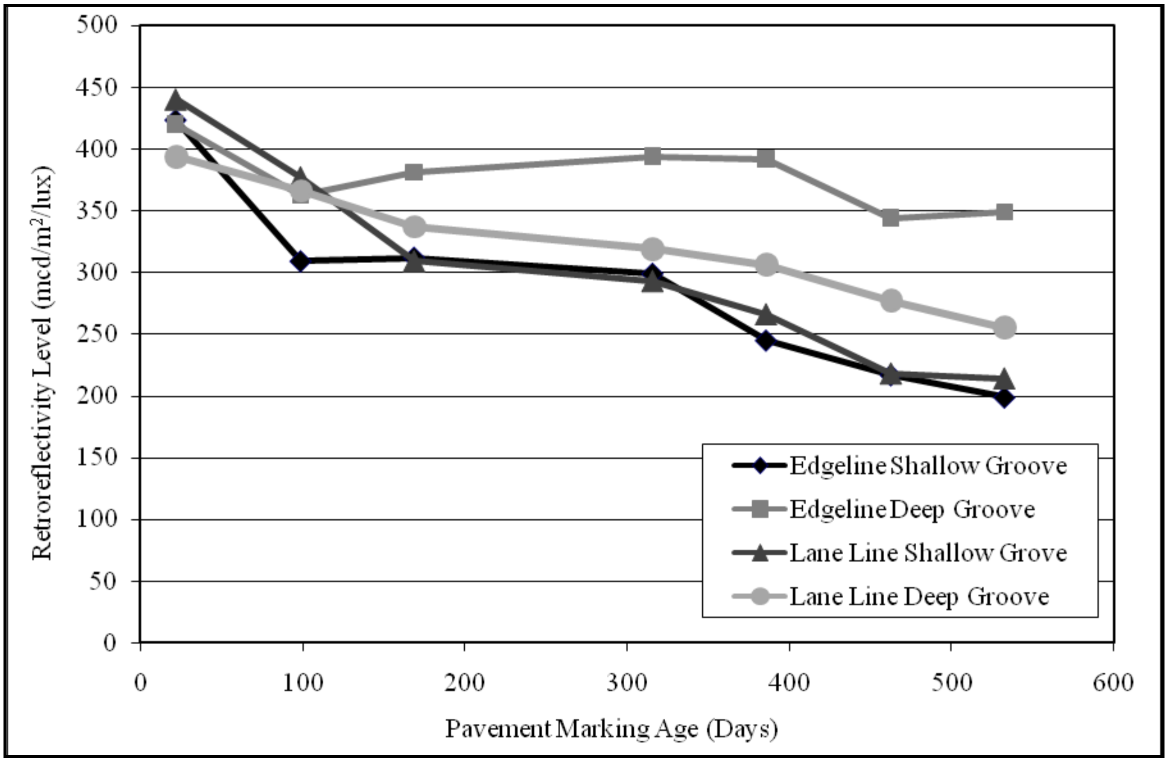

Figure 51. Graph. Retroreflectivity degradation section 3 TN-T.

