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

PUBLICATION NO. FHWA-HRT-12-048

NOVEMBER 2013

U.S. Department of Transportation
Federal Highway Administration

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

FOREWORD

This report provides information on four topics related to advanced pavement marking systems: (1) an evaluation of the durability and cost effectiveness of alternative marking materials, (2) a two-part study on the safety impacts of wider edge lines, the first part using operational effects as surrogate safety metrics and the second part based on a post-hoc analysis of safety data, (3) an evaluation of the potential environmental impacts of cost effective pavement marking systems, and (4) a review of the effect of State procurement processes on the quality of installed markings. This report amplifies information that may be found in *Pavement Marking Demonstration Projects: State of Alaska and State of Tennessee: Report to Congress* (FHWA-HRT-09-039). 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.

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

TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-HRT-12-048	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Pavement Marking Demonstration Projects: State of Alaska and State of Tennessee		5. Report Date November 2013
		6. Performing Organization Code
7. Author(s) Paul Carlson, Eun-Sug Park, Adam Pike, R.J. Porter, Jeffrey Miles, Bryan Boulanger, Omar Smadi, Neal Hawkins, Seth Chalmers, Frank Darmiento, Adrian Burde, Beverly Kuhn, and Wendy Ealding		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 SAIC 1710 SAIC Drive McLean, VA 22101-2296		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFH61-05-D-00025 Task T-06-002
12. Sponsoring Agency Name and Address Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		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. The Contracting Officer's Technical Representative (COTR) was Carl K. Andersen, Office of Safety Research and Development.

16. Abstract
This project evaluates the safety impacts, environmental impacts, and cost effectiveness of different pavement marking systems as well as the effect of State bidding and procurement processes on the quality of pavement marking material employed in highway projects. The findings indicate that States are pursuing alternative procurement strategies to provide high-quality durable markings in a cost effective manner, often as part of a strategic safety plan, while industry has responded to requirements for more environmentally benign materials. A multi-State retrospective crash analysis suggests that the use of 6-inch edge lines reduces several crash types on rural two-lane two-way roads as compared to 4-inch edge lines. The monitored performance of pavement markings installed as part of the demonstration project was used to evaluate pavement marking cost effectiveness. The same results were also used to populate a framework for a pavement marking selection tool.

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 Alexandria, VA 22312

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 298	22. Price

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AADT	Average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ACGIH	American Conference of Governmental Industrial Hygienists
ADOT	Arizona Department of Transportation
ADT	Average daily traffic
AGBMA	American Glass Bead Manufacturers Association
AKDOT	Alaska Department of Transportation
ALDOT	Alabama Department of Transportation
ANOVA	Analysis of variance
ANSI	American National Standards Institute
AWPM	All-weather pavement marking
BMP	Best management practices
CAA	Clean Air Act
CAS	Chemical Abstracts Service
CDOT	Colorado Department of Transportation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CMRG	Chemical Manufacturer Recommended Guideline
EB	Empirical Bayes
EEC	European Economic Community
EHS	Environment, Health, and Safety
EPA	Environmental Protection Agency
F+I	Fatal plus injury
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FP-XRF	Field-portable x ray fluorescence
GDOT	Georgia Department of Transportation
GEE	Generalized estimating equation

GEV	Generalized extreme value
HMAC	Hot mix asphalt concrete
HMIS	Hazardous Materials Identification System
HSIS	Highway Safety Information System
HSL	Hue, saturation, and lightness
IARC	International Agency for Research on Cancer
IIA	Independence of irrelevant alternatives
Iowa DOT	Iowa Department of Transportation
ISO	Organization for Standardization
KDOT	Kansas Department of Transportation
LC50	Median lethal concentration
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle inventory assessment
LD50	Median lethal dose
LRS	Longitudinal reference system
MC	Midpoint of curve
mcd/lux/m^2	millicandela per lux per square meter
MDOT	Michigan Department of Transportation
mil	One thousandth of an inch
MMA	Methyl methacrylate
MnDOT	Minnesota Department of Transportation
MSDS	Material safety data sheet
MUTCD	*Manual on Uniform Traffic Control Devices*
NAAQS	National Ambient Air Quality Standards
NCDOT	North Carolina Department of Transportation
nd	Non-detectable
NEPA	National Environmental Policy Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NFPA	National Fire Protection Association
NJDOT	New Jersey Department of Transportation
NJIT/RU	New Jersey Institute of Technology/Rowan University
NOAEL	No observed adverse effect level

NTP	National Toxicology Program
NTPEP	National Transportation Product Evaluation Program
OSHA	Occupational Safety and Health Administration
PC	Point of curve
PDO	Property damage only
PEL	Permissible exposure limit
PM	Particulate matter
PMST	Pavement marking selection tool
PCC	Portland cement concrete
PPE	Personal protective equipment
ppm	Parts per million
RCRA	Resource Conservation and Recovery Act
REML	Restricted maximum likelihood
R.I.	Refractive index
R.P.	Reference post
RPM	Raised pavement marker
RTLTW	Rural two-lane two-way
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SAIC	Scientific Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act
SAS®	Statistical Analysis Software®
SCBA	Self-contained breathing apparatus
SIP	State Implementation Plan
SPF	Safety performance function
SPLP	Synthetic precipitation leaching procedure
SR	State route
TCLP	Toxicity characteristic leaching procedure
TDOT	Tennessee Department of Transportation
TSCA	Toxic Substances Control Act
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
U	Upstream location

UV	Ultraviolet
VDOT	Virginia Department of Transportation
VOC	Volatile organic compound
W	Advance curve warning sign location
WSDOT	Washington State Department of Transportation

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 (lowercase), minimum detectable difference
μ	Mu (lowercase), represents one millionth, or 10^{-6}
n	Sample size
Σ	Sigma (upper case), sum of parts that follow
σ	Sigma (lowercase), one standard deviation

CHAPTER 1. INTRODUCTION

Section 1907 of Public Law 109-59 Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) directs the Secretary of Transportation to perform the following:

> "…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 in. to 6 in. and an evaluation of advanced acrylic waterborne pavement markings."(1)

Furthermore, the Secretary is directed as follows:

> "…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 Federal Highway Administration (FHWA) established a research project to address the directives. In order to satisfy the requirements of section 1907, FHWA divided the legislative directive into the following main topics:

- **Durability study**: A study of the cost effectiveness of different pavement marking systems based on maintained retroreflectivity, including advanced acrylic waterborne systems. Chapter 2 of this report contains a description of these project activities.

- **Safety study**: An evaluation of the operational and safety impacts of using wider-than-normal pavement marking edge lines. The operational studies conducted under this research are described in chapter 3, and the safety studies are described in chapter 4.

- **Environmental study**: An evaluation of the potential environmental impacts of pavement marking systems. Chapter 5 contains a description of the environmental work performed and the findings.

- **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. Chapter 6 describes the details of the efforts conducted for this study.

BACKGROUND

The U.S. transportation sector 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 (10.4 percent) to the $12.5 trillion U.S. gross domestic product.(2) A large amount of transportation occurs on the Nation's 4 million mi 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 inform drivers of the intended travel path for short-range operations and the roadway alignment for long-range delineation. The *Manual on Uniform Traffic Control Devices* (MUTCD) describes their characteristics and warranting criteria to ensure consistent application of pavement markings, setting national standards on their application.[3]

Despite the national pavement marking standards described in MUTCD, according to a recent American Association of State Highway and Transportation Officials (AASHTO) report, a highway death occurs every 21 min as a result of a lane departure.[4] In total, that is more than 25,000 fatalities per year or almost 60 percent of the Nation's highway fatalities. (Note that FHWA cites 53 percent compared to 60 percent.)[5] Because these types of crashes are the largest safety problem in the United States, FHWA promotes a strategic approach to prioritize and implement 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 *Implementing the AASHTO Strategic Highway Safety Plan*, which is designed to reduce these numbers.[6] A key objective of the FHWA roadway departure focus area and the AASHTO safety plan is to keep vehicles in their lanes and on the roadway. Installing and maintaining effective pavement markings is one immediate way to meet these objectives.

The national highway crash trends noted are not exclusive to highways and interstates. Historically, approximately 50 percent of fatal crashes occur on local roadways (i.e., county, township, and city).

As called for in SAFETEA-LU, individual States have developed Strategic Highway Safety Plans.[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 pavement marking widths from 4 to 6 inches on all major highways, which have led to a 25 percent reduction in lane departure fatalities from 2005 to 2007.[7]

The science and effort dedicated to effective pavement marking materials and practices can sometimes be overlooked. Perhaps this is a function of pavement marking unit costs, typically presented in cents per foot, which are \$0.10 to \$0.25 per 1 ft for installation of conventional markings. However, when each marking on a highway and each mile of a highway are summed, the annual cost of pavement markings can be surprising. Several sources of State agency information were combined to develop an estimated annual cost of pavement markings. The estimate is based on data from 18 States, making up 45 percent of the State-maintained highway miles in the United States.[8] 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).[9]

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 (or 2.93 million mi) of the Nation's highways and roads, of which about 1.65 million mi are paved.[10,11] While many of these roads are not marked, there is undoubtedly a substantial proportion that are marked.

The task of effectively managing pavement markings falls jointly on 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 see the pavement markings during the day and night and that the markings have 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, contractors, rather than agency personnel, install many of the newer materials. 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 that it is most efficient to apply waterborne paint pavement markings twice per year because of the 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 performance levels.

In addition to testing marking visibility and durability, many agencies are experimenting with advances in pavement markings to reduce crashes. For instance, agencies are working with profiled pavement markings that produce a combination of vibration and noises to notify drivers that they are leaving the intended travel path. Other factors, such as an emphasis on accommodating older drivers, have also inspired State transportation departments to evaluate their pavement marking programs. Finally, States are also experimenting with different bidding and procurement processes in an effort to more efficiently install and maintain quality pavement markings on the road.

The research topics included in the SAFETEA-LU section 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 concisely address the topics as described in SAFETEA-LU section 1907.[1]

CHAPTER 2. COST EFFECTIVENESS OF PAVEMENT MARKINGS

INTRODUCTION

This chapter includes descriptions of the types of pavement marking test decks and summaries from past studies. It also describes the pavement markings test decks installed and monitored for this research project. Using the results from the pavement marking test decks, this chapter also contains a methodology for determining the cost effectiveness of pavement markings, including management tools.

Alaska and Tennessee Test Decks

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 and was 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 produce biased results. The Anchorage, AK, and Tusculum, TN, test decks also included transverse markings. The test decks in Alaska and Tennessee included high-build and low-temperature acrylic markings. All three test decks were installed on divided multilane highways with asphalt pavements in good condition. Appendix A provides detailed information about the test deck locations, pavement marking materials, and applications.

During 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.

LITERATURE REVIEW

There are two main types of on-the-road pavement marking evaluations: transverse test decks and long-line test decks. 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.

Transverse Test Decks

Transverse test decks are the field method used by the National Transportation Product Evaluation Program (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 ASTM D713.[12]

Transverse test decks are installed using the protocol established by the NTPEP standards and best practices.(13,14) This protocol indicates the design of the test deck, appropriate installation conditions, and when and how to collect data after installation. Figure 1 shows an example of an NTPEP removable tape test deck, and figure 2 shows an example of a transverse test deck in Alaska.(14,15)

Figure 1. Photo. Example of NTPEP removable tape transverse test deck.

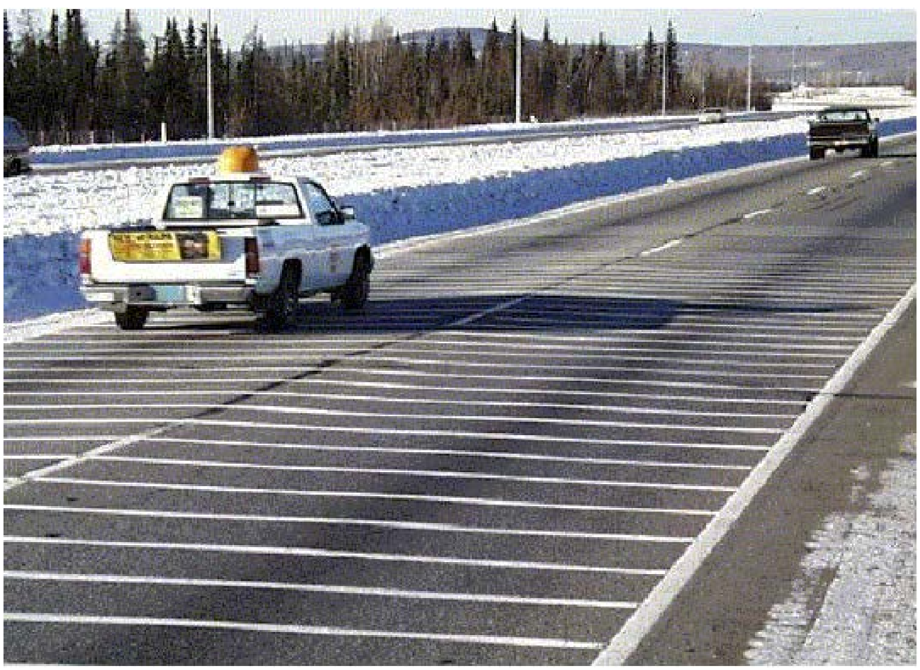


Figure 2. Photo. Transverse test deck in Alaska.

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 subjected to normal traffic conditions. Long-line test decks can provide 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 cause variations in design from one test deck to another, which may lead to variations in results between studies; however, these variations are typical when normal pavement markings are applied to roadways.

Transverse Test Deck Pavement Marking Studies

The Transportation Research Center at the University of Nevada-Las Vegas performed field evaluations of pavement markings for the Regional Transportation Commission of Southern Nevada.[(16)] The goal of the evaluations was to identify products that meet the criteria to be included on the qualified products list. A transverse test deck was installed on the right lane of a high-volume roadway with an average daily traffic (ADT) of over 43,000. The test deck consisted of two sections, asphalt concrete (AC) and portland cement concrete (PCC). Each product was installed on both surfaces, with four lines per product at each location. Some vendors performed their own installation, while others hired contractors to perform the work. A private company provided traffic control and charged it to the participating vendors. All installations occurred at night to minimize impact on traffic.

The pavement markings were evaluated every 3 months over the 2-year course of the study. Retroreflectivity, chromaticity, and presence were evaluated each time. Researchers found that most markings only retained 60 to 70 percent of their initial retroreflectivity value for white products and 70 to 90 percent of their initial retroreflectivity value for yellow products. Chromaticity readings reduced significantly more for the yellow products as compared to the white products. Chromaticity readings dropped significantly for almost all the markings. For many products, the luminance factor "Y" was generally higher on the PCC deck as compared to the AC deck. Durability evaluations were good, with over 95 percent material retained for all products.

A major finding from the study was that many products retained a greater percentage of initial retroreflectivity in the tire tracks as compared to the skip areas for the most recent set of readings. This was most likely due to the increased amount of rain before the measurements were taken. Researchers believed that the rain and tire interaction cleaned the marking, which would be more prevalent in the wheel path instead of in the skip line area. This finding would indicate that measurements should be conducted not only during similar environmental conditions but also after a period of similar environmental conditions. Any variation from similar conditions before or during data collection would increase variability in the data and should be monitored throughout the data collection process.

The Transportation Research Center at the University of Nevada-Las Vegas also performed a study to compare the results of an NTPEP test deck to the results of testing horizontal markings at intersections.[17] Local conditions were evaluated as well as a comparison between the results of an NTPEP test deck with the results of the same markings installed as they normally would be at intersections. Test decks were set up on free-flowing highways and at six different intersections. The intersection test decks were all PCC, and the free-flowing NTPEP test deck had both AC and PCC surfaces. All markings were installed at all three test decks.

Researchers conducted 21 pavement marking tests on the decks. Vendors were responsible for installing their own materials. Durability, retroreflectivity, and color measurements were measured at 2-month intervals during the first year and at 4-month intervals during the second year. Traffic counts were conducted during the first year of the study to account for differences in traffic flows.

Durability was worse at the intersections in comparison to the highway test areas. The paint product durability dropped below 40 percent within the first 6 months at the intersection test deck, and the other products all remained above 80 percent. On the NTPEP test deck, the durability of paint was at 90 percent, as was the durability of the other markings. Similar to the durability, the retroreflectivity differences between the markings were more pronounced at the intersections than at the NTPEP test deck.

The results of the study demonstrated that using NTPEP test decks for evaluating intersection markings may produce erroneous evaluations. Products that may appear to have better performance than other products on the test deck may actually perform worse when installed at intersections. The results from this study may also pertain to longitudinal markings. Markings that perform best in NTPEP test decks may not always perform best when installed as long lines.

Long-Line Test Deck Pavement Marking Studies

The Michigan Department of Transportation (MDOT) contracted Michigan State University to conduct a 4-year project to evaluate various pavement marking materials used for longitudinal lines.[18] Five major test areas around the State were selected, and each test area had numerous measurement locations within it. The sites were selected to give a range of ADT values, varying amounts of heavy vehicle traffic, and a range of snow removal activity. The areas for measurement were also selected to maximize safety for those who were collecting the handheld retroreflectivity and subjective examination of durability data.

Degradation curves were developed for the pavement markings. These were based on 1 year of data collection (data were collected every 3 months) before the markings were restriped. These curves assume linear degradation of retroreflectivity for all marking types. The traffic variables and snow removal variables were compared to the retroreflectivity decay to see if there was any correlation. Speed limit, ADT, and percentage of heavy vehicles did not display any correlation to the retroreflectivity degradation. In contrast, snow removal activities were correlated to the retroreflectivity degradation rate.

The test materials did not have a wide range of retroreflectivity values; a wide range of retroreflective materials may have yielded more insight into the degradation associated with varying traffic parameters. Degradation was much greater in northern Michigan due to frequent snow removal activities. Alternate means of snowplowing were recommended to minimize the impact on the rate of retroreflectivity degradation. An exploration into the impact of marking brightness on crash rates was also attempted. The database did not seem to lead to any meaningful conclusions. Researchers recommended a more comprehensive analysis of crashes and retroreflectivity of the pavement markings.

The University Transportation Center for Alabama evaluated flat thermoplastic and profiled pavement markings on Alabama highways.[19] Researchers decided to only study the right shoulder line to reduce data collection time, which allowed them to cover more miles of roadway and collect more data on those markings. They selected 16 1-mi segments of flat thermoplastic and 21 1-mi segments of profiled markings for evaluation. These test sections were selected because they were not too spread out from each other, reducing travel time between sites. The sites covered the varying geography of the State, and there were enough sites with long lengths to provide the necessary data for statistically valid results.

A mobile retroreflectometer was used to collect the retroreflectivity data in dry conditions. In an attempt to simulate a wet condition on the roadway, a water truck was used in conjunction with the mobile retroreflectometer to collect data in wet conditions. All study sites were constructed so that they started and ended at a milepost for ease of data logging. Each location was tested three times over 12 months. Potential sources of variation included the following:

- Accuracy of the mobile retroreflectometer. The mobile retroreflectometer had been documented to have an uncertainty within 15 percent.
- Dust and dirt buildup on the road combined with the cleaning effects of rain can change retroreflectivity readings depending on when precipitation last occurred.
- Variations in speed while collecting data, both for the mobile retroreflectometer and the water truck.
- Change in geometry of the mobile retroreflectometer when going around horizontal curves.

It was found that it was feasible to test pavement markings at a large scale using a mobile retroreflectometer under wet pavement conditions with the aid of a water truck. The flat thermoplastic markings had higher initial retroreflectivity and similar retroreflectivity decay as compared to the profiled pavement marking. Estimated service lives were created based on the collected data, the roadway ADT, and two different threshold retroreflectivity values. The profiled pavement marking had higher end-of-life wet retroreflectivity than the flat thermoplastic marking had when it was new. Rumble stripes were also briefly explored and showed wet retroreflectivity values similar to that of the profiled pavement marking. Researchers suggested similar research on higher volume roads to continue research into the benefits of rumble stripes. They also suggested that the development of minimum wet retroreflectivity values may significantly impact pavement marking selection.

The Iowa Department of Transportation (Iowa DOT) contracted the Center for Transportation Research and Education at Iowa State University to conduct a project to develop an integrated approach to pavement marking management.[20] The researchers used retroreflectivity data collected by Iowa DOT during spring (before restriping activities) and fall (before winter maintenance activities) evaluation periods as well as initial retroreflectivity levels collected after striping to evaluate the degradation of the markings. This information was combined with other Iowa DOT managed systems, including pavement management and safety. This allowed the striping and retroreflectivity information to be compared to crash, road surface type, surface condition, and daily traffic information. The researchers also monitored five long-line test areas to refine the performance parameters and material selection practices that the initial study developed. These sites evaluated a range of regular and high-build waterborne materials, thermoplastic, and preformed tape markings. These binders were combined with a variety of bead types that were either surface applied or recessed in a groove. Retroreflectivity, traffic characteristics, and winter maintenance activities were monitored.

The Vermont Transportation Agency conducted a study to determine the service life and overall cost of various marking types in terms of degradation with respect to durability, retroreflectivity, and cost.[21] The goal was to develop a pavement marking application and replacement strategy. The test sites were selected randomly based on mile markers, and some had markings that had existed for more than 2 years. Pavement marking retroreflectivity was collected at 10-ft intervals at selected locations within each test site using a handheld retroreflectometer.

Researchers noted significant variability in the data, but the markings displayed similar degradation patterns. Service life was estimated using statistical modeling of the degradation of the lines based on traffic characteristics, roadway characteristics, and other attributes. In the evaluation, the large variability and the need for a predetermined minimum retroreflectivity value had to be considered. The results indicated that larger data sets provided more accurate degradation models. Further analyses will consider other independent variables such as average snowfall amounts, pavement types, and curved versus tangent sections. An economic analysis of the life-cycle costs will also be evaluated.

The Washington State Transportation Center conducted a study to develop retroreflectivity degradation curves for roadway pavement markings.[22] The goal was to forecast the performance of pavement markings to help determine a cost effective schedule for reapplying them. In total, 80 test sections were selected throughout Washington State, and they mostly consisted of paint products. Retroreflectivity data were collected several times over the course of 1 year using a mobile retroreflectometer.

The retroreflectivity values from roadways with similar ADT and environmental conditions displayed a significant amount of variability. Suggested causes of variability were changes in application methods by different striping crews, inherent variability in the mobile retroreflectometer, difficulty calibrating the device, different environmental conditions on data collection trips, or simply that retroreflectivity measurements can be inconsistent. Given the variability of the data, the degradation curves that were created had little statistical precision. The researchers indicated that it may be impossible to create accurate degradation curves even with the collection of more data.

The University of Utah conducted a study to determine the relationship between pavement marking life expectancy and traffic volumes.[23] The goal was to minimize marking costs by determining which type of pavement marking is the most economical. This study focused on solvent-based paint, epoxy, and preformed tape. Researchers used a mobile retroreflectometer to collect retroreflectivity data one time on a selection of markings of various ages. After collecting the retroreflectivity data, sites were verified for marking type, roadway type, and application date of the material. ADT values were collected from the Utah Department of Transportation, as were initial retroreflectivity for the studied types of pavement markings. The study found that road surface type and ADT affect the degradation of retroreflectivity. The lack of initially collecting their own retroreflectivity values, as well as retroreflectivity values collected over a period of time are areas that should be addressed in future research.

The Washington State Department of Transportation (WSDOT) conducted a pavement marking study located in the Snoqualmie Pass mountain area on 13 state-of-the-art materials.[24] This area was selected because of the adverse conditions the markings would face from traffic and snow removal activities. Five test areas were selected to give varying conditions along the mountain pass. All markings were placed on PCC road surfaces because bonding to PCC is often more difficult than to AC. Researchers assumed that any material that works on PCC would probably work on AC as well. Markings were applied in 0.2-mi segments at each test location, resulting in 1 mi of edge lines and lane lines for each marking. Manufacturers were allowed to select material application thickness and groove depth based on what they thought would provide the most durable and retroreflective marking. Waterborne paint was applied to the road surface to serve as a control in all test sections.

The environmental conditions on the pass during the study period were not as extreme as usual. Temperatures were warmer, and there was less precipitation than normal. The effects of sanding and deicing were also less than typical, in part due to the mild winter and in part due to a new policy on the use of sand and deicers. The number and type of snowplow passes over the markings were not monitored, nor were the areas where sand and deicer were applied. Knowing these locations and amounts could add further insight into the effects of winter maintenance activities on the retroreflectivity degradation of pavement markings.

Retroreflectivity data were scheduled to be collected every 2 months using handheld retroreflectometers. Because the road surface needed to be dry, weather windows needed to be found and traffic control was scheduled so that data could be collected. Retroreflectivity readings were collected at locations representative of the entire marking. The representative areas did not include areas in curves where markings typically experience greater wear than in tangent sections. Six measurements were made on representative lane lines, and six measurements were made on the edge lines for each marking.

Results from the study indicate that there are pavement markings and pavement making systems that can provide acceptable year-round performance. Researchers recommended that WSDOT allow the use of these new materials and incorporate effective material installation systems into the State’s standard specifications. The recessed markings performed better than the markings applied to the surface. The products in the study would continue to be monitored until failure.

The Swedish National Road and Transport Research Institute conducted a study on the performance of wet visibility road markings.[25] This study determined the durability, retroreflectivity performance in both wet (recovery) and dry conditions, and luminance coefficient for a variety of markings that are intended to perform well in wet conditions. The study covered the course of two winter seasons.

All markings were applied to the road surface on either a new AC surface or a new sealcoat surface. Each marking was applied to a 656-ft section on both sides of the two-lane highway. The markings were applied on both sides to try and account for curvature of the roadway. Two sets of retroreflectivity data were collected on the markings. The first set measured the retroreflectivity of the markings when dry or artificially wet. These measurements were conducted four times during the study. The second set measured the retroreflectivity of the markings in the state that the marking was in on a predetermined measuring date during the winter months. These measurements indicated the typical performance of the markings on any given winter day, including the environment as an independent variable. These measurements were conducted on 10 predetermined dates throughout the winter months.

The markings on the sealcoat surface did not perform as well as the markings on the AC surface. Many of the markings were able to maintain good retroreflectivity under dry conditions after 2 years but did not retain retroreflectivity under wet conditions. Researchers assumed that the wet retroreflectivity experienced greater degradation than the dry retroreflectivity due to the snow removal activities. The retroreflectivity values measured during the winter were used to determine an estimated availability of the marking. The availability of the marking is the time when the marking is above a minimum retroreflectivity threshold. When a marking is below this threshold, it is considered to be ineffective and thus unavailable. The availability of the wet visibility markings was higher than that of the standard pavement marking applied as a control.

The Arizona Department of Transportation (ADOT) conducted a long-line study as part of a larger FHWA study on all-weather pavement markings (AWPMs).[26] The ADOT study looked at the effects of varying traffic paint application procedures. The wet thickness of the markings, bead loading, and application speed of the truck spraying the marking affected the results of the study. Applying a proper wet thickness of 12 to 15 mil with a higher rate of drop on beads of 8 lb versus the typical 6 lb of beads per gallon of paint could provide a line that would last 12 to 18 months. Applying the markings in a lane closure allows for slower application speed, resulting in a higher quality marking.

Recommendations to ADOT's striping practices focused on the application of the line. A line of proper thickness with higher bead application rates will improve marking quality. Proper surface preparation will also improve the quality of the line. Researchers recommended using lane closures or traffic control that will allow for slower application speeds to maximize line quality and minimize exposure to traffic prior to curing.

A large-scale evaluation of pavement markings was conducted for FHWA as part of the Intermodal Surface Transportation Efficiency Act.[26] The objectives of the study were to evaluate the service life, safety, and cost benefit of AWPMs. An *AWPM* is defined as a pavement marking that is visible under dry conditions and also under rainy conditions of up to 0.25 inches/h of rainfall. In practice, *AWPMs* are defined as marking materials that would be expected to have greater retroreflectivity and/or longer life than conventional markings.

Over the 3-year study period from 1994 to 1996, 19 States participated in the FHWA study as part of the Intermodal Surface Transportation Efficiency Act. A total of 85 sites (ranging from 1 to 50 mi in length) were located in these States and consisted of many durable marking types. Sites were not selected based on any criteria for the safety analysis, so the possibility of regression-to-the-mean could exist in the safety analysis.

The service life analysis divided the road section into three categories. The categories were freeways and two groups of non-freeways based on a speed threshold of 45 mi/h. Retroreflectivity of the pavement markings was measured using mobile retroreflectometers at approximately 6-month intervals over the course of the study. Life-cycle costs were found using installation costs and the estimated service life of the product.

The results of the study found large site-to-site variations in retroreflectivity for the same type of marking material. Modeling of retroreflectivity degradation was conducted for each line at each site because of the large variations between sites. The variability of materials of the same type at different locations suggests that the retroreflectivity of a marking is affected by a number of roadway, traffic, application, and weather-related variables. Some of these variables may be easily quantifiable, but others may not. Reducing the variability within the study design is the first approach to reducing the variability of the study results.

Due to the variability in the retroreflectivity data, there was variability in the service life analysis of the products. The service life of the markings had large ranges, which resulted in large ranges in the life-cycle costs for the markings. Researchers recommended a more controlled study of fewer markings placed closer to each other to try and reduce some of the variables inherent to pavement marking test decks. More analysis could be feasible if the markings experienced similar conditions and did not display as much variability.

Test Deck Summary

Both transverse and long-line test decks have advantages and disadvantages. Each method of pavement marking testing can provide good information depending on the information being sought after. Table 1 summarizes the advantages and disadvantages of each test desk design.(4)

Table 1. Advantages and disadvantages of transverse and long-line test decks.

Transverse Test Decks	Long-Line Test Decks
Advantages • Most common form of on-the-road testing. • Used by the AASHTO NTPEP program. • Markings can be placed close together in a relatively short length of roadway, which can help minimize biases and provide reasonable uniform wear. • The close proximity of the materials on a transverse deck allows data to be quickly collected. • 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.	**Advantages** • Marking materials are placed on the test deck with the same equipment that is regularly used to install markings. • Markings can be evaluated under real climate and traffic conditions. • Retroreflectivity is measured 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.
Disadvantages • The results may be good for comparing products to each other but 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 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.	**Disadvantages** • There is not an established protocol for long-line testing as 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 also 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.

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 average annual daily traffic (AADT) of approximately 51,000. The Anchorage pavement marking test deck area consists of 12 test sections along the Glenn Highway between Boniface Parkway and East Eagle River Loop Road. Table 2 lists the different pavement markings installed on the Alaska test deck.

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

Table 2. Pavement markings installed in Alaska.

Test Section	Marking Type	Installation Date	Application Type	Placement (Inlaid)	Groove Depth (mil)	Material Thickness (mil)
1 AK a	Alaska Department of Transportation (AKDOT) paint	8/7/2006	Spray	Surface	0	12
				Shallow	65	12
				Deep	160	12
2 AK a	All-weather paint	8/7/2006	Spray	Shallow	65	30
				Deep	160	30
3 AK a	Methyl methacrylate (MMA)	8/7/2006	Extruded	Shallow	70	100
				Deep	175	100
4 AK a	MMA	8/7/2006	Agglomerate	Shallow	90	200
				Deep	275	200
5 AK a	Tape	8/7/2006	Rolled	Deep	175	100
5 AK b	Tape	8/7/2006	Rolled	Deep	175	100
6 AK a	MMA	8/7/2006	Extruded	Shallow	60	100
				Deep	120	100
6 AK b	Modified urethane	8/7/2006	Spray	Surface	0	20
				Shallow	70	20
				Deep	120	20
7 AK a	Low-temperature acrylic paint	8/7/2006	Spray	Surface	0	12
				Shallow	140	12
				Deep	175	12
8 AK a	MMA	8/7/2006	Agglomerate	Shallow	120	200
				Deep	320	200
9 AK a	High-build acrylic paint	8/7/2006	Spray	Shallow	60	30
				Deep	145	30
10 AK a	Polyurea	8/7/2006	Spray	Shallow	65	20
				Deep	155	20
All sections	Paint	6/21/2007	Spray	Over existing	Existing	12
1 AK b	Preformed thermoplastic	9/24/2007	Heat in Place	Deep	160	125
2 AK b	MMA	10/2/2007	Spray	Shallow	85	60
				Deep	180	60
7 AK b	MMA and paint	8/5/2008	Extruded with raised edges, double spray	Shallow	60	100
				Deep	145	40
9 AK b	MMA and paint	8/5/2008	Extruded with raised edges, spray	Deep	175	100
				Deep	175	20

TENNESSEE TEST DECKS

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 snowfall 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 test deck materials were primarily installed with handcarts, similar to the Anchorage test deck. However, there were differences. For example, most materials on the Nashville test deck were installed with long-line trucks. These installation techniques were chosen to assess possible differences between handcart-applied and long-line truck-applied materials.

Nashville Test Deck

The Nashville pavement marking test deck area was installed in October 2006. This test deck has 9 sections along SR 840 between I-65 and I-24 with an AADT of approximately 19,000.

Table 3 shows the different pavement markings that were installed. Unlike the other test decks, which had markings applied at widths of 4 inches, all markings along the Nashville test decks were 6 inches wide due to the TDOT policy for markings on highways of this functional classification.

Table 3. Nashville, TN, test deck pavement markings.

Test Section	Marking Type	Installation Date	Application Type	Placement (Inlaid)	Groove Depth (mil)	Material Thickness (mil)
1 TN-N	Thermoplastic	10/16/2007	Spray	Over rumble strip edge line only	N/A	40
2 TN-N	Thermoplastic	10/16/2007	Spray	Shallow	75	40
				Deep	185	40
3 TN-N	Thermoplastic	10/16/2007	Spray	Shallow	85	90
				Deep	270	90
4 TN-N	Thermoplastic	10/16/2007	Extruded	Shallow	95	120
				Deep	180	120
5 TN-N	Thermoplastic	10/16/2007	Inverted profile	Shallow	75	50/225*
6 TN-N	Low-temperature acrylic paint	10/16/2007	Spray	Shallow	55	12
				Deep	145	12
7 TN-N	Polyurea	10/16/2007	Spray	Shallow	110	20
				Deep	165	20
8 TN-N	All-weather paint	10/16/2007	Spray	Shallow	135	26
				Deep	175	26
9 TN-N	High-build acrylic paint	10/16/2007	Spray	Shallow	100	25
				Deep	175	25
10 TN-N	Lead-free	6/5/2008	Extruded	Surface	0	80
11 TN-N	Lead-free	6/5/2008	Extruded	Surface	0	80
12 TN-N	Lead-free	6/5/2008	Extruded	Surface	0	85

N/A = Not applicable.
*50-mil nominal thickness with 225-mil thickness of profile.

In June 2008, the researchers added three lead-free yellow thermoplastic sections to this test deck to accomplish two objectives. One 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 chapter 5, Environmental Safety and Health Considerations.

Tusculum Test Deck

The Tusculum pavement marking test deck area was installed in May 2007. This test deck has 9 sections along SR 34 between SR 107 and SR 75 with an AADT of approximately 12,000. Table 4 shows the different pavement markings that were installed.

Table 4. Tusculum, TN, test deck pavement markings.

Test Section	Marking Type	Installation Date	Application Type	Placement (Inlaid)	Groove Depth (mil)	Material Thickness (mil)
1 TN-T	Modified epoxy	5/14/2007	Spray	Shallow	100	22
				Deep	125	22
2 TN-T a	MMA	5/14/2007	Extruded	Shallow	100	90
				Deep	170	90
2 TN-T b	MMA	5/14/2007	Agglomerate	Shallow	100	200
				Deep	170	200
3 TN-T	Low-temperature acrylic paint	5/14/2007	Spray	Shallow	50	15
				Deep	110	15
4 TN-T	High-build paint	5/14/2007	Spray	Shallow	105	24
				Deep	150	24
5 TN-T a	Tape	5/14/2007	Rolled	Shallow	60	100
				Deep	130	100
5 TN-T b	Tape	5/14/2007	Rolled	Shallow	25	100
				Deep	195	100
6 TN-T	Thermoplastic	5/14/2007	Extruded	Shallow	70	90
				Deep	320	90
7 TN-T	Modified urethane	5/14/2007	Spray	Shallow	110	15
				Deep	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 typical marking installation costs, the overall cost effectiveness of the tested pavement markings could be determined. 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. 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.

Retroreflectivity Measurements

Retroreflectivity data were collected using a handheld pavement marking retroreflectometer and a mobile retroreflectometer. The handheld retroreflectometer was used to measure the edge line markings only, whereas the mobile retroreflectometer was used to measure the edge line and lane line markings. The handheld dataset was used to verify the mobile retroreflectivity dataset. All retroreflectivity measurements were collected in dry conditions.

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 to a minimum. The data collection protocol for this project was partially modeled after that described in ASTM D6359.[27] All retroreflectivity devices meet the criteria set in ASTM E1710-05.[28] 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 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 at a 95 percent confidence level was within a half standard deviation 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 to document the general marking condition and to be used later to quantify the presence 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.

Monitoring Snowfall

All three pavement marking test decks were installed in areas that typically receive snow and have snowplowing activities. The National Oceanic and Atmospheric Administration’s National Weather Service historic data were used to monitor the snowfall at each of the test decks. The closest National Weather Service station to each test deck was used to provide a reasonable approximation of the snowfall at the test decks and thus an idea of how often snowplowing activities may have occurred on each road segment.