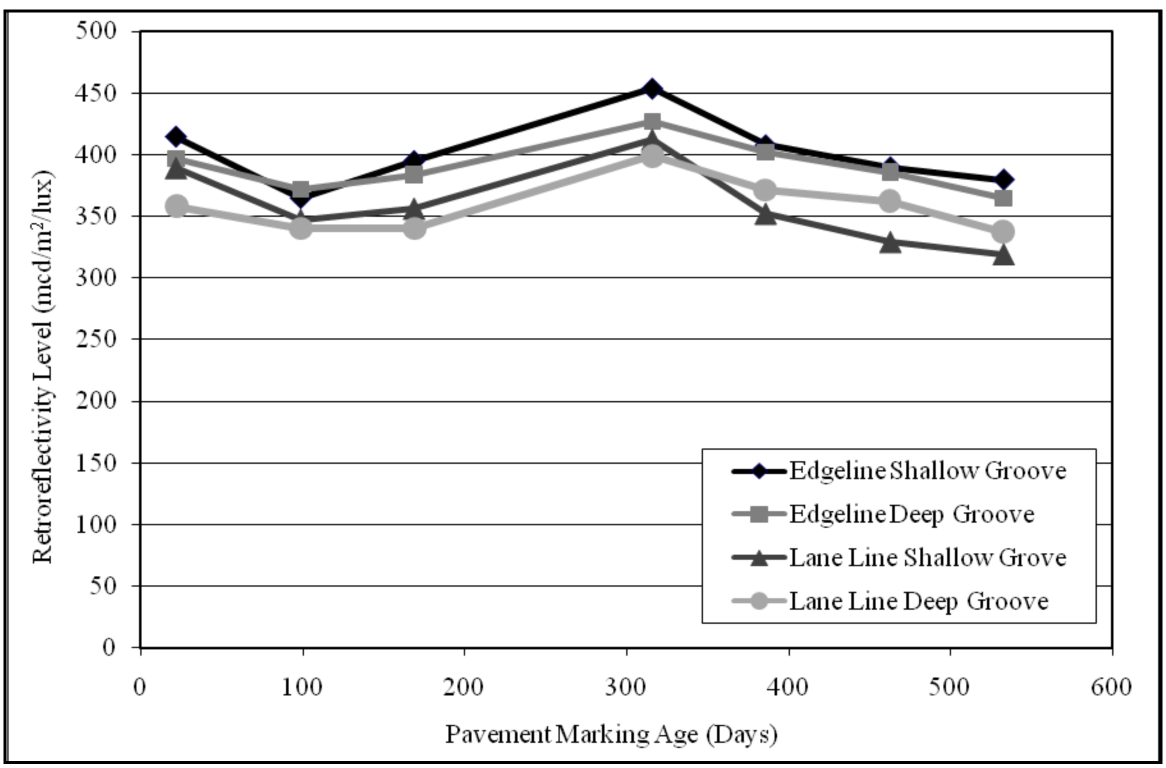

Figure 52. Graph. Retroreflectivity degradation section 4 TN-T.

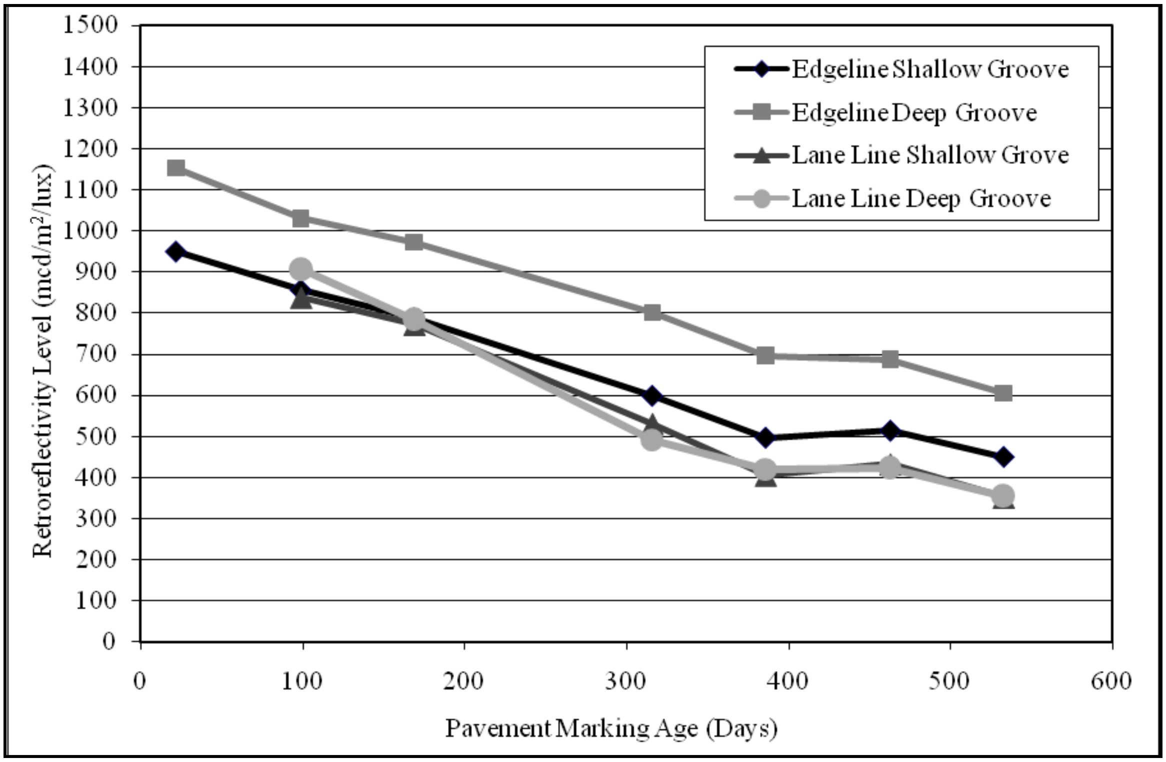

Figure 53. Graph. Retroreflectivity degradation section 5 TN-T a.