The Anchorage test deck typically receives an average of 70 inches of snow per year. Table 5 provides the individual daily snowfall totals rounded to the nearest inch for the Anchorage test deck for days where an inch or more of snow fell. Each year of the pavement marking study received more snow than a typical year in Anchorage. The Nashville test deck typically receives an average of 9 inches of snow per year. Table 6 provides the individual daily snowfall totals for the Nashville test deck for days where more than 0.3 inches of snow fell. The average snowfall at the Nashville test deck over the study period was less than the typical annual average. The Tusculum test deck typically receives an average of 15 inches of snow per year. Table 7 provides the individual daily snowfall totals for the Tusculum test deck for days where more than 0.3 inches of snow fell. The average snowfall at the Tusculum test deck over the study period was close to the typical annual average. It should be noted that the sum of the individual snowfall amounts listed does not equal the total snowfall due to rounding and not including individual amounts below 0.5 inches for Alaska or 0.3 inches for the two Tennessee test decks.

Table 5. Anchorage, AK, test deck snowfall.

Winter	Total Snowfall (inches)	Individual Snowfall (inches)	Number of Events
2006/2007	84	1	2
		2	5
		3	3
		4	4
		5	2
		6	2
		10	1
		11	1
2007/2008	109	1	9
		2	8
		3	5
		4	2
		5	2
		6	3
		7	3
2008/2009	93	1	9
		2	11
		3	5
		4	5
		5	1
		6	1
		8	1

Table 6. Nashville, TN, test deck snowfall.

Winter	Total Snowfall (inches)	Individual Snowfall (inches)
2006/2007	2.2	Only trace amounts of snowfall
2007/2008	2	Only trace amounts of snowfall
2008/2009	1.7	0.3
	1.7	0.7
2009/2010	7.1	3.7
2010/2011	12	0.7
	12	1.1
	12	1.4
	12	2.5

Table 7. Tusculum, TN, test deck snowfall.

Winter	Total Snowfall (inches)	Individual Snowfall (inches)
2007/2008	5.3	1.2
		2.5
2008/2009	8.3	0.4
		0.7
		0.8
		0.9
		0.9
		1.0
2009/2010	26.7	0.3
		0.3
		0.3
		0.5
		0.6
		1.3
		1.6
		1.7
		1.7
		4.8
		6.4
2010/2011	15.6	0.4
		0.4
		0.5
		0.6
		0.7
		1.0
		1.2
		1.3
		1.3
		1.5
		2.0

PAVEMENT MARKING DURABILITY

For this project, a pavement marking system was deemed to have remaining service life if it maintained adequate presence (greater than 75 percent remaining), as subjectively evaluated in situ using ASTM D913 as a reference and retroreflectivity of at least 100 mcd/m^2/lux.[1(29)] 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, quality of installation, and winter maintenance activities are some of the major influences on the service life of a pavement marking

[1]The presence of the pavement markings was also evaluated using a digital image analysis technique described in appendix G.

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 B includes figures showing the retroreflective degradation of markings that lasted more than 1 year. For the Tennessee test decks, the figures in appendix B also include retroreflectivity degradation trend lines and their associated equations and R^2 values. The exponential regression line was predominantly the best fit line for the pavement marking data. As a result, it was used in all cases.

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 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 8 provides the results of the various pavement marking sections along the Alaska test deck. It only includes the results from the edge line. In all cases but one, which is explained in the following paragraph, the lane line results were similar.

Table 8 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 AKDOT pavement marking paint and beads, as initially installed on test section 1 AK a. This material failed to maintain presence and retroreflectivity through the first winter. The results in table 8 show that the performance of the paint in the second winter was the same. However, using paint to refresh durable markings that lose retroreflectivity but not presence over the winter appears to be a viable solution for regions that experience winter conditions similar to those in Anchorage.

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 the systems. The paint-based pavement markings systems were the only markings to fail in both durability measures (retroreflectivity and presence) after their first winter. The most recently applied paint in sections 7 AK b and 9 AK b was applied in a very deep groove and was able to maintain retroreflectivity in the areas where it was able to maintain presence, but overall presence was generally less than 50 percent of the original material remaining.

The only markings to maintain an adequate level of presence and retroreflectivity past their first winter were the tape products installed in sections 5 AK a and 5 AK b and the experimental MMA marking system installed in sections 7 AK a and 9 AK a. The tape products maintained adequate retroreflectivity past the second winter, although the presence on the lane line was judged as less than adequate. As shown in table 8, the tape on the edge line continued to provide adequate presence and retroreflectivity through the end of 2008. The structured MMA marking installed in fall 2008 was able to survive the winter and still maintain a retroreflectivity along the length of the line that was typically above 100 mcd/m^2/lux. The structure of the marking itself was designed to shield the majority of the marking from the damaging plow blades and studded tires.

Table 8. Alaska test deck edge line pavement marking results.

Test Section		8/28/2006		9/25/2006		4/23/2007		7/16/2007		10/2/2007		5/13/2008		8/5/2008		9/28/2008		5/20/2009	
		P	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**	**P**	**R**
1	a	A	93	A	93	F	N/A	A	135	—	—	—	—	—	—	—	—	—	—
	b									A	404	A	80	A	78	A	77	A	71
2	a	A	294	A	276	F	N/A	A	164	—	—	—	—	—	—	—	—	—	—
	b									A	286	A	64	A	74	A	59	M	38
3	a	A	482	A	452	A	62	A	232	A	182	A	41	A	< 30	A	<30	M	<30
4	a	A	196	A	209	A	48	A	128	A	64	F	N/A	F	N/A	F	N/A	F	N/A
5	a	A	773	A	869	A	236	A	193	A	166	A	193	A	151	A	191	A	126
	b	A	526	A	562	A	262	A	185	A	164	A	165	A	181	A	169	A	115
6	a	A	153	A	173	A	44	A	243	A	133	A	59	A	—	A	54	M	53
	b	A	500	A	347	A	40	A	231	A	118	M	44	M	—	M	44	M	44
7	a	A	358	A	305	F	N/A	A	173	A	107	F	N/A	—	—	—	—	—	—
	b													A	218	A	210	A	130
8	a	A	550	A	446	A	108	A	189	A	91	M	107	M	—	M	98	F	87
9	a	A	436	A	369	F	N/A	A	186	A	106	F	N/A	—	—	—	—	—	—
	b													A	385	A	337	M/F	142
10	a	A	410	A	335	A	40	A	246	A	157	M	53	M	—	M	50	F	46

P = Presence rating from in situ evaluations (A = Adequate (> 75 percent), M = Marginal (50–75 percent), and F = Fail (< 50 percent)).
R = Average retroreflectivity (mcd/m^2/lux).
— Indicates periods when the markings were not evaluated.
Note: Test deck sections with shaded cells indicate a pavement marking failed and was replaced with a different material to test. All sections were restriped with standard paint prior to the measurements on July 16, 2007.

The only other pavement marking systems to maintain 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, or deep groove applications for the individual marking systems in Alaska.

Tennessee

The pavement marking test sections on the Nashville test deck have been in service for more than 4 years. As of March 30, 2011, all marking systems were still showing adequate retroreflectivity and presence except for 1 TN-N, which is marginal in presence and retroreflectivity. Table 9 and table 10 display the initial and most recent retroreflectivity readings for each of the different test sections. The data clearly show that not all markings degrade at the same rate and that the initial retroreflectivity level is not a reliable predictor of long-range performance across marking types.

Table 11 displays retroreflectivity readings from the initial day of installation, after 2.5 months, and the most recent readings for the three lead-free yellow thermoplastic sections. The most recent retroreflectivity readings are much higher than the initial retroreflectivity readings. Additionally, for section 11 TN-N, the readings are slightly higher than the 2.5-month readings. The day of installation readings were taken just after the marking was applied. This did not allow much time for excess beads to be removed and poorly embedded beads to be dislodged, resulting in the low initial retroreflectivity readings. Daytime color and nighttime color measurements using methods outlined in ASTM D 6628 were recorded over time to address concerns that lead-free thermoplastic materials do not provide the same level of saturated yellow color as do thermoplastic markings with lead chromate as a pigment.[30] The results of the lead-free color measurements can be found in appendix B. The lead-free results indicate that the nighttime color for all markings tested were near the edge or outside of the required color box, indicating a less saturated yellow color for the nighttime 98-ft viewing condition. The 45-degree/zero-degree illuminant D65 (representing daytime lighting) and illuminant A (representing nighttime lighting from vehicles or tungsten-filament lighting) measurements for all sections indicated that the markings color remained within the color boxes for diffuse viewing conditions.

Table 9. Nashville, TN, test deck edge line durability information.

	Edge Line Retroreflectivity Levels ($mcd/m^2/lux$)			
	11/8/2006	**3/30/2011**	**11/8/2006**	**3/30/2011**
Test Section	**Shallow Groove**	**Shallow Groove**	**Deep Groove**	**Deep Groove**
1 TN-N	N/A	N/A	390	107
2 TN-N	433	153	420	200
3 TN-N	398	208	384	229
4 TN-N	721	371	716	637
5 TN-N	732	200	N/A	N/A
6 TN-N	423	243	418	256
7 TN-N	1,217	176	1,413	262
8 TN-N	371	226	409	203
9 TN-N	598	234	599	218

N/A = Not applicable.

Table 10. Nashville, TN, test deck lane line durability information.

Test Section	Lane Line Retroreflectivity Levels ($mcd/m^2/lux$) 11/8/2006 Shallow Groove	3/30/2011 Shallow Groove	11/8/2006 Deep Groove	3/30/2011 Deep Groove
1 TN-N	N/A	N/A	N/A	N/A
2 TN-N	489	202	450	218
3 TN-N	428	175	389	203
4 TN-N	N/A	N/A	563	559
5 TN-N	659	201	N/A	N/A
6 TN-N	398	161	368	211
7 TN-N	991	150	1,021	160
8 TN-N	392	207	416	177
9 TN-N	496	181	495	235

N/A = Not applicable.

Table 11. Nashville, TN, test deck lead-free thermoplastic durability information.

Test Section	Yellow Edge Line Retroreflectivity Levels ($mcd/m^2/lux$) 6/5/2008	8/20/2008	3/30/2011
10 TN-N	95	258	198
11 TN-N	152	267	274
12 TN-N	97	238	167

The pavement marking test sections at the Tusculum test deck have been in service for approximately 4 years. Marking systems still show adequate retroreflectivity and presence, with the exception of the modified epoxy in section 1 TN-T and the surface-applied epoxy in sections 3 TN-T, 5 TN-T a, and 5 TN-T b. The presence of the 1 TN-T material reduced at a faster rate than the retroreflectivity level, as the remaining marking was reading 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 3). Evaluation of section 1 TN-T ended after 2 years when the markings were mostly not present (greater than 75 percent loss) even though the retroreflectivity of the remaining material remained above the 100 $mcd/m^2/lux$ level.

Figure 3. Photo. Tusculum test deck section 1 TN-T presence failure.

Sections 5 TN-T a and 5 TN-T b were damaged during the 2009/2010 winter. Table 7 indicates that there were two snowstorms during that winter that provided considerable snowfall for the area. It is thought that during these storms, snowplowing activity caused the shallow groove-applied tape to be scraped from the road surface. Figure 4 and figure 5 show the test sections after the failure of the marking material.

Figure 4. Photo. Tusculum test deck section 5 TN-T a shallow groove-applied presence failures.

Figure 5. Photo. Tusculum test deck section 5 TN-T b shallow groove-applied presence failures.

Table 12 and table 13 display the initial and most recent retroreflectivity readings for each of the test sections. Like the Nashville test deck, the Tusculum data clearly show that markings degrade at different rates. The only edge line markings falling below the 100-mcd/m^2/lux level were those that were shallow groove-applied in 3 TN-T and 5 TN-T b. The deep grooved sections of these markings remained well above and slightly above 100 mcd/m^2/lux, respectively. The only lane line markings falling below the 100-mcd/m^2/lux level were those that were shallow groove-applied in 5 TN-T b and deep groove-applied in 5 TN-T a and 5 TN-T b. Several other edge line and lane line sections are approaching the 100-mcd/m^2/lux level.

Table 12. Tusculum, TN, test deck edge line durability information.

Test Section	Edge Line Retroreflectivity Levels ($mcd/m^2/lux$)			
	6/5/2007	3/29/2011	6/5/2007	3/29/2011
	Shallow Groove	Shallow Groove	Deep Groove	Deep Groove
1 TN-T	673	N/A	686	N/A
2 TN-T a	510	290	531	337
2 TN-T b	509	150	494	161
3 TN-T	423	80	420	261
4 TN-T	415	213	397	205
5 TN-T a	856	109	945	163
5 TN-T b	1,030	82	966	104
6 TN-T	468	260	464	286
7 TN-T	650	265	695	274

N/A = Not applicable.

Table 13. Tusculum, TN, test deck lane line durability information.

Test Section	Lane Line Retroreflectivity Levels ($mcd/m^2/lux$)			
	6/5/2007	3/29/2011	6/5/2007	3/29/2011
	Shallow Groove	Shallow Groove	Deep Groove	Deep Groove
1 TN-T	560	N/A	496	N/A
2 TN-T a	549	275	447	145
2 TN-T b	470	192	472	173
3 TN-T	440	126	394	194
4 TN-T	389	100	358	115
5 TN-T a	838	104	780	97
5 TN-T b	908	91	861	72
6 TN-T	477	255	470	261
7 TN-T	505	219	470	234

N/A = Not applicable.

PAVEMENT MARKING COSTS

The three pavement marking test decks have many different types of pavement markings installed, each of which has a range of expected costs. Geographical location, availability of materials, contract size, application type, material thickness, type of retroreflective optics used, timing of application, surface preparation requirements (e.g., removal of pre-existing marking material, preparation of grooves, etc.), and traffic control costs all impact the installation cost of the pavement markings. The researchers reviewed information on typical costs for the materials that were installed on the test decks. Primary sources for information were State transportation department annual averages of bid prices. The research team reviewed 22 States' bid prices for the price of the marking materials that were installed on the test decks. Additional sources of information came from the pavement marking industry suppliers and contractors. Raw material costs (beads and binder) as well as some installed pricing for marking materials were gathered. The drawback to using bid pricing is that each State uses different names for their line items and are not always descriptive enough to ensure their price is specific to the particular marking of interest. Many bid prices do not mention material thickness or the specific application technique. In these instances, researchers looked at State specifications to determine application types and required thicknesses. Paint and thermoplastic were found in most States' bid pricings, but other markings were found less often. For markings where costs could not be found in bid pricing, estimated costs were developed based on the cost of raw materials and expected installation costs using similar materials where bid prices could be found. The pavement marking costs, combined with the pavement marking durability data, are the primary elements needed to determine cost effectiveness levels.

Wider pavement markings were found to increase the cost of the marking by varying degrees. State bid prices indicated a 16 to 45 percent increase for paint and a 15 to 76 percent increase for thermoplastic when going from a 4-inch-wide white solid marking to a 6-inch-wide marking. A 2002 report by Gates and Hawkins indicates that the main drawback of using 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.[(31)] Recent cost estimates by ADOT predicted a 38 percent increase in contracted cost for 6-inch thermoplastic markings compared to 4-inch markings.[2]

Grooving the road surface to create an area to recess the markings can be a substantial cost addition to the pavement marking system. In 2006, Lagergren et al. reported that groove costs could be $1.05/ft for a 100-mil groove and $0.95/ft for a 60-mil groove.[(24)] In 2007, Hawkins et al. reported that grooves can cost between $0.40 and $1.40/ft.[(32)] Milled shoulder rumble strips that are used for rumble stripes were found to cost between $0.10 and $0.35/ft depending on the road surface.

Table 14 through table 19 display the estimated costs for the markings applied at the Anchorage, Nashville, and Tusculum test decks. The costs are also on a per-linear-foot and per-mile basis. The first table for each test deck provides the raw material costs, and the second table provides the estimated installed costs for each material. The costs displayed are for a typical new application on the surface of the road and for an inlaid marking where the cost of the groove is $0.75/ft.

[2] These estimates are from an unpublished internal memo from ADOT.

Table 14. Estimated Anchorage, AK, test deck pavement marking material costs.

Marking Type	Application Type	Material Thickness (mil)	Bead Type	Bead Material Cost ($/lb)	Binder Material Cost ($/lb)	Total Material Cost ($/lb)	Binder Material Costs	Bead Costs ($/lb)
AKDOT low volatile organic compound (VOC) paint	Spray	12	AASHTO M247 type 1[33]	0.0072	0.035	0.0422	$14/gal = $0.105/$\text{ft}^2$	0.27
All-weather paint (3M Company)	Spray	30	Swarco type 2 and 3M elements	0.0965	0.0883	0.1849	$14/gal = $0.265/$\text{ft}^2$	Type 2: 0.33 elements: 5.0
MMA 98:2 (Stirling Lloyd)	Extruded	100	Type 2	0.0099	0.8333	0.8432	$40/gal = $2.50/$\text{ft}^2$	0.33
MMA 98:2 (Stirling Lloyd)	Agglomerate	200	Type 2	0.0099	1	1.0099	$40/gal = $3.00/$\text{ft}^2$	0.33
MMA 4:1 (Ennis)	Extruded	100	30/50 mesh Swarco Megalux T13 coated	0.018	0.8333	0.8513	$40/gal = $2.50/$\text{ft}^2$	0.6
Modified urethane (Ennis)	Spray	20	Potters type 1 AC110 coating and type 4 Visibead plus 2	0.0272	0.1466	0.1739	$35/gal = $0.44/$\text{ft}^2$	Type 1: 0.27 type 4: 0.6
Low-temperature acrylic waterborne paint (Ennis)	Spray	12	Swarco AASHTO M247[33]	0.0072	0.035	0.0422	$14/gal = $0.105/$\text{ft}^2$	0.27
MMA 4:1 (Degussa-Pathfinder™)	Agglomerate	200	Swarco AASHTO M247[33]	0.0081	1	1.0081	$40/gal = $3.00/$\text{ft}^2$	0.27
High-build acrylic waterborne paint (Ennis)	Spray	30	Swarco Megalux type 3	0.024	0.0883	0.1123	$14/gal = $0.265/$\text{ft}^2$	0.6
Polyurea (IPS)	Spray	20	Potters type 1 AC110 coating and type 4 Visibead plus 2	0.0272	0.2083	0.2355	$50/gal = $0.625/$\text{ft}^2$	Type 1: 0.27 type 4: 0.6
AKDOT standard MMA	Spray	60	AASHTO M247[33]	0.0081	0.4966	0.5048	$40/gal = $1.49/$\text{ft}^2$	0.27
MMA (Ennis)	Extruded with raised edges	100	30/50 mesh, 30-30-40 Swarco mega blend	0.0166	1	1.0167	$40/gal = $3.00/$\text{ft}^2$	0.5
Paint (Pervo)	Spray	20	30/50 mesh, 30-30-40 Swarco mega blend	0.02	0.0583	0.0783	$14/gal = $0.175/$\text{ft}^2$	0.5

Note: The cost per linear foot was based on a 4-inch-wide pavement marking line.

Table 15. Estimated Anchorage, AK, test deck pavement marking costs.

Test Section	Marking Type	Application Type	Surface Applied		Inlaid at $0.75/lf	
			$/lb	$/mi	$/lb	$/mi
1 AK a	AKDOT paint	Spray	0.10	528	0.85	4,488
2 AK a	All-weather paint	Spray	0.27	1,426	1.02	5,386
3 AK a	MMA	Extruded	1.75	9,240	2.50	13,200
4 AK a	MMA	Agglomerate	2.00	10,560	2.75	14,520
5 AK a	Tape	Rolled	2.75	14,520	3.50	18,480
5 AK b	Tape	Rolled	2.75	14,520	3.50	18,480
6 AK a	MMA	Extruded	1.75	9,240	2.50	13,200
6 AK b	Modified urethane	Spray	0.31	1,637	1.06	5,597
7 AK a	Low-temperature acrylic paint	Spray	0.09	475	0.84	4,435
8 AK a	MMA	Agglomerate	2.00	10,560	2.75	14,520
9 AK a	High-build acrylic paint	Spray	0.16	845	0.91	4,805
10 AK a	Polyurea	Spray	0.65	3,432	1.40	7,392
1 AK b	Preformed thermoplastic	Heat in place	2.50	13,200	3.25	17,160
2 AK b	MMA	Spray	1.04	5,491	1.79	9,451
7 AK b	MMA	Extruded with raised edges	2.25	11,880	3.00	15,840
9 AK b	Paint	Double spray	0.20	1,056	0.95	5,016

Table 16. Estimated Nashville, TN, test deck pavement marking material costs.

Marking Type	Application Type	Material Thickness (mil)	Bead Type	Bead Rate (per 100 ft^2)	Bead Material Cost ($/lb)	Binder Material Cost ($/lb)	Total Material Cost ($/lb)	Binder Material Costs	Bead Costs ($/lb)
Thermoplastic (Ennis)	Spray	40	Potters type 1 AC110 coating	8 lb	0.0072	0.1183	0.1255	$1600/ton = $0.355/$ft^2$	0.27
Thermoplastic (Ennis)	Spray	90	Potters type 1 AC110 coating	8 lb	0.0072	0.2333	0.2405	$1400/ton = $0.70/$ft^2$	0.27
Thermoplastic (Ennis)	Extruded	120	Potters type 1 AC110 coating and type 4 Visibead plus 2	6 lb type 1 and 10 lb type 4	0.0254	0.31	0.3354	$1400/ton = $0.93/$ft^2$	Type 4: 0.6 type 1: 0.27
Thermoplastic (Gulfline)	Inverted profile	50/225	Potters type 1 AC110 coating and type 4 Visibead plus 2	6 lb type 1 and 10 lb type 4	0.0254	0.31	0.3354	$1400/ton = $0.93/$ft^2$	Type 4: 0.6 type 1: 0.27
Low-temperature acrylic waterborne paint (Ennis)	Spray	12	Potters type 1 AC110 coating	8 lb	0.0072	0.03	0.0372	$12/gal = $0.09/$ft^2$	0.27
High-build acrylic waterborne paint (Ennis)	Spray	25	Swarco type 3 virgin glass	10–12 lb	0.0201	0.0626	0.0828	$12/gal = $0.188/$ft^2$	0.55
Polyurea (Epoplex)	Spray	20	Prismo high index cluster and Potters type 4 Visibead plus 2	8 lb cluster and 10 lb type 4 per gal	0.1908	0.2083	0.3992	$50/gal = $0.625/$ft^2$	Cluster: 5.0 type 4: 0.6
3M all-weather paint	Spray	26	Swarco type 2 and 3M elements	12 lb type 2 and 5 lb elements	0.0965	0.0646	0.1612	$12/gal = $0.194/$ft^2$	Type 2: 0.33 elements: 5.0

Table 17. Estimated Nashville, TN, test deck pavement marking costs.

Test Section	Marking Type	Application Type	Surface Applied		Inlaid at $0.75/lf	
			$/lb	$/mi	$/lb	$/mi
1 TN-N	Thermoplastic at 40 mil	Spray on rumble strip	0.40	2,112	N/A	N/A
2 TN-N	Thermoplastic at 40 mil	Spray	0.20	1,056	0.98	5,016
3 TN-N	Thermoplastic at 90 mil	Spray	0.30	1,584	1.05	5,544
4 TN-N	Thermoplastic	Extruded	0.5	2,640	1.25	6,600
5 TN-N	Thermoplastic	Inverted profile	0.7	3,696	N/A	N/A
6 TN-N	Low-temperature acrylic paint	Spray	0.08	422	0.83	4,382
7 TN-N	Polyurea	Spray	0.80	4,224	1.55	8,184
8 TN-N	All-weather paint	Spray	0.24	1,267	0.99	5,227
9 TN-N	High-build acrylic paint	Spray	0.15	792	0.90	4,752
10 TN-N	Lead-free thermoplastic	Extruded	0.50	2,640	1.25	6,600
11 TN-N	Lead-free thermoplastic	Extruded	0.50	2,640	1.25	6,600
12 TN-N	Lead-free thermoplastic	Extruded	0.50	2,640	1.25	6,600

N/A = Not applicable.

Table 18. Estimated Tusculum, TN, test deck pavement marking material costs.

Marking Type	Application Type	Material Thickness (mil)	Bead Type	Bead Rate (per 100 ft^2)	Bead Material Cost ($/lb)	Binder Material Cost ($/lb)	Total Material Cost ($/lb)	Binder Material Costs	Bead Costs ($/lb)
Modified epoxy (Epoplex)	Spray	22	Type 4 Visibead plus II, type 1 Minnesota Department of Transportation (MnDOT) spec	10 lb type 4 and 6 lb type 1	0.0254	0.1599	0.1854	$35/gal = $0.327/$ft^2$	Type 4: 0.6 type 1: 0.27
MMA (Degussa)	Extruded	90	Swarco AASHTO M247[33]	8–10 lb	0.0081	0.776	0.7848	$40/gal = $2.33/$ft^2$	0.27
MMA (Degussa - Pathfinder™)	Agglomerate	200	Swarco AASHTO M247[33]	8–10 lb	0.0081	1	1.0081	$40/gal = $3.00/$ft^2$	0.27
Low-temperature acrylic waterborne paint (Ennis)	Spray	15	AASHTO M247[33]	8 lb	0.0072	0.0373	0.0445	$12/gal = $0.11.2/$ft^2$	0.27
High-build acrylic waterborne paint (Ennis)	Spray	24	Potters type 4 Visibead pus II	12 lb	0.024	0.06	0.0840	$12/gal = $0.18/$ft^2$	0.60
Advanced Traffic Markings (ATM) pavement marking tape 300	Rolled	100	N/A	N/A	0	0.7	0.7000	2.10/ft^2	N/A
ATM pavement marking tape 400	Rolled	100	N/A	N/A	0	1.07	1.0700	3.21/ft^2	N/A
TN standard thermoplastic (Superior)	Extruded	90	Swarco AASHTO M247[33]	8–10 lb	0.0081	0.2333	0.2414	$1400/ton = $0.70/$ft^2$	0.27
Modified urethane (IPS)	Spray	15	Type 4 Visibead plus 2, type 1 MnDOT spec	10 lb type 4 and 8 lb type 1	0.0272	0.109	0.1362	$35/gal = $0.327/$ft^2$	Type 4: 0.6 type 1: 0.27

N/A = Not applicable.

Table 19. Estimated Tusculum, TN, test deck pavement marking costs.

Test Section	Marking Type	Application Type	Surface Applied		Inlaid at $0.75/lf	
			$/lb	$/mi	$/lb	$/mi
1 TN-T	Modified epoxy	Spray	0.35	1,848	1.10	5,808
2 TN-T a	MMA	Extruded	1.60	8,448	2.35	12,408
2 TN-T b	MMA	Agglomerate	2.00	10,560	2.75	14,520
3 TN-T	Low-temperature acrylic paint	Spray	0.08	422	0.83	4,382
4 TN-T	High-build paint	Spray	0.15	792	0.90	4,752
5 TN-T a	Tape	Rolled	1.50	7,920	2.25	11,880
5 TN-T b	Tape	Rolled	1.90	10,032	2.65	13,992
6 TN-T	Thermoplastic	Extruded	0.48	2,534	1.23	6,494
7 TN-T	Modified urethane	Spray	0.28	1,478	1.03	5,438

PAVEMENT MARKING COST EFFECTIVENESS

There are several aspects to achieving the most cost effective pavement marking. The most direct method is to compare the present cost of the installed marking to the expected service life of each candidate marking. Researchers designed and implemented an experimental plan to evaluate the service life of various pavement marking materials under different environmental conditions.

To determine the cost effectiveness of the tested pavement marking systems, the service life of the marking at various retroreflectivity levels was determined by using the regression equation for each line type (see appendix B for regression line equations). The researchers also used the cost information from the previous section to determine the annual cost for each marking for each retroreflectivity level.

Appendix C contains tables showing the age of the pavement markings as they reached various levels of retroreflectivity. The retroreflectivity degradation curves from appendix B were used to determine the age of the markings when they reached 250, 200, 150, and 100 mcd/m^2/lux. These levels of retroreflectivity were selected as they incrementally represent a marking that is approaching a lower level of maintained retroreflectivity. As the marking reaches a minimum retroreflectivity level, the marking will need to be replaced. In addition to the age of the marking at these retroreflectivity levels, the tables include the cost of the marking per mile per year of service.

The Alaska test deck data are not useful for such a comparison, as the harsh winter conditions resulted in most of the materials failing to provide 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 after the winter season.

The Tennessee test decks near Nashville and Tusculum had essentially all of the markings under evaluation provide adequate presence and retroreflectivity for several years. While the markings did not degrade at the same rate, only a few reached a point where the retroreflectivity fell below 100 mcd/m^2/lux, which is the minimum level established for this project over the 4-year evaluation period. In addition, the marking presence in only two sections degraded to an unacceptable level. The cost effectiveness analysis shows that the acrylic paint and extruded thermoplastic markings on the Nashville test deck were the most cost effective markings. At the Tusculum test deck, the acrylic paint, extruded thermoplastic, and modified urethane markings may be considered the most cost effective markings in the studied conditions. The extruded MMA marking in section 2 TN-T a provided a long service life, but the initial cost of the marking kept it from being one of the more cost effective systems.

Installing the markings in a deep groove did not increase service life enough to be considered a cost effective solution. Only sections 4 TN-N and 2 TN-T b showed that the deep grooved marking was more cost effective than the shallow grooved section. Section 4 TN-N, which was extruded thermoplastic, was found to be one of the more cost effective markings; however, the service life predicted by the regression equation is not realistic. The regression equation predicted an extremely long service life due to the limited degradation of the grooved marking over the evaluation period. It is unrealistic to expect a marking to last 44 to 125 years, as the regression predicts, clearly showing the need for continued evaluation. Section 2 TN-T b was the least cost effective marking on either Tennessee test deck due to its high cost and comparatively short service life. The deep grooved marking in this situation extended the service life long enough to account for the additional expense.

Other factors that may impact the overall cost effectiveness of a pavement marking system are the delay and safety aspects imposed by striping and restriping activities as well as retroreflectivity measurements and inspection activities. These other costs vary by roadway classification, traffic volume, and each specific marking material's installation complexity and dry time. Another indirect cost that an agency may want 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 raised retroreflective pavement markers. The compatibility between current materials and restriping materials also needs to be considered when selecting a marking. In addition, the need for surface preparation and the required installation weather conditions need to be considered during material selection.

FINDINGS PERTAINING TO ADVANCED ACRYLIC WATERBORNE PAVEMENT MARKINGS

Two types of advanced acrylic waterborne pavement markings, commonly referred to as low-temperature and high-build markings, were installed at each of the pavement marking test decks. These markings are 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 are equivalent in cost to conventional highway paint (by volume) and much less expensive than other durable pavement markings systems.

The durability of the advanced acrylic paints on the Anchorage 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 and, in some instances, performs better than the durable markings. Only the shallow groove section 3 TN-T has fallen below the minimum retroreflectivity level. Both advanced acrylic markings perform comparably to some of the other alternative pavement marking systems. The comparatively low cost of these systems and ability to provide service lives comparable to durable markings makes the advanced acrylic paints a cost effective marking system.

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 a harsh location for all the tested pavement marking systems. Most of the markings 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 are exposed is 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 is the most expensive marking installed on the Anchorage test deck and requires application in a groove where snowplow operations are expected. If maintained retroreflectivity and presence are deemed necessary throughout the winter months and into spring, then the inlaid tape marking was the only system tested that was able to achieve these performance levels and only for 1 year on the lane lines.

One strategy that AKDOT uses is to apply a durable MMA marking in a groove and then remark the MMA with low-VOC paint each spring to provide adequate retroreflectivity through 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 may 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 evaluated on the Tennessee test decks provided adequate presence and retroreflectivity for several years. While the markings did not degrade at the same rate, only a few reached a point where the retroreflectivity fell below the minimum level of 100 mcd/m^2/lux established for this project. In addition, the marking presence in only two sections degraded to an unacceptable level. The cost effectiveness analysis of the markings shows that the acrylic paint markings, extruded thermoplastic markings, and modified urethane markings can be considered the most cost effective markings in the studied conditions. Installing the markings in a deep groove did not increase service life enough to be considered a cost effective solution.

Using the data from the test decks described here, the framework for a pavement marking selection tool (PMST) was developed to demonstrate the key variables and their sensitivity in terms of pavement marking service life and cost. Appendix H contains a description of the Web-based PMST along with screenshots and descriptions of the user interface. The PMST is available for review online.[34]

CHAPTER 3. OPERATIONAL EFFECTS OF WIDE EDGE LINES

INTRODUCTION

This chapter describes the activities conducted to understand the operational effects of wide edge lines. Researchers summarized the literature and then conducted a before-after study on horizontal curves in Tennessee to determine the operational impacts of wider edge lines.

LITERATURE REVIEW

Measures such as speed and lateral position in the travel lane are surrogate measures for safety that are commonly used in the absence of crash data. The following subsections describe research that relates to the operational effects of pavement markings.

Vehicle Speed

While there have been several studies that used vehicle speed as a measure of pavement marking performance, most show no significant effect in absolute speed difference or, perhaps more importantly, speed variance (which is correlated with crash rates).(35,36) For instance, in 2004, Van Driel et al. performed a meta-analysis of vehicle operating speeds based on edge line presence.(37) The range of reported before-after results was -3 mi/h (reduction in mean speed) to +8.1 mi/h. An overall increase in mean speed after installing edge lines on roadways that previously only had a centerline was less than 0.5 mi/h. The authors came to the conclusion that the net speed effect was essentially zero.

In 2005, researchers from Louisiana reported on a before-after study of adding edge lines to narrow two-lane highways (with pavement widths of 20 to 22 ft).(38) Conclusively, the researchers found that the addition of an edge line on narrow two-lane highways did not impact vehicle speeds, day or night.

A recent study performed by Donnell et al. focused on the effectiveness of pavement marking delineation on curves to induce consistency in vehicle speed and lateral position based on a nighttime driving experiment.(39) Based on the results of the experiment, the use of brighter or wider pavement markings did not improve speed consistency between an approach tangent and the midpoint of a horizontal curve.

Tsyganov et al. conducted a before-after study on rural two-lane highways where edge line markings were added.(40) The highways had lane widths of 9, 10, and 11 ft. The researchers discovered that there were no significant differences in vehicle speeds before and after adding edge lines to the narrow highways. They also learned that there were no statistical differences in vehicle speeds when considering daytime versus nighttime conditions. The researchers' findings consistently showed that speeds increased slightly in all conditions after edge lines were applied, but the differences were not statistically significant. They also showed that absolute speed standard deviations were all less than 1 mi/h.

Many experts believe that drivers reduce speeds based solely on their perceived risk. For instance, if drivers perceive sharp curves, narrow lanes or shoulders, steep roadside drop-offs, low side friction, etc., they will lower their speeds accordingly.

Lateral Vehicle Position

While research shows that the variance of vehicle lateral placement is strongly correlated with crash rates, findings related to the effect of pavement markings have been inconsistent.[41,42] A meta-analysis of lateral vehicle position was performed by Van Driel et al.[37] Based on research conducted in the United States, the change in mean lateral position after installing edge lines on roadways that previously only had a centerline was approximately 0.5 inches toward the centerline. The range of reported before-after results was a -10.5-inch shift (toward the centerline) to a +14-inch shift away from the centerline. The authors came to the conclusion that the net lane position effect was essentially zero.

The work by Donnell et al. found little evidence to show that enhanced pavement markings change the way in which motorists transition from a tangent into a curve.[39] As such, the authors concluded that the use of enhanced pavement markings does not improve driver lane position differential between an approach tangent and the midpoint of a horizontal curve.

Conversely, Cottrell compared the lateral vehicle position of vehicles using 4- and 8-inch-wide edge lines.[43] The results indicated that lateral vehicle position variance was unchanged at locations with a 4-inch edge line but was lowered both during the day and at night for the 8-inch edge line condition.

Another study using lateral vehicle position was conducted on a closed-course study in the early 1980s and showed improvements in vehicle positioning measures for an 8-inch edge line versus a 4-inch edge line on curved roadways using alcohol-impaired versus non-impaired drivers.[44] In this study, 16 males in their early 20s drove on an isolated section of a two-lane roadway in New Jersey between 12 and 3 a.m. Each person drove the course twice, the first time after consuming a placebo drink (0.0 percent blood alcohol content) and the second time after consuming either a placebo drink or controlled alcohol dosage (0.05 or 0.08 percent blood alcohol content). Fewer centerline encroachments, more central positioning within the lane, and less variability in positioning among drivers were observed for the wider edge lines (6 and 8 inches) versus the 4-inch edge lines. The authors concluded that the improved driving performance of the test subjects in the presence of wide edge lines indicates that strengthening the visual signal at the road edge may help partially compensate for visual impairments, although benefits are provided to all drivers.

Research conducted in Louisiana also investigated lateral placement as a function of adding edge lines to rural two-lane highways.[38] The before-after measurements showed that edge lines helped drivers confine their traveling path, particularly at night. They found that with edge lines, centralization of a vehicle's position was more apparent at nighttime and that drivers generally positioned their vehicles away from the edge line, irrespective of the roadway alignment.

Tsyganov et al. evaluated lateral placement after adding edge lines to narrow two-lane highways.[40] They discovered a reduction in vehicle lateral placement variability, meaning vehicles were more consistently following a specific path. The exact location of that path depended on the overall lane width. For the 9-ft lane width, the vehicle path shifted closer to the newly installed edge line, especially in the curve sections. For 10-ft lane widths, there were no consistent changes noted. However, for the 11-ft lane width highways, the majority of the drivers moved closer to the centerline, especially on the curve sections. However, all changes were subtle.