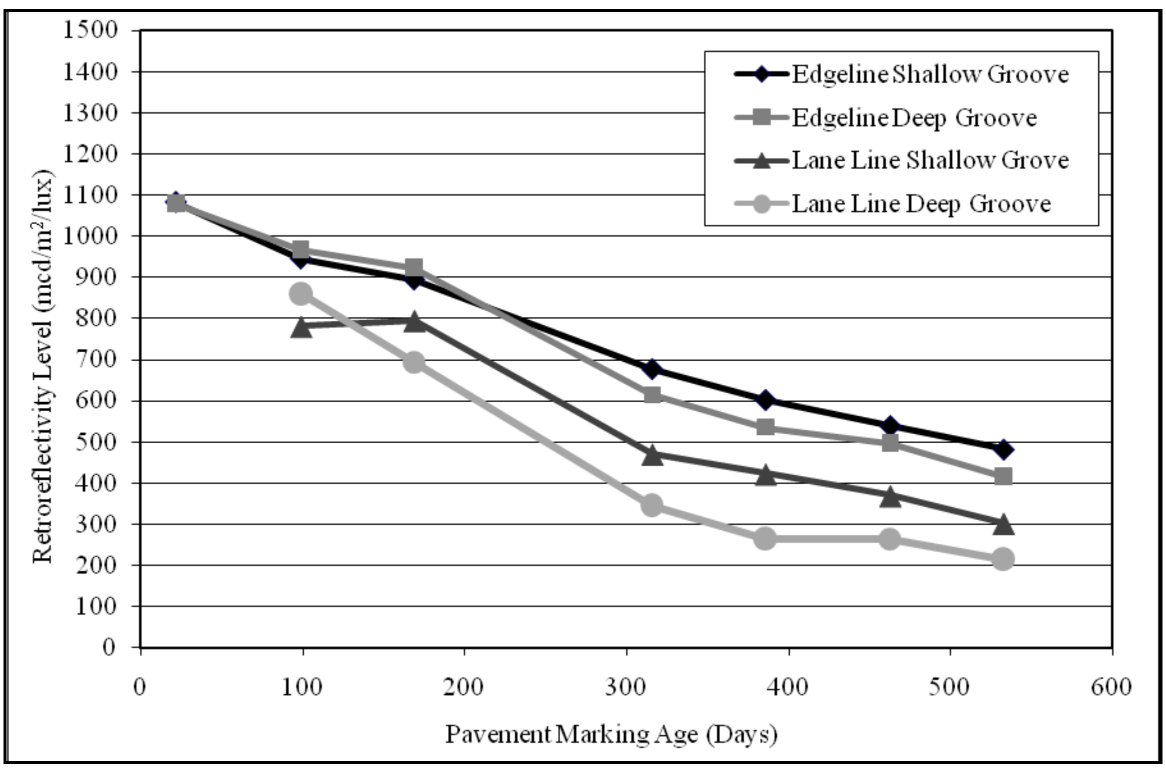

Figure 54. Graph. Retroreflectivity degradation section 5 TN-T b.