TENNESSEE HORIZONTAL CURVE STUDY

A crash surrogate study was designed to detect possible operational impacts of 4- versus 6-inch pavement marking edge lines on horizontal curves on rural two-lane two-way (RTLTW) highways. Through the literature review and team discussions, three curve site selection criteria (curve radius, posted speed limit, and presence of paved shoulder) were identified as having the greatest potential impact on the effectiveness of wider edge lines. The crash surrogate study employed a before-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, lead to the decision to study the impacts of wider pavement markings exclusively on horizontal curves. The operational measures of effectiveness that were studied included the following:

- Change in mean speed.
- Change in speed variability.
- Change in mean lateral placement measured from the inside of the edge line.
- Change in lateral placement variability.

Even with a before-after technique, it is possible that some uncontrolled extraneous factor may impact the data. As a result, 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 period.

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 20).

Table 20. 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, $t \geq 3$ 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 be studied in Tennessee, with 10 treatment sites and 9 comparison sites. The black dots in figure 6 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.

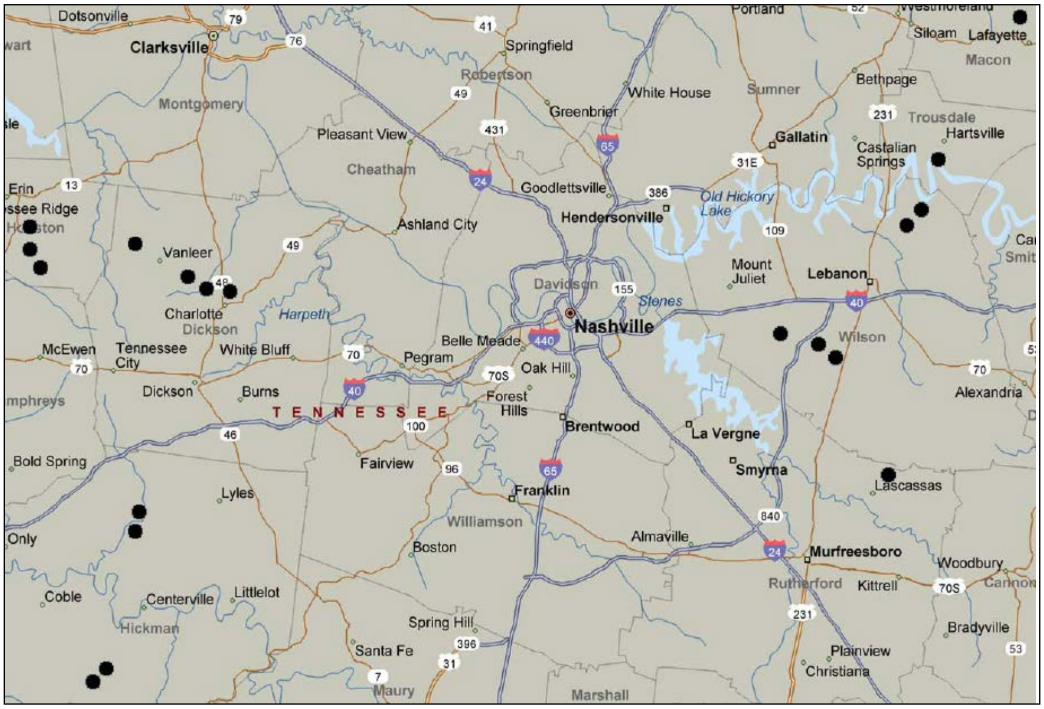


Figure 6. Illustration. Map of 19 curve study sites in Tennessee.

The researchers categorized the horizontal curves based on three factors that were 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). Table 21 shows the study matrix that includes 2-by-2-by-2 levels of those factors. The curves were split into 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 21. Study site matrix.

	Curve Design Safety Rating (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**	
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

*2/1 indicates that there will be at least two treatment sites and one comparison site for each category.
**For this project, a paved shoulder is present when there is at least 36 inches of usable pavement beyond the inside edge of the edge line. A paved shoulder is absent 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 to August 2008. Traffic classifiers were installed on a Monday and retrieved on a Thursday in the same week by a team of two to four researchers. Approximately 96 h 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 show that drivers use the adjacent pavement marking edge line to negotiate curves regardless of whether they are in the inside or outside lane.[(45)]

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/lux/m^2, with none of the sites below 100 mcd/lux/m^2, while the average edge line retroreflectivity for the after period was 288 mcd/lux/m^2. The pavement markings were installed in late May 2008 for the after period. After the pavement markings were installed, at least 1 month was provided to allow drivers to acclimate to the new markings.

Equipment Setup

The traffic classifiers recorded when a vehicle passed through a particular curve, 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 researchers to collect raw data with time stamp precision of 0.001 s.

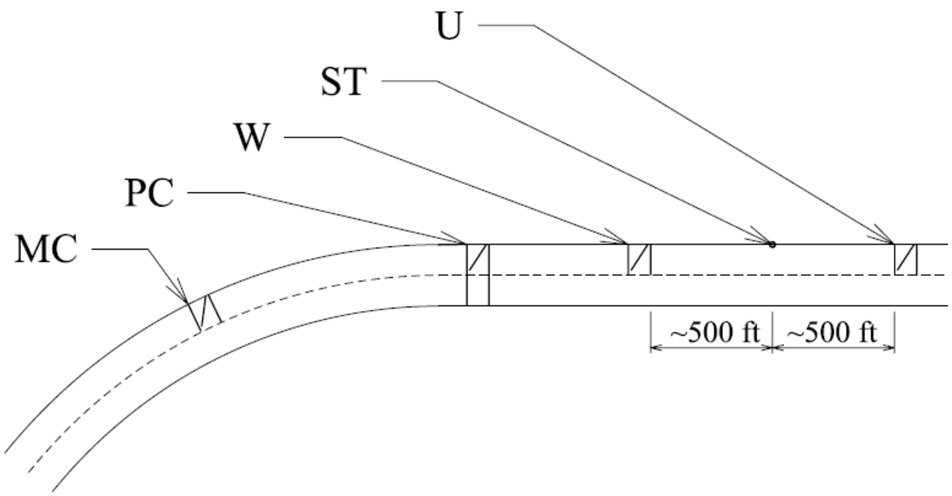
Four traffic classifiers were used at each study site to track the movements of the vehicles traveling through the outside of each horizontal curve. These locations are defined as follows and are shown in figure 7:

- **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 (W) 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 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.



This figure contains the layout of 4 traffic counters, and the abbreviations denote:

ST - location of the start of the treatment which will be approximately 500 ft prior to the advance warning sign
U - located upstream which will be approximately 500 ft upstream of the treatment location
W - located at advanced curve warning sign
PC - located at point of curve (opposing direction trap with tubes)
MC - located at midpoint of curve

Figure 7. Illustration. Horizontal curve traffic classifier layout.

Sample Size

A power analysis was used to determine the sample size (the number of vehicles) 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.[46–48] Because the necessary sample size (*n*) varies with the desired significance level (α), the desired power, the standard deviation (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 standard deviations in speed and lateral placement in curves similar to those used in this study are 8 mi/h and 20 inches, respectively.[49] 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.[49,50] 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.[49] The 3-mi/h minimum difference of interest was selected as a value between the values chosen by other researchers 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.[49,50]

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

The minimum sample size (n_{ip}) necessary for detecting a mean lateral placement difference (Δ) of 6 inches with σ of 20 inches before and after installation of wider lines at each site is shown in figure 9.

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

Figure 9. 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 10, where 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 10. 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 11.

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

Figure 11. 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 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 was at least 100 vehicles.

Statistical Analysis Methodology

The horizontal curve study to compare 4- and 6-inch pavement marking edge lines along an isolated RTLTW highway was a field experimental before-after study. Researchers collected continuous quantitative data from traffic classifiers. Two primary treatments (that correspond to the levels of the main study factor, edge line width) 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 variability, mean lateral position, and lateral position variability 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 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 standard deviation 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 standard deviation 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. Box plots, 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 (ANOVA), 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.

Descriptive Statistical Analysis

The descriptive statistics are separated into several tables. Table 22 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 22. 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 23 shows summary statistics for the general trends. The values were calculated from the difference in the before and after period mean and standard deviation values. A positive value for a change in mean lateral placement indicates that drivers in the after period were driving closer to the centerline, while a negative value for the change in standard deviation in lateral placement indicates that the drivers were more centrally located within their respective lane of travel.

Table 23. Change in speed and lateral position statistics for the treatment sites.

		Curve Design Safety Rating (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	
Speed Limit	**Change in Statistical Measure**	**Speed (mi/h)**	**Lateral Position (inches)**	**Speed (mi/h)**	**Lateral Position (inches)**	**Speed (mi/h)**	**Lateral Position (inches)**	**Speed (mi/h)**	**Lateral Position (inches)**
≥ 55 mi/h	Mean	1.6	3.8	-0.1	4.0	0.0	-0.4	0.2	-0.4
	Std. dev.	0.1	0.0	0.4	1.9	0.2	0.4	0.1	0.4
≤ 50 mi/h	Mean	N/A	N/A	-0.7	2.1	0.7	-1.5	-1.1	0.0
	Std. dev.	N/A	N/A	0.1	1.6	0.7	1.1	0.2	1.1

N/A = Not applicable.

Table 24 through table 28 contain the detailed mean and standard deviation values for the speed and lateral position data collected between the before and after periods for all 19 study sites. Table 24 provides the sample size for the crash surrogate study, while table 25 through table 28 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.

Other descriptive 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 standard deviation. There are no apparent trends that would immediately suggest that the installation of wider edge lines affected a driver's selection of speed, but it does appear that the installation of wider edge line markings in rural curves with small radii (≤ 700 ft) and higher speed limits (≥ 55 mi/h) may have impacted a driver's selection of lateral position through horizontal curves with a slight shift toward the centerline once in the curve (see table 23). 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 24. Sample size.

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

Table 25. 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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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	
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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	
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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 no data were available.

Table 26. 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
		Std. dev.	9.2	5.9	12.0	5.8	4.5	4.9
2	1*	Mean	.2					-4.6
		Std. dev.	6.7					5.0
3	2	Mean	-2.9	-2.9	-4.4	-5.0	-10.5	-9.6
		Std. dev.	4.1	4.3	2.1	2.3	4.4	4.8
4	2	Mean	5.7	5.0	-0.5	-1.0	-3.4	-2.5
		Std. dev.	3.1	5.3	2.0	2.1	2.6	2.5
5	2*	Mean	-1.7		-5.3		-2.9	
		Std. dev.	7.3		5.2		6.4	
6	2*	Mean	1.1	2.3	-1.2	-0.7	-2.5	-2.9
		Std. dev.	7.9	15.8	3.5	13.2	3.3	12.0
7	3	Mean	-0.9	-0.3	-0.8	0.9	-1.6	-0.5
		Std. dev.	2.8	3.1	2.5	2.7	2.3	2.1
8	3	Mean		8.0		-0.8	-1.0	-0.9
		Std. dev.		13.1		3.4	2.9	2.3
9	3*	Mean	-1.6	-0.3	-2.0	-2.3	0.2	0.2
		Std. dev.	3.2	3.7	3.1	3.7	2.2	3.0
10	4	Mean	0.1	-0.4	-0.4	-0.3	-0.8	-0.5
		Std. dev.	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	
		Std. dev.	7.3	8.0	3.9	3.7	3.5	
12	6	Mean	2.1		-3.1	-10.0	-6.4	-0.5
		Std. dev.	10.6		3.2	8.0	8.7	3.3
13	6	Mean	2.5	3.1	-3.6	-3.7	-1.5	-0.8
		Std. dev.	7.7	10.2	2.8	2.5	1.8	1.7
14	6*	Mean	-3.2	0.1	-0.9	-2.9	-7.0	-7.5
		Std. dev.	6.5	5.5	3.5	3.0	4.4	4.5
15	6*	Mean	-3.3	-3.0		-5.9		-4.0
		Std. dev.	4.1	8.4		9.6		8.5
16	7	Mean	0.8	0.9	0.1	0.1	-6.4	-5.9
		Std. dev.	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	
		Std. dev.	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
		Std. dev.	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
		Std. dev.	3.6	4.6	4.1	3.8	2.1	2.2

*Indicates a comparison study site.
Note: Blank cells indicate no data were available.

Table 27. 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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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	
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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	
		Std. dev.	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
		Std. dev.	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
		Std. dev.	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 no data were available.

Table 28. 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
		Std. dev.	20.4	14.5	16.8	10.9	17.5	15.6
2	1*	Mean	-3.0					21.9
		Std. dev.	11.7					15.1
3	2	Mean	-7.7	-17.3	-5.8	-4.4	13.9	17.3
		Std. dev.	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
		Std. dev.	12.7		10.7	11.2	13.3	14.4
5	2*	Mean	-10.5		0.5		23.1	
		Std. dev.	12.6		10.9		15.7	
6	2*	Mean	-5.9		-10.4	-5.0	16.9	13.8
		Std. dev.	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
		Std. dev.	14.1	13.6	12.8	13.6	13.3	14.1
8	3	Mean		10.4		1.0	9.4	13.2
		Std. dev.		14.1		12.5	17.3	16.7
9	3*	Mean	-0.3		-5.5		11.7	10.5
		Std. dev.	11.5		11.8		13.2	14.8
10	4	Mean	-2.7		-0.8		1.2	3.2
		Std. dev.	15.0		8.9		12.4	12.3
11	4*	Mean	-4.0	-6.2	-7.4	2.7	7.6	
		Std. dev.	14.5	16.0	11.1	11.7	12.3	
12	6	Mean	1.8		-21.3	-9.2	25.5	25.8
		Std. dev.	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
		Std. dev.	13.6	16.8	10.5	9.5	10.8	11.6
14	6*	Mean	14.3	7.9	-5.0	0.6	14.7	14.5
		Std. dev.	11.9	11.3	12.4	12.3	15.8	16.4
15	6*	Mean	13.0	17.4		18.1		1.6
		Std. dev.	15.9	15.3		16.3		17.8
16	7	Mean	-6.7	-3.5	-7.6	-11.1	15.1	15.8
		Std. dev.	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	
		Std. dev.	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
		Std. dev.	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
		Std. dev.	15.1	10.8	14.9	11.1	13.0	13.9

*Indicates a comparison study site.
Note: Blank cells indicate no data were available.

Enhanced Statistical Analysis

The research team also conducted an enhanced statistical analysis of the lateral position data at MC and the speed change from PC to MC. There were a total of 40,673 measurements of lateral position at MC and 33,458 values on the speed change from PC to MC (MC − PC speed) before and after installation of wider edge lines, along with curve characteristic variables such as shoulder width, speed limit, and radius. Note that 40,673 and 33,458 correspond to the number of vehicles for which the measurements (for lateral position at MC and speeds at both MC and PC) were taken.

The lateral position data at MC were analyzed by employing a split-plot analysis having curve as a random effect and before-after, day/night, presence of paved shoulder, speed limit (high = ≥ 55 mi/h and low = ≤ 50 mi/h), radius (large = ≥ 800 ft and small = ≤ 700 ft), site type (trt = treatment and comp = comparison) and interaction effects among them as fixed effects. Note that the before-after variable for treatment sites corresponds to both the passage of time and edge line width (before = 4 inches and after = 6 inches), while the same variable for comparison sites corresponds to the passage of time (edge line width is 4 inches for both before and after periods). The initial analysis, including all main effects, two-way interactions, and some three-way interactions of interest, revealed that there were statistically significant three-way interactions such as before/after × day/night × site type, before/after × shoulder × site type, and before/after × radius × site type. This implies that the effect of edge line width on the lateral position at MC may change with the level of other variables such as day/night and/or radius.

Researchers conducted separate analyses for each combination of day/night and large/small radius. The results of the split-plot analyses were obtained by the restricted maximum likelihood (REML) method.

For curves with a small radius (≤ 700 ft), the mean lateral placement at MC at the treatment sites increased after installation of wider edge lines. The change was larger for the nighttime data (4.9 inches during the nighttime versus 2.4 inches during the daytime). No significant changes were observed for the comparison sites or curves with a large radius (≥ 800 ft).

Next, the speed change from PC to MC (MC − PC speed) was used as a dependent variable. The initial analysis, including all main effects, two-way interactions, and three-way interactions of interest, revealed that two three-way interactions, before/after × speed limit × site type and before/after × radius × site type, produced statistically significant results. This implies that the effect of edge line width on speed change (MC − PC speed) may be different for various levels of variables such as speed limit and/or radius. Researchers conducted separate analyses for each combination of speed limit (high/low) and radius (large/small). The results of the split-plot analyses were obtained using the REML method implemented using a statistical package (Statistical Analysis Software (SAS®) product).

For the treatment sites, the mean speed change (MC − PC speed) during the after period (6-inch edge lines) was consistently smaller (in magnitude) than the mean speed change during the before period (4-inch edge lines), which suggests that drivers decelerated (from the beginning of the curve to MC) less after installation of wider edge lines. However, this change seems to be significant only for the curves with a small radius (≤ 700 ft) and low speed limit (≤ 50 mi/h).

SUMMARY

Previous studies on the operational effects of pavement markings and wider edge lines showed mixed results regarding lateral placement and vehicle speed. The study reported herein produced similar findings to previous research. While some particular instances of either lateral placement and/or change in speed were found to be statistically significant, the findings were not consistent, and the magnitude of the change was not deemed practical. For the conditions studied in this report, it appears that wider edge line had a net zero impact in terms of vehicle lateral placement and speed.

CHAPTER 4. SAFETY EFFECTS OF WIDE EDGE LINES

INTRODUCTION

This chapter provides a description of the activities conducted in this study to better understand the safety effects of wider edge lines. First, a brief literature review is provided of previous research findings related to wider pavement markings, which were inconclusive in terms of demonstrating the safety effects of wider edge lines. Next, the data collection and data preparation activities conducted are described. Finally, the analyses and findings of the safety effect of wider edge lines are provided.

LITERATURE REVIEW

Many agencies are experimenting with enhanced pavement markings to reduce crashes and/or crash rates (i.e., adding markings to rural two-lane highways, adding wider edge lines, installing specially designed markings with relatively high retroreflectivity under wet conditions, etc.). Much of this emphasis has resulted from national programs such as AASHTO's *Implementing the AASHTO Strategic Highway Safety Plan*, as described earlier.(6) Other factors, such as increased emphasis on accommodating older drivers, have also inspired agencies to evaluate their marking programs.

Studies have found that the use of markings plays a role in the reduction of specific crash types under certain conditions.(51–53) Run-off-road and opposite direction crashes are generally overrepresented on U.S. highways, especially on horizontal curves and at night when fatal crashes are three to four times more likely to occur. In addition, due to visual and cognitive deficiencies, older and impaired drivers are especially susceptible to these types of crashes. Therefore, crash types that are most likely affected by added or enhanced markings (added width or greater retroreflectivity) are run-off-road and opposite-direction crashes that occur at night, occur on curves, and involve drivers with reduced visual or cognitive capabilities (e.g., older drivers or impaired drivers).

Before-after crash studies conducted in Virginia and New Mexico in 1987 and 1988 suggest that wider lines have no safety benefit in terms of reducing crashes.(51,52) However, these studies were hampered by insufficient data and lack of experimental control.

DATA COLLECTION AND PREPARATION

This section summarizes the safety analysis efforts associated with various pavement marking widths and provides a general description of the data collection approach. The focus is RTLTW highways. The results of three types of analyses are then presented. The first analysis is a cross-sectional safety comparison of rural two-lane segments with 5-inch edge lines to similar segments with 4-inch edge lines. The second and the third analyses are an empirical Bayes (EB) before-after analysis and an interrupted time series analysis of rural two-lane segments on which the edge line width was changed from 4 to 6 inches.

Identifying Available Data

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

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

Several rounds of follow-up telephone calls were made to identify States with previous or current wider line experience. State traffic engineers, district traffic engineers, maintenance engineers, and staff from other safety-related agency branches were contacted to determine whether the following factors applied:

- Locations (by route number and linear reference) of the wider lines could be determined.
- Use of wider lines was extensive on roadway segments (i.e., not small spot treatments).
- Approximate dates of wider line installation were known.
- Sufficient crash, traffic, and roadway databases existed in a format that could be merged with each other and with available pavement marking information.

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

Illinois Data Collection and Preparation

Illinois has varying pavement marking practices across its nine districts. The minimum line width in district 6 is 5 inches. This includes edge lines on both sides of the traveled way, skip lines, and other types of centerline markings. In district 3, edge lines and solid yellow centerline markings on two-lane highways are 4 inches wide, while skip lines on multilane highways and in two-lane highway passing zones are 6 inches wide. The pavement marking practices date back 15+ years before the availability of reliable crash and roadway data. Accordingly, a cross-sectional analysis approach was developed using current crash, traffic, and roadway data.

Illinois is a participating State in the Highway Safety Information System database (HSIS).[54] HSIS is a multi-State database managed by the University of North Carolina Highway Safety

Research Center and Lendis Corporation under contract with 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 *Highway Safety Manual* and S*afetyAnalyst*.(55,56)

Illinois crash and roadway inventory files for districts 6 and 3 from 2001 through 2008 were obtained from HSIS. Crashes were located by county, route number, and milepost. Roadway segments were defined by county, route number, begin milepost, and end milepost. Crashes were assigned to appropriate roadway segments and counted using a variation of SAS® code provided by the HSIS lab manager as well as with structured query language code written by the Texas Transportation Institute (TTI). Over 115 different crash type variations were originally counted. After preliminary model estimation runs and research team decisions were conducted related to the most relevant crash counts for this analysis, the number of crash types was reduced to the following:

- 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 at 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 single-vehicle crashes at night.
- Total number of F+I single-vehicle crashes.
- Total number of F+I single-vehicle crashes at night.
- Total number of crashes with at least one driver 55 years old or older.
- Total number of fixed object crashes.

Roadway segments and associated crash counts for rural two-lane highways, which are the focus of this report, 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 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 were deleted to minimize the influence of any major reconstruction project on the analysis results. The number of segments included in the analysis decreased as the number of observation years increased as a result of this criterion.

A large number of segments were redefined in 2007 and 2008. The rural two-lane dataset for Illinois for 2001 through 2006 included 6,531 segments (1,733 mi): 5,343 segments (1,446 mi) with 4-inch edge lines and centerlines and 1,188 segments (287 mi) with 5-inch edge lines and centerlines. From 2001 through 2008, the number of segments reduced to 3,214 segments (643 mi): 2,572 segments (520 mi) with 4-inch edge lines and centerlines and 642 segments (123 mi) with 5-inch edge lines and centerlines. The 2001 through 2006 rural two-lane highway database was used for the final analysis to preserve the larger sample of segments. Table 29 and table 30 summarize the descriptive statistics for the primary segment variables considered in the analysis.

Table 29. Descriptive statistics for continuous Illinois rural two-lane highway segment variables.

	5,343 Segments (1,446 mi) with 4-Inch-Wide Markings			1,188 Segments (287 mi) with 5-Inch-Wide Markings		
Segment Variable	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Length (mi)	0.01	5.45	0.27	0.01	2.51	0.24
ADT (vehicles)	100	25,900	3,316	100	11,100	2,140
Daily commercial traffic (trucks)	0	4,500	379	0	1,100	281
Lane width (ft)	8	16	11.7	9	16	11.6
Shoulder width (ft)	0	14	6.5	0	12	6.0
Paved shoulder width (ft)	0	14	3.8	0	12	4.3

Table 30. Descriptive statistics for categorical Illinois rural two-lane highway segment variables.

	5,343 Segments (1,446 mi) with 4-Inch-Wide Markings		1,188 Segments (287 mi) with 5-Inch-Wide Markings	
Segment Variable	**Frequency**	**Percent**	**Frequency**	**Percent**
Posted speed = 25 mi/h	6	0.1	4	0.3
Posted speed = 30 mi/h	180	3.4	62	5.2
Posted speed = 35 mi/h	301	5.6	73	6.1
Posted speed = 40 mi/h	287	5.4	45	3.8
Posted speed = 45 mi/h	302	5.7	86	7.2
Posted speed = 50 mi/h	164	3.1	21	1.8
Posted speed = 55 mi/h	4,103	76.8	897	75.5
Presence of horizontal curve sharper than 2.5 degrees	962	18.0	140	11.8

Kansas Data Collection and Preparation

Kansas began installing 6-inch edge lines on all State-owned roads in July 2005. Implementation was not immediate but was accomplished during normal construction and maintenance activities. An email to Kansas district engineers, maintenance engineers, and maintenance paint crews dated

July 7, 2005, contains instructions to begin painting edge lines 6 inches wide on all projects beginning as soon as provisions could be made to accommodate 6-inch tips on guns and glass bead shrouds.

Changes from 4- to 6-inch edge lines in Kansas occurred primarily from 2005 through 2009. Data related to the timing and locations of these changes are available for districts 2 and 6. There were some segments in these districts where edge lines were not changed from 4 to 6 inches until 2008 or later. There are a few remaining segments in Kansas that still have 4-inch edge lines. The structure of the data allowed an EB analysis. A majority of the available data in districts 2 and 6 were for rural two-lane roadways. This facility type is the focus of the analysis in Kansas.

Crash and roadway data were obtained directly from Kansas Department of Transportation's (KDOT) Bureau of Transportation Planning. Pavement marking data were obtained from maintenance engineers in districts 2 and 6. While data were available for 2000 through 2009, data for 2001 through 2007 were ultimately used for analysis due to incomplete roadway data for 2000 and incomplete crash data for 2009, as well as to increase the number of segments in the reference group (i.e., include road segments where edge lines were not changed until 2008 and later in the reference group). There was a group of 718 segments where 6-inch edge lines were implemented but the implementation year was unknown. Analysis was conducted with and without these segments, and a conservative estimate of implementation year was made for the analysis.

Crashes were located by county, route number, and county milepost, while roadway segments were located by county, route number, and begin and end county milepost. Crashes were assigned to appropriate roadway segments and counted using a variation of the SAS® and structured query language codes used for the Illinois data. The following types of crashes were counted for analysis:

- Total number of crashes.
- Total number of F+I crashes.
- Total number of 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 at 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 F+I single-vehicle crashes.
- Total number of single-vehicle crashes at night.
- Total number of F+I single-vehicle crashes at night.
- Total number of fixed object crashes.

The roadway segment definitions (i.e., begin and end county mileposts) were dependent on the procedure used to query the data. Segments were often defined differently from year to year even if the features describing the segment (e.g., lane width, shoulder width, etc.) did not change. Several variables, which differed from project to project, were used to define the pavement marking conversions from 4 to 6 inches Available information and notations were different between districts 2 and 6. The following sections summarize a manual roadway segment data coding process that included a variable for pavement marking width. It begins with a discussion of district 6 data, which was more detailed than district 2 and was used to develop the data coding procedure. Adjustments to the coding procedure were then made to accommodate the less detailed district 2 data.

Pavement Marking Data

District 6 provided information on the date and locations of installations (with locations defined in a variety of ways) from July 2005 (when the wider line policy was implemented) through August 2007. Table 31 shows an example of these data in raw form.

Table 31. Example of Kansas district 6 pavement marking data from April to June 2006.

Date	Route Striped	Paint Used (gal)	Beads Used (lb)	Miles Painted (mi)
4/17	K-23 Meade Co. Meade north city limit to reference post (R.P). 34.0 (both sides)	545	6,537	14.0
4/19	K-23 Meade Co. R.P. 34.0 to R.P. 37.3 (both sides)			
4/19	K-23 Meade Co. R.P. 38.3 to R.P. 41.5 (both sides)	314	3,929	9.8
4/21	K-23 Gray/Meade Co. Jct US 56/K-23 to R.P. 38.3 (west side) and R.P. 41.5 to Jct US 56/K-23 (east side)	743	8,856	
4/26	K-23 Gray Co. Cimarron south city limit to Jct US 56/K-23 (both sides)	793	9,649	24.0
4/27	US 283 Clark Co. Kansas/Okla. State line to South Jct US-283/US-160 (east side)			13.6
4/27	US 283 Clark Co. South Jct US 160/US 283 to R.P. 9.5 (west side)	554	6,834	4.1
5/2	US 283 Clark Co. R.P. 9.5 to Kansas/Okla. State line (west side)	298	3,684	9.5
5/8	K-96 Scott Co. Scott/Lane Co. line to R.P. 67.0 (both sides)	466	5,825	14.0
5/12	K-96 Scott Co. R.P. 67.0 to Scott City east city limit (both sides)—includes lane lines in Scott City	631	7,572	8.0
5/16	US 83 Finney Co. R.P. 70.6 (end of concrete) to R.P. 85.0 (both sides)	774	9,506	31.2
5/17	US 83 Finney/Scott Co. R.P. 85.0 to Scott City south city limit (east side)			23.4
5/17	US 83 Scott Co. Scott City south city limit to R.P. 101.4 (west side)	811	10,154	7.0
5/18	US 83 Scott/Finney Co. R.P. 101.4 to R.P. 85.0 (west side)	572	6,951	16.4
5/19	K-95 Scott Co. North Jct US 83/K-95 to south Jct US 83/K-95 (west side)	228	2,850	6.5
5/22	K-95 Scott Co. South Jct US-83/K-95 to north Jct US 83/K-95 (east side)	214	2,645	6.5
6/6	US 50 Kearny Co. Finney/Kearny Co. line to Lakin east city limit (north side)	356	4,450	9.5
6/7	US 50 Kearny/Hamilton Co. Lakin west city limit to Syracuse east city limit (north side)	873	10,645	26.3
6/13	US 50 Hamilton Co. Syracuse east city limit to Kearny/Hamilton Co. line (south side)	180	5,376	11.3
6/14	US 50 Kearny Co. Hamilton/Kearny Co. line to Lakin west city limit (south side)	283	6,344	18.6
6/15	US 50 Kearny Co. Lakin east city limit to Finney/Kearny Co. line (south side)	180	4,283	9.4

Note: Blank cells indicate that data were unavailable.

The research team developed a method to convert the information in the “Route Striped” column to a beginning and ending State milepost. Route numbers and county names were always provided, but the extent of a striping project on any given day and route was defined by one or more of the following features:

- State milepost.
- Junction of two roads.
- City limits.
- County lines.
- State borders.

A few examples of converting the “Route Striped” descriptions to beginning and ending State mileposts are provided in the following sections.

Example 1. Mileposts directly provided. The State mileposts are provided in the “Route Striped” column of table 31 in this case. For example, the western side of US 83 was striped on May 18, 2006, from R.P. 101.4 to R.P. 85.0. The road sections of interest were then identified in the Kansas roadway files (see table 32 for an example excerpt from the road file where segments were painted with wider lines on May 18, 2006). Several other Kansas variables are available in the road file. Table 32 is for illustration purposes only.

Table 32. Excerpt from Kansas road file for US 83.

Longitudinal Reference System (LRS)	Begin ST_MP	End ST_MP	AADT	Heavy Commercial	Shoulder Width (inches)
028U0008300S0	79.107	86.107	3,410	1,250	3
028U0008300S0	86.107	93.328	3,230	1,250	3
086U0008300S0	93.328	97.628	3,190	1,260	3
086U0008300S0	97.628	100.628	3,510	1,260	3
086U0008300S0	100.628	103.628	3,700	1,270	3

ST_MP = State milepost.

Example 2. Striping project defined from State line to road junction. In this example, the “Route Striped” column provides the extents of the striping project from the State line to a road junction. The eastern side of US 283 in Clark County was striped from the Kansas/Oklahoma State line to the south junction of US 283 and US 160 on April 27, 2006 (see table 31). County maps, available through the KDOT Web site, were used to convert this type of information to beginning and ending State mileposts. For this example, the Kansas Clark County map was used (see figure 12). A screenshot of a portion of the Clark County map shows that US 283 is a northbound-southbound route from the Kansas/Oklahoma State line through Clark County. The State milepost is zero at the southern State border and increases from south to north.

The south junction of US 283 and US 160 is shown in the top part of the screenshot. Road segments on the Kansas county maps contain asterisk (*) symbols. An approximate distance between these asterisks is provided at the midpoint of each segment. The example in figure 12 shows that the distance between the asterisk at the Kansas/Oklahoma border and the asterisk at the south junction of US 283 and US 160 is approximately 13.8 mi. (Green circles have been added to the screenshot to help identify the asterisks at the beginning and end of the segment and the distance indication.)

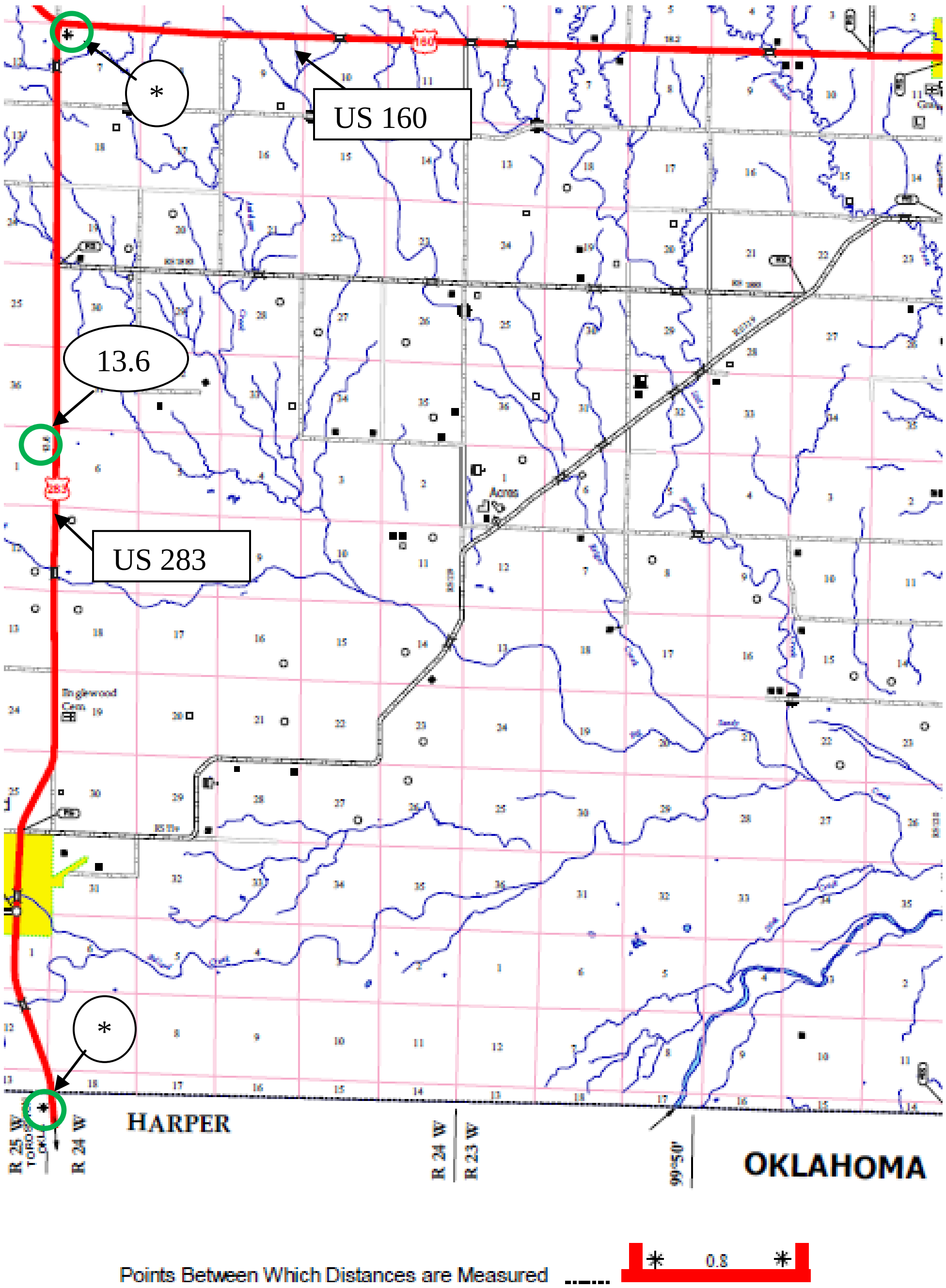


Figure 12. Screenshot. Map of Clark County, KS.

Next, the respective road segments in the Kansas road files were identified. Table 33 provides an excerpt from the road file data for US 283 in Clark County. The table shows that the junction of US 283 and US 160 occurs at milepost 13.579. Therefore, the road segments represented in the first nine rows were striped with wider lines on April 27, 2006.

Table 33. Excerpt from Kansas road file for US 283.

LRS	Begin ST_MP	End ST_MP	Begin CO_MP	End CO_MP	AADT	Heavy Commercial	Shoulder Width (inches)
013U0028300S0	0	2.034	0	2.034	710	285	3
013U0028300S0	2.034	2.049	2.034	2.049	1,020	225	3
013U0028300S0	2.049	2.336	2.049	2.336	1,020	225	0
013U0028300S0	2.336	2.683	2.336	2.683	1,110	245	0
013U0028300S0	2.683	3.046	2.683	3.046	940	255	2.7
013U0028300S0	3.046	3.35	3.046	3.35	940	255	3
013U0028300S0	3.35	10.557	3.35	10.557	710	290	3
013U0028300S0	10.557	13.355	10.557	13.355	715	300	3
013U0028300S0	13.355	13.579	13.355	13.579	715	300	1.8
013U0028300S0	20.16	26.16	20.16	26.16	725	275	3
013U0028300S0	26.16	27.16	26.16	27.16	875	260	3
013U0028300S0	27.16	31.285	27.16	31.285	865	260	3
013U0028300S0	31.285	31.388	31.285	31.388	1,530	275	0
013U0028300S0	31.388	31.568	31.388	31.568	1,530	275	0
013U0028300S0	31.568	31.672	31.568	31.672	1,790	265	0
013U0028300S0	31.672	31.734	31.672	31.734	2,480	265	3
013U0028300S0	31.734	31.927	31.734	31.927	2,010	560	3
013U0028300S0	31.927	33.718	31.927	33.718	2,010	560	3

ST_MP = State milepost.
CO_MP = County milepost.
Note: Shading indicates that road segments were striped with wider lines on April 27, 2006.