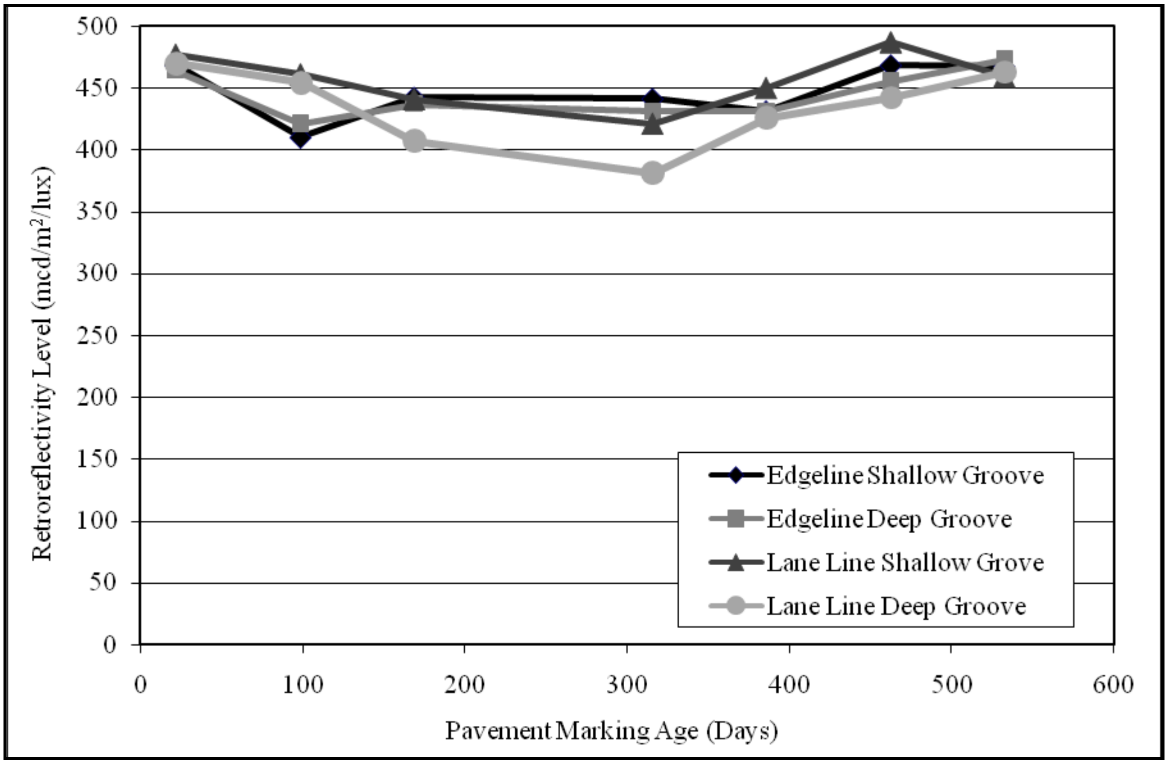

Figure 55. Graph. Retroreflectivity degradation section 6 TN-T.

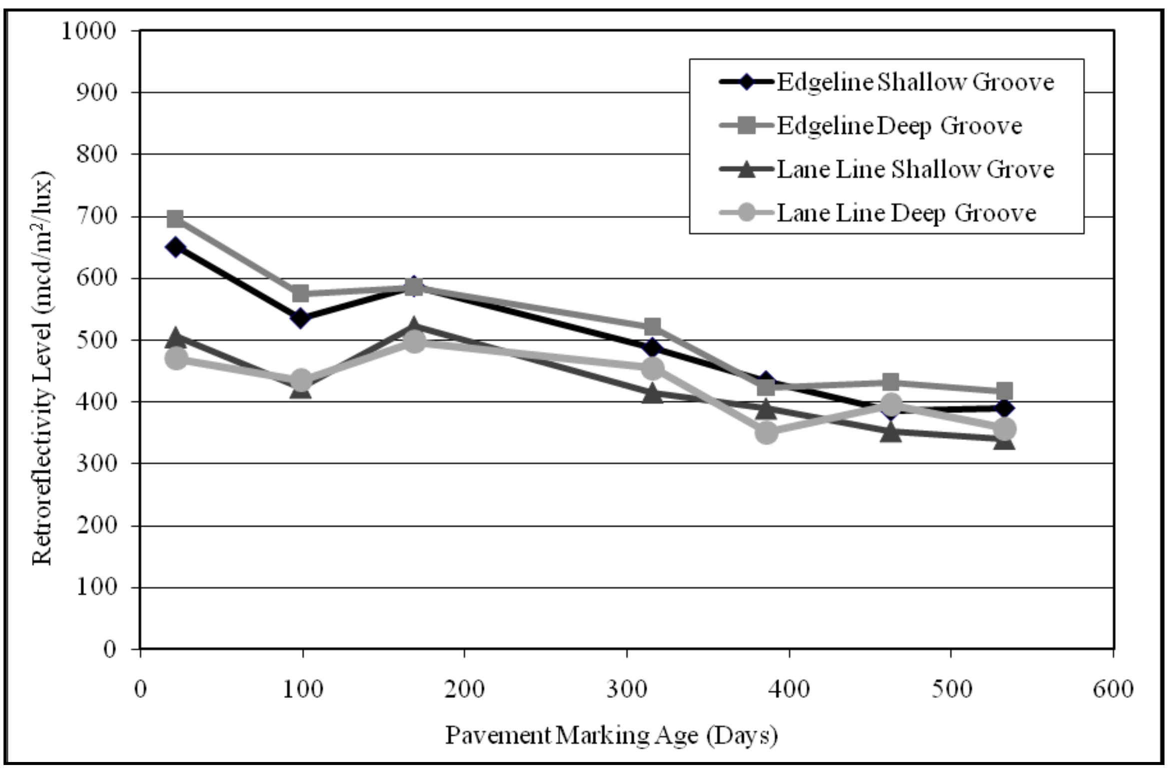

Figure 56. Graph. Retroreflectivity degradation section 7 TN-T.

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