Example 3. Striping project defined from city limit to county line. The final example involves a "Route Striped" description that provides the extents of the striping project from a city limit to a county line. The north side of US 50 in Kearny County from the Finney-Kearny County line to the Lakin east city limit was restriped on June 6, 2006 (see table 31). The Kearny County map shows that US 50 is an eastbound-westbound route running the entire length Kearny County. Figure 13 shows a screenshot of the segment of interest from Lakin City to the Finney/Kearny County line. (Green circles have been added to the screen shot to help identify the asterisk symbols at the beginning and end of the segment and the distance indication.) Table 34 provides an excerpt from the road file data for US 50 in Kearny County. Segments were painted with wider lines on June 6, 2006, which is evident by the shading of the last seven rows.

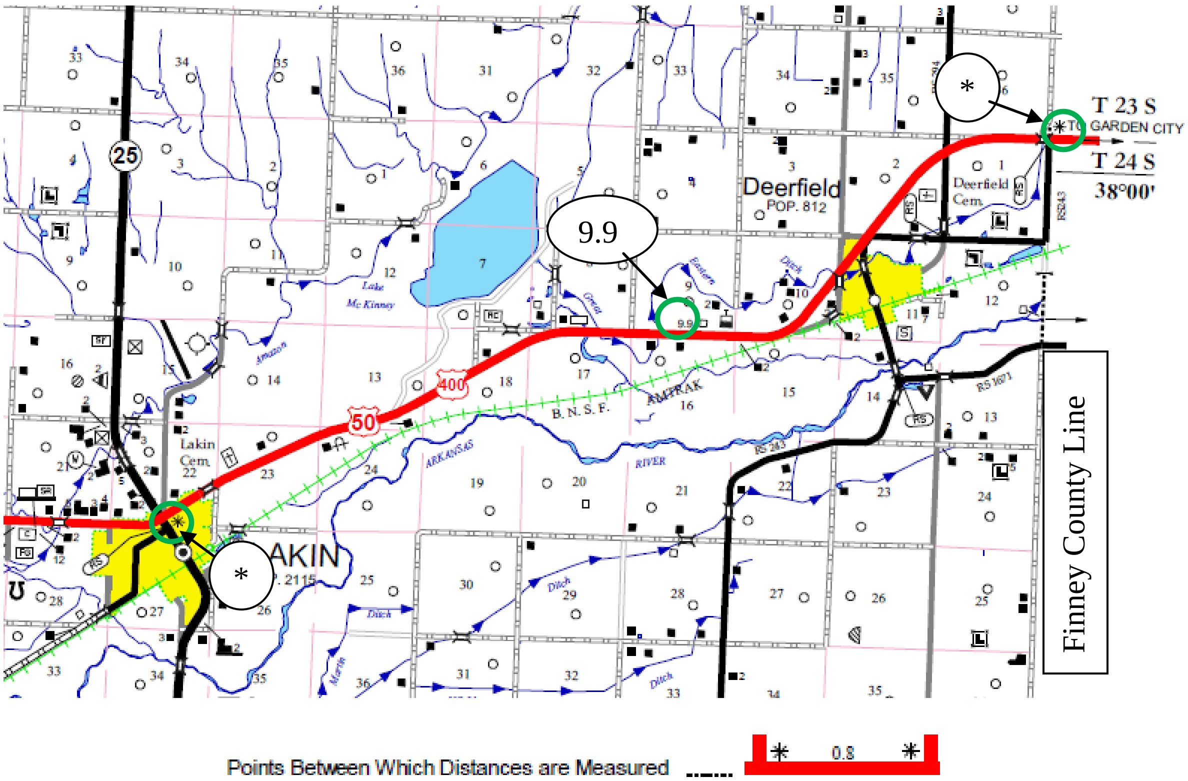


Figure 13. Screenshot. Map of Kearny County, KS.

Table 34. Excerpt from Kansas road file for US 50.

LRS	Begin ST_MP	End ST_MP	Begin CO_MP	End CO_MP	AADT	Heavy Commercial	Shoulder Width (inches)	Speed Limit (mi/h)
047U0005000S0	28.498	29.776	0	1.278	1,860	740	3	65
047U0005000S0	29.776	30.497	1.278	1.999	1,860	740	3	65
047U0005000S0	30.497	30.668	1.999	2.17	1,860	740	3	65
047U0005000S0	30.668	32.035	2.17	3.537	1,860	740	3	65
047U0005000S0	32.035	34.875	3.537	6.377	1,860	740	3	65
047U0005000S0	34.875	35.498	6.377	7	1,860	740	1.8	65
047U0005000S0	35.498	35.729	7	7.231	1,930	740	1.8	65
047U0005000S0	35.729	37.482	7.231	8.984	1,930	740	3	65
047U0005000S0	37.482	37.776	8.984	9.278	2,030	750	3	65
047U0005000S0	37.776	39.196	9.278	10.698	2,030	750	3	65
047U0005000S0	39.196	42.163	10.698	13.665	2,030	750	3	65
047U0005000S0	42.163	42.498	13.665	14	2,030	750	1.8	65
047U0005000S0	42.498	42.784	14	14.286	2,470	770	1.8	65
047U0005000S0	42.784	43.461	14.286	14.963	2,470	770	3	65
047U0005000S0	43.461	43.818	14.963	15.32	2,470	770	0	40
047U0005000S0	43.818	43.965	15.32	15.467	5,730	795	0	40
047U0005000S0	43.965	44.104	15.467	15.606	6,160	940	0	40
047U0005000S0	44.104	44.411	15.606	15.913	4,010	970	0	40
047U0005000S0	44.411	48.98	15.913	20.482	4,010	970	3	65
047U0005000S0	48.98	49.08	20.482	20.582	4,190	970	3	65
047U0005000S0	49.08	49.78	20.582	21.282	4,190	970	3	65
047U0005000S0	49.78	51.276	21.282	22.778	4,190	970	3	65
047U0005000S0	51.276	51.661	22.778	23.163	4,190	970	3	55
047U0005000S0	51.661	51.665	23.163	23.167	4,190	970	3	65
047U0005000S0	51.665	53.865	23.167	25.367	4,320	1,040	3	65

ST_MP = State milepost.
CO_MP = County milepost.
Note: Shading indicates that these road segments were striped with wider lines on June 6, 2006.

County mileposts are zero at western and southern county lines and increase from west to east and from south to north. The final row of table 34 is the last segment of US 50 in Kearny County. US 50 crosses into Finney County at county milepost 25.367 (State milepost 53.865). Asterisks and the respective segment length in figure 13 indicate that the distance from the US 50/K25 junction to the Finney-Kearny County line is 9.9 mi. Therefore, the US 50/K25 junction is at county milepost 15.467 (25.367 − 9.9) and State milepost 43.965 (53.865 − 9.9). The posted speed limit changes from 40 to 65 mi/h at State milepost 44.411. This is probably the Lakin east city limit. This was verified using Google Maps® and Google Earth® to measure the distance from the US 50/K25 junction to the Lakin east city limit (see figure 14). This distance is 0.44 mi, which means the Lakin east city limit is at county milepost 15.907 (15.467 + 0.44) and State milepost 44.405 (43.965 + 0.44). These numbers are very close to where the speed limit changes from 40 to 65 mi/h in table 34. Therefore, it was concluded that the road segments represented in the last seven rows of table 34 were striped with wider lines on June 6, 2006.

©DigitalGlobe, Google, and Europa Technologies

Figure 14. Photo. Measurement from US 50/K25 junction to Lakin east city limit.

The pavement marking records for Kansas district 2 were not as specific as those for district 6. The major features referenced by the maintenance engineer for locating the termini of the pavement marking jobs were generally the same and included State mileposts, city limits, junctions, county lines, and State lines. The method used by the research team to identify the mileposts associated with these features was identical to that discussed in the preceding section for district 6. The pavement marking records for district 2 did not provide county names where the marking installation took place. The information from district 2 also did not include the date of the striping job. The records only showed the job timing by year.

Table 35 provides an example of the district 2 striping data. Data collection involved additional searching through county maps to find the locations of interest. The yearly data also limited the ultimate level of data aggregation used for data analysis.

Table 35. Example of district 2 striping data.

Route	Route Description	Miles	Center Line	Edge Line	White	Yellow	Beads
K-15	K-15/K-18 W Jct to the DK-MN line	33	33	66	1,452	726	11,616
K-15	K-18 E Jct to the SCL of Clay County	23.5	23.5		0	517	2,068
K-15	K-15 W to K-15 E	4	4	8	176	88	1,408
K-15	US-36 to the KS/NE State line				0	0	0
K-18	OT-DK to the K-15 Jct	9	9	18	396	198	3,168
K-18	Jct K15 to the US-77 Jct	14	14	28	616	308	4,928
K-18	I-70 to Ogden (K-114)	4	4	8	176	88	1,408
K-43	I-70 to the K-4 Jct (Hope)	21	21	42	924	462	7,392
I-70	Abilene to milepost 303	18	18	36	792	396	6,336
I-70	Niles Road	6	6	12	264	132	2,112
K-115	Palmer Road	0.5	0.5	1	22	11	176
K-148	K-15/148 to the WS/RP line	17	17	34	748	374	5,984
K-157	Rock Springs 4-H Camp Road	4	4	8	176	88	1,408
K-197	Industry Road	2	2	4	88	44	704
K-189	Miltonville Road	1	1	2	44	22	352
K-206	Chapman Road	1	1	2	44	22	352
K-209	Woodbine	2.5	2.5		0	55	220
US 24	Clay W to K-189	16.5	16.5	33	726	363	5,808
US 36	Washington Road to the K-22 Jct	16	16		0	352	1,408
US 36	Washington Road to the multilane start	10	10	20	440	220	3,520
BUSS-40	Super 8 to end Business 40	2	2	4	88	44	704

Roadway Data

Two separate roadway databases, including a 6-inch stripe timing variable, were built for districts 6 and 2 and later combined for analysis. The databases spanned 2001 through 2007. 2001 was selected as the beginning of the observation period because data for several roadway segments were missing for 2000. 2007 was selected as the end of the observation period to increase the number of segments in the reference group (i.e., to include road segments where edge lines were not changed until 2008 and later in the reference group). The remainder of this section describes the procedure developed to build Kansas databases for districts 6 and 2 with roadway and pavement marking characteristics from 2001 through 2007. A similar procedure was applied to build both databases. Important differences are identified.

Data Screening:

The raw data files received from KDOT included statewide routes. The files for different years did not always have the same set of variables. Data screening procedures were developed to extract rural two-lane highway segments in districts 2 and 6 and remove unnecessary variables. This process simplified the data files and transformed them into an identical format with the same set of variables across years, a characteristic needed in order to merge the files into a single dataset.

The data files had several variables for segment location and functional classification. The variables used to extract the rural two-lane roadway segments included the following:

- RSE_COUNTY: County number.
- LNCL_DESCR: Description of the roadway.
- FUNC_DESCR: Functional classification.
- LN1L_DESCR: Description of the first left lane.
- LN1R_DESCR: Description of the first right lane.

All two-lane rural highways were extracted using the following five steps:

1. Filter RSE_COUNTY: Keep all roadway segments located in counties of the district of interest.
2. Filter LNCL_DESCR: Keep all roadway segments defined as “2LU_Two Lane, Undivided.”
3. Filter FUNC_DESCR: Remove roadway segments described as urban.
4. Filter LN1L_DESCR: Keep roadway segments with through lanes, left-turn lanes, right-turn lanes, and passing or creeper lanes (e.g., truck lanes), and remove roadway segments with parking lanes.
5. Filter LN1R_DESCR: Follow step 4 except for the opposite direction of travel.

These steps, applied to data from both districts 2 and 6, produced seven data files (one for each year from 2001 through 2007) with rural two-lane highway segments in those districts. Each of these data files contained a set of 50 or more variables. Many of these were not applicable to rural two-lane highways. Only variables of interest were retained, including year, county, route number, beginning and ending mileposts (State and county), segment length, functional classification, daily traffic, daily truck traffic, speed limit, lane widths, and shoulder widths and types.

Defining Road Segments:

Segment definitions (i.e., beginning milepost and ending milepost) were nearly identical for years 2002 through 2006. Therefore, the 2002 data file was selected as a “base” file for segment definition. Roadway segments for other years where all relevant variable values had not changed from 2002 were redefined to match the 2002 segment definition. The dataset was initially structured so that one row equaled one segment observed for 1 month. The rows were then aggregated so that one row equaled one segment observed for 1 year due to the level of detail available in the pavement markings data for district 2. The dataset building process consisted of the following steps:

1. Copy an entire row (i.e., segment) from the 2002 roadway data file to a “Combined Data” file and copy this same row to the next 11 rows (a total of 12 rows for 12 months). Create a column for “Month” and “Year” and fill in these columns with appropriate values.

2. Locate the same segment in other data files (2001 and 2003–2007). If the beginning and ending mileposts of the segment match those in the 2002 data file, copy the entire row to the “Combined Data” file. Repeat this 11 more times as described in step 1 for a total of 12 rows representing 12 months of the year. If data from other years have different beginning and ending mileposts from those of 2002 (i.e., the base year), redefine the segment by combining short segments or splitting up longer segment to match the 2002 segment. Check all variables to make sure that variable values on the segments being combined are the same.

   In this study, the estimated AADT was different in some cases, and a weighted average AADT was computed. The result of this process was 84 observations (i.e., rows) for each road segment: one row per month over 7 years. The data were later aggregated, resulting in seven observations (i.e., rows) for each road segment: one row per year over 7 years.

3. Create a variable, “Time_paint,” to indicate the timing of the 4- to 6-inch edge line conversion. “Time_paint” equals zero if the row in the roadway dataset is before the 6-inch edge line conversion, equals 1 for the month and year when the 6-inch edge line is first painted on the segment, equals 2 if the row in the roadway dataset is after the 6-inch edge line conversion, and equals 3 if the timing of the conversion is unknown.

There were 718 segments where 6-inch edge lines were implemented but the implementation year was unknown. For these segments, “Time_paint” equaled 3. Analysis was conducted without (analysis 1) and with (analysis 2) these 718 segments, and a conservative estimate of implementation year was made for analysis 2. During the course of several years, some segments were painted more than once. The timing of the first edge line conversion from 4 to 6 inches was coded as “Time_paint” equals 1, with all following rows equaling 2 (i.e., the after period). Table 36 and table 37 provide the descriptive statistics for analysis 1 and analysis 2, respectively.

Table 36. Descriptive statistics for Kansas rural two-lane highway segments (analysis 1).

	Treatment Group 1,615 Segments (1,165.3 mi)			Reference Group 261 Segments (158.1 mi)		
Segment Variable	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Length (mi)	0.002	8.1	0.72	0.005	6.16	0.61
ADT (vehicles)	65	12,800	1,036	40	4,745	746
Daily commercial traffic (trucks)	3	1,790	217	5	540	148
Lane width (ft)	10	14	11.8	11	15	11.5
Shoulder width (ft)	1	10	4.7	0	10	4.1
Paved shoulder width (ft)	0	10	1.4	0	8	0.7

Table 37. Descriptive statistics for Kansas rural two-lane highway segments (analysis 2).

Segment Variable	Treatment Group 2,333 Segments (1,909.9 mi)			Reference Group 261 Segments (158.1 mi)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Length (mi)	0.002	8.1	0.82	0.005	6.16	0.61
ADT (vehicles)	65	12,800	1,238	40	4,745	746
Daily commercial traffic (trucks)	3	2,260	293	5	540	148
Lane width (ft)	10	15	11.9	11	15	11.5
Shoulder width (ft)	0	12	5.4	0	10	4.1
Paved shoulder width (ft)	0	12	2.0	0	8	0.7

Michigan Data Collection and Preparation

Michigan edge lines are currently 6 inches wide on all State-owned roadways (except those with curbs and gutters). The change was made from 4-inch edge lines in 2004. An 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 minimizes the concern of selection bias or regression to the mean. However, it does not allow a before-after analysis using comparison sites within the same State. The research team examined several comparison site alternatives but ultimately used an interrupted time series analysis.

Michigan crash data from 2001 through 2009 were obtained from the Michigan State Police Traffic Crash Reporting Unit. MDOT provided roadway inventory files for those years. Crashes were located by county, route number, physical reference number, and milepost, while 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® and structured query language. Counts for 14 of the 15 crash types available for Illinois were also available for Michigan (crash type 15, total number of fixed object crashes, was not available).

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. Analysis of two Michigan datasets was reported: (1) a dataset for years 2001 through 2007 with 253 segments (851.5 mi) and (2) a dataset for years 2001 through 2009 with 238 segments (787.8 mi). Each segment was observed for 3 years with 4-inch lines (2001 through 2003) and for 3–5 years with 6-inch lines (2005 through 2007 or 2005 through 2009, depending on the dataset). Table 38 and table 39 summarize descriptive statistics for the primary segment variables considered in the 2001 through 2007 analysis. The descriptive statistics are very similar for the 2001 through 2009 dataset and are not reported.

Table 38. Descriptive statistics for continuous Michigan segment variables.

Segment Variable	253 Segments (851.5 mi) with 4-Inch Edge Lines for 3 Years (2001–2003) and 6-Inch Edge Lines for 3 Years (2005–2007)		
	Minimum	Maximum	Average
Length (mi)	0.04	12.69	3.37
ADT (vehicles)	200	18,600	4,470
Daily commercial traffic (trucks)	20	2,200	350
Lane width (ft)	10	12	11.5
Shoulder width (ft)	3	12	8.1
Paved shoulder width (ft)	0	11	4.2

Table 39. Descriptive statistics for categorical Michigan segment variables.

Segment Variable	253 Segments (851.5 mi) with 4-Inch Edge Lines for 3 Years (2001–2003) and 6-Inch Edge Lines for 3 Years (2005–2007)	
	Frequency	Percent
Posted speed = 25 mi/h	5	2.0
Posted speed = 30 mi/h	1	0.4
Posted speed = 35 mi/h	4	1.6
Posted speed = 40 mi/h	3	1.2
Posted speed = 45 mi/h	10	4.0
Posted speed = 50 mi/h	4	1.6
Posted speed = 55 mi/h	226	89.3
Level terrain	165	65.2
Rolling terrain	88	34.8

WIDER LINE RETROSPECTIVE CRASH ANALYSES

This section focuses on the analysis of wider edge lines on rural two-lane highways (findings from analyses on multilane highways are provided in appendix D). The results of safety analyses for three States are presented (Illinois, Kansas, and Michigan). Three separate analyses were required due to unique characteristics of the data, including how, when, and the extent to which States made the transition to wider lines, as well as how long it took the States to complete the transition. The first analysis is a cross-sectional safety comparison of rural two-lane segments with 5-inch centerlines and edge lines to segments with 4-inch centerlines and edge lines for Illinois. The second analysis is an EB before-after analysis of rural two-lane segments in Kansas for which the edge line width was changed from 4 to 6 inches in multiple years. The third analysis is a piecewise regression analysis of interrupted time series design with the change from 4 to 6 inches in 2004 being treated as an intervention for Michigan data.

Analysis of Illinois Rural Two-Lane Roadway Crash Data

Illinois crash data from 2001 through 2006 were obtained from 6,531 segments, which roughly corresponded to 1,733 mi of rural two-lane highways. Out of the 6,531 segments, 5,343 segments

(1,446 mi) have 4-inch edge lines and 4-inch centerlines and 1,188 segments (287 mi) have 5-inch edge lines and 5-inch centerlines. Crashes occurring at the segments with 4-inch edge lines were compared to crashes occurring at the segments with 5-inch edge lines using the cross-sectional data analysis. Only the non-intersection/interchange crashes were considered. Crashes occurring during the winter months (November through March) were excluded from the analysis to avoid any potential confounding by snow crashes.

During the course of data analysis, it was revealed that about 50 percent of total crashes (about 60 percent of PDO crashes, 60 percent of single-vehicle crashes, and 10 percent of F+I crashes) were animal collisions. While animal collisions were deemed to be irrelevant for assessing safety effects of wider edge lines, the proportion of animal collisions was significant. Therefore, researchers conducted cross-sectional analyses for two different Illinois datasets from 2001 through 2006, one with animal collisions included and the other with animal collisions excluded. Types of crashes analyzed included the following:

- Total crashes.
- F+I crashes.
- PDO crashes.
- Daytime crashes.
- Nighttime crashes.
- Daytime F+I crashes.
- Nighttime F+I crashes.
- Wet crashes.
- Wet nighttime crashes.
- Single-vehicle crashes.
- Single-vehicle wet crashes.
- Older-driver (≥ 55 years old) crashes.
- Single-vehicle nighttime crashes.
- Single-vehicle daytime F+I crashes.
- Single-vehicle nighttime F+I crashes.
- Fixed object crashes.

Table 40 summarizes the 2001 through 2006 Illinois crash datasets used for the analysis. The table shows the aggregated crash counts and crash rates computed as crashes per million vehicle miles of travel per year (non-winter month crash counts for 7 months were first multiplied by a factor of 12 divided by 7 before computing crash rates) for Illinois rural two-lane highways. It is categorized by edge line width for each of two datasets (dataset with animal collisions included and dataset without animal collisions).

Table 40. Summary of Illinois crash data for 2001–2006 used in the analysis.

Variable	Dataset With Animal Collisions				Dataset Without Animal Collisions			
	4 inches	5 inches	4 inches	5 inches	4 inches	5 inches	4 inches	5 inches
Number of segments	5,343	1,188	5,343	1,188	5,343	1,188	5,343	1,188
Total segment length (mi)	1,446.1	286.7	1,446.1	286.7	1,446.1	286.7	1,446.1	286.7
Mile-years	8,676.8	1,720.1	8,676.8	1,720.1	8,676.8	1,720.1	8,676.8	1,720.1
Average AADT	3,316.0	2,339.9	3,316.0	2,339.9	3,316.0	2,339.9	3,316.0	2,339.9
Crash Type	**Crash Counts**		**Crash Rates**		**Crash Counts**		**Crash Rates**	
Total	6,135	957	1.00	1.12	3,397	342	0.55	0.40
F+I	1,595	169	0.26	0.20	1,451	137	0.24	0.16
PDO	4,540	788	0.74	0.92	1,946	205	0.32	0.24
Daytime	2,802	331	0.46	0.39	2,213	219	0.36	0.26
Nighttime	2,805	504	0.46	0.59	1,027	109	0.17	0.13
Daytime F+I	964	92	0.16	0.11	919	88	0.15	0.10
Nighttime F+I	555	69	0.09	0.08	466	46	0.08	0.05
Wet	666	78	0.11	0.09	464	45	0.08	0.05
Wet nighttime	297	36	0.05	0.04	155	16	0.03	0.02
Single-vehicle	4,669	818	0.76	0.95	1,942	203	0.32	0.24
Single-vehicle wet	519	69	0.08	0.08	317	36	0.05	0.04
Single-vehicle nighttime	2,581	485	0.42	0.57	810	90	0.13	0.11
Single-vehicle daytime F+I	1,025	122	0.17	0.14	884	90	0.14	0.11
Single-vehicle night F+I	455	60	0.07	0.07	368	37	0.06	0.04
Older driver (≥ 55 years old)	1,280	195	0.21	0.23	706	74	0.12	0.09
Fixed object	1,127	133	0.18	0.16	1,127	133	0.18	0.16

The crash rates shown in table 40 might be useful if all of the segments included in the study were identical except for edge line width, segment length, and AADT and also if crashes increased 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. Additionally, the relationship between crashes and AADT was not necessarily linear. As a result, the effects of edge line width may not be estimated correctly by the differences in simple crash rates between 4- and 5-inch edge line segments.

In order to separate the effect of edge line width from other important roadway characteristics, the negative binomial regression models (or Poisson regression models when negative binomial regression models could not be fitted) were applied to these cross-sectional data. The general form of the expected number of crashes in a negative binomial regression model is given in figure 15.

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

Figure 15. Equation. General form of the mean 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. After exploring various negative binomial regression model forms with different predictors and interaction terms, the model including wider edge line (coded as “1” when edge line width = 5 inches and “0” when edge line width = 4 inches), lane width, shoulder width, log of AADT, presence of horizontal curve with degree of curve greater than 2.5 degrees (1 = present, 0 = not present), and log of segment length as predictors seemed to be most appropriate for these data. The horizontal curve indicator variable was created using the non-zero entries for horizontal curve beginning and ending mileposts contained in the HSIS road files. A comparison of the curve mileposts to the road segment mileposts indicated that the entire road segment with the curve presence indicator variable equal to 1 was located inside the boundaries of the horizontal curve. The natural logarithm of segment length may be included with the parameter set to 1.0 (i.e., an offset variable) or specified more generally as a covariate with a parameter to be estimated. The second option was used in this report. There is no reason to think that crashes will not increase linearly with segment length (an estimated parameter different than one is likely capturing the effect of one or more omitted variables that are correlated with segment length). Specifying the natural logarithm of segment length as a covariate and estimating its parameter may improve model prediction and reduce the standard error of the pavement marking parameter, which are desirable attributes given the objectives of this research. The disadvantage is that strict interpretation of a segment length parameter different than one may seem counterintuitive. As a sensitivity analysis, the log of segment length was also included as an offset variable and the analysis was repeated; the results did not change materially. (The coefficients for wider edge line as well as percent crash reduction estimates changed only slightly.)

Temporal correlations in the crash counts obtained from the same road segment over 6 years were handled by employing two different approaches: (1) negative binomial regression analysis on the crash frequencies aggregated over 6 years and (2) analysis on yearly crash frequencies using the negative binomial regression models with yearly trend and accounting for temporal correlations in the parameter estimation using the generalized estimating equations (GEEs) procedure. Similar conclusions were reached from both approaches. Only the results from the first approach (analyzing the aggregated crash counts over 6 years) are presented in this report.

Table 41 shows the estimates of the negative binomial regression model coefficients applied to Illinois non-intersection/interchange crashes during non-winter months for 6,531 segments (1,732.8 mi) aggregated for 6 years (2001 through 2006) and percent crash reduction estimates (animal collisions included). The regression coefficient for wider edge line 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, daytime, daytime F+I, wet, single-vehicle F+I, and fixed object crashes. Lane departure crashes obtained as the sum of fixed object, head-on, and sideswipe crashes were also analyzed, and a positive safety effect of wider edge lines was observed as well.

Percent crash reduction estimates were computed by $[1 - \mathrm{Exp}(\beta_{edge})] \times 100$, where β_{edge} represents the estimated coefficient of wider edge line. It can also be observed that the signs of the coefficients for lane width, shoulder width, log of AADT, and curve presence were consistent with intuition in most cases. 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 41. Estimates of regression coefficients of negative binomial regression models applied to Illinois non-intersection/interchange crashes with animal collisions (2001–2006).

Crash Type	Intercept	Wider Edge Line	Lane Width	Shoulder Width	Log (AADT)	Presence of Curve	Log (Length)	Dispersion	Pearson Chi-Square/DF	Percent Crash Reduction
Total	**-5.1248**	0.0077	**-0.0665**	**-0.0183**	**0.6878**	**0.2038**	**0.8197**	0.3253	1.1248	-0.8
	(0.2797)	(0.0442)	(0.0198)	(0.0062)	(0.0257)	(0.0550)	(0.0148)	(0.0236)		
F+I	**-6.9810**	**-0.3792**	**-0.0727**	**-0.0499**	**0.7846**	**0.6199**	**0.8614**	0.4003	1.0813	**31.6**
	(0.5120)	(0.0885)	(0.0353)	(0.0109)	(0.0456)	(0.0916)	(0.0267)	(0.0658)		
PDO	**-5.2852**	**0.1127**	**-0.0668**	-0.0089	**0.6637**	0.0432	**0.8083**	0.3814	1.1197	**-11.9**
	(0.3158)	(0.0488)	(0.0223)	(0.0069)	(0.0290)	(0.0655)	(0.0167)	(0.0299)		
Day	**-7.4326**	**-0.2141**	**-0.0956**	**-0.0452**	**0.9315**	**0.1564**	**0.7685**	0.3242	1.0819	**19.3**
	(0.4046)	(0.0656)	(0.0277)	(0.0084)	(0.0358)	(0.0768)	(0.0198)	(0.0396)		
Night	**-4.8206**	0.0931	-0.0389	0.0007	**0.5044**	**0.2737**	**0.8746**	0.3756	1.0935	-9.8
	(0.3683)	(0.0577)	(0.0262)	0.0082)	(0.0342)	(0.0773)	(0.0205)	(0.0399)		
Daytime F+I	**-7.6401**	**-0.4580**	**-0.1370**	**-0.0612**	**0.9040**	**0.4398**	**0.8381**	0.3948	1.0994	**36.7**
	(0.6490)	(0.1161)	(0.0448)	(0.0136)	(0.0574)	(0.1208)	(0.0329)	(0.0955)		
Nighttime F+I*	**-7.9660**	-0.2295	0.0316	**-0.0359**	**0.6161**	**0.9747**	**0.9293**		1.0554	20.5
	(0.7893)	(0.1311)	(0.0538)	(0.0164)	(0.0681)	(0.1361)	(0.0411)			
Wet	**-7.3318**	**-0.2936**	-0.0684	**-0.0435**	**0.7059**	**0.3372**	**0.8033**	0.9072	1.0208	**25.4**
	(0.7675)	(0.1309)	(0.0537)	(0.0165)	(0.0688)	(0.1478)	(0.0395)	(0.1747)		
Wet nighttime*	**-6.4462**	-0.3297	-0.1006	-0.0212	**0.5313**	**0.4629**	**0.8524**		1.0673	28.1
	(0.9922)	(0.1809)	(0.0707)	(0.0223)	(0.0909)	(0.2078)	(0.0544)			
Single-vehicle	**-3.9282**	0.0394	-0.0406	**−0.0145**	**0.4692**	**0.3274**	**0.8544**	0.3941	1.1383	-3.9
	(0.3034)	(0.0482)	(0.0218)	(0.0069)	(0.0285)	(0.0609)	(0.0169)	(0.0299)		
Single-vehicle	**-6.1985**	-0.2440	-0.0324	**-0.0516**	**0.4927**	**0.4512**	**0.8430**	1.1907	1.0138	21.7
wet	(0.8318)	(0.1414)	(0.0593)	(0.0186)	(0.0761)	(0.1643)	(0.0452)	(0.2354)		
Single-vehicle	**-4.6353**	**0.1181**	−0.0239	0.0031	**0.4483**	**0.3303**	**0.8873**	0.4057	1.1028	**-12.5**
nighttime	(0.3795)	(0.0593)	(0.0271)	(0.0086)	(0.0355)	(0.0795)	(0.0215)	(0.0436)		
Single-vehicle	**-5.1562**	**-0.4017**	-0.0258	**-0.0646**	**0.4477**	**0.8342**	**0.8760**	0.5748	1.0747	**33.1**
F+I	(0.5837)	(0.1046)	(0.0413)	(0.0135)	(0.0540)	(0.1066)	(0.0330)	(0.1050)		
Single-vehicle	**-7.3570**	-0.2171	0.0516	**-0.0472**	**0.4951**	**1.1010**	**0.9390**		1.0567	19.5
nighttime F+I*	(0.8462)	(0.1411)	(0.0582)	(0.0182)	(0.0741)	(0.1454)	(0.0456)			
Older driver	**-7.2419**	-0.0168	**-0.0758**	-0.0213	**0.7691**	0.1166	**0.7871**	0.1733	1.0639	1.7
(≥ 55 years old)	(0.5254)	(0.0818)	(0.0363)	(0.0110)	(0.0465)	(0.1092)	(0.0264)	(0.0595)		

Fixed object	**-6.4892** (0.5880)	**-0.3495** (0.1009)	-0.0307 (0.0408)	**-0.0889** (0.0130)	**0.6433** (0.0530)	**0.4572** (0.1079)	**0.7786** (0.0306)	0.6207 (0.1009)	1.1105	**29.5**
Lane departure	**-7.1562** (0.5283)	**-0.2429** (0.0875)	**-0.0845** (0.0365)	**-0.0674** (0.0114)	**0.8225** (0.0474)	**0.3958** (0.0967)	**0.7855** (0.0268)	0.5112 (0.0757)	1.1230	**21.6**

*These crashes were fitted by Poisson regression models because negative binomial regression models could not be fitted due to insufficient data. Poisson regression models do not have dispersion parameters.

Note: Standard errors are provided in parenthesis. Results showing significant effects (at α = 0.05) are in bold.

The coefficients of the wider edge line for some of the crash types in table 41 (total, PDO, night, single-vehicle, and single-vehicle nighttime crashes) were positive, which indicates a negative safety effect of wider edge lines for those crash types. Researchers suspected that these counter-intuitive negative safety effects of wider lines on total, PDO, night, single-vehicle, and single-vehicle nighttime crashes were because of a high proportion of irrelevant crashes (animal collisions) in those types of crashes and reanalyzed the data after removing animal collisions.

The results of the analysis after the removal of animal collisions are presented in table 42. The table shows estimates of regression coefficients of negative binomial regression models applied to Illinois non-intersection/interchange crashes in non-winter months without animal collisions for 6,531 segments (1,732.8 mi) aggregated for 6 years (2001 through 2006) and percent crash reduction estimates. It can be observed from the table that the coefficients of the wider edge for all crash types were negative and statistically significant, which suggests a positive safety effect of wider lines. As expected, inclusion of irrelevant crashes, such as animal collisions, in the safety evaluation of wider lines can lead to erroneous results when the proportion of such irrelevant crashes in the data is non-negligible. The safety analysis results for F+I crashes were not significantly affected because only 10 percent of F+I crashes were animal collisions.

For Illinois, raised pavement markers (RPMs) are used statewide, as well as rumble strips on interstates. Discussions with Illinois Department of Transportation staff indicated that RPM and rumble strip use was not correlated with the presence of wider lines (i.e., the presence of RPMs and rumble strips was not more or less likely on roads with wider lines). It needs to be noted, however, that information on additional delineation and guidance measures (other than RPMs and rumble strips) was not available and could not be incorporated into the analysis. Therefore, the above observations are based on the same assumption made for rumble strips and RPMs that the effects of the variables not in the database such as additional delineation/guidance measures are the same (or averaged out) for the segments with and without wider edge lines. Finally, it should be restated that the pavement marking widths in Illinois vary by district. The pavement marking variable in the model may capture other differences between districts that also influence safety. Possible examples include differences in crash reporting (likely more significant at the minor to non-injury level), terrain differences, and roadside differences. This limitation is relevant to most cross-sectional studies.

The research team obtained Illinois crash data for two additional years, 2007 and 2008. While the 2001 through 2008 data covered a longer time period, the number of segments that were defined with exactly the same roadway geometric variable values throughout the observation period and the roadway mileage that they cover (643.3 mi) was considerably smaller compared to the 2001 through 2006 data (1,732.8 mi). As a result, the actual number of crashes contained in the 2001 through 2008 data was considerably smaller than the 2001 through 2006 data (see table 43). The research team determined that the 2001 through 2006 data gave the optimal coverage in terms of the amount of crash data when both time and space were considered.

Table 42. Estimates of regression coefficients of negative binomial regression models applied to Illinois non-intersection/interchange crashes without animal collisions (2001–2006).

Crash Type	Intercept	Wider Edge Line	Lane Width	Shoulder Width	Log (AADT)	Presence of Curve	Log (Length)	Dispersion	Pearson Chi-Square/DF	Percent Crash Reduction
Total	**-7.9368** (0.3952)	**-0.3587** (0.0659)	**-0.0651** (0.0269)	**-0.0579** (0.0083)	**0.9801** (0.0350)	**0.3460** (0.0690)	**0.7714** (0.0192)	0.4334 (0.0402)	1.0907	**30.1**
F+I	**-7.4089** (0.5477)	**-0.4727** (0.0975)	**-0.0861** (0.0377)	**-0.0566** (0.0117)	**0.8471** (0.0486)	**0.6968** (0.0947)	**0.8505** (0.0282)	0.4701 (0.0759)	1.0944	**37.7**
PDO	**-9.6705** (0.5154)	**-0.2728** (0.0823)	-0.0500 (0.0344)	**-0.0599** (0.0103)	**1.0996** (0.0443)	0.0703 (0.0933)	**0.7241** (0.0235)	0.4688 (0.0590)	1.0821	**23.9**
Day	**-9.0662** (0.4810)	**-0.3438** (0.0791)	**-0.0809** (0.0323)	**-0.0595** (0.0097)	**1.0878** (0.0417)	**0.1721** (0.0861)	**0.7487** (0.0224)	0.4135 (0.0520)	1.0893	**29.1**
Night	**-8.0035** (0.6469)	**-0.3559** (0.1103)	-0.0371 (0.0442)	**-0.0614** (0.0137)	**0.8108** (0.0571)	**0.7443** (0.1104)	**0.8567** (0.0332)	0.6157 (0.1069)	1.0611	**29.9**
Daytime F+I	**-7.9157** (0.6718)	**-0.4468** (0.1191)	**-0.1350** (0.0461)	**-0.0670** (0.0141)	**0.9324** (0.0592)	**0.4647** (0.1228)	**0.8332** (0.0338)	0.4403 (0.1033)	1.1022	**36.0**
Nighttime F+I*	**-8.8646** (0.8947)	**-0.4186** (0.1581)	0.0185 (0.0606)	**-0.0389** (0.0182)	**0.7231** (0.0759)	**1.1627** (0.1432)	0.9291 (0.0456)		1.0926	**34.2**
Wet	**-9.4281** (0.9938)	**-0.4260** (0.1706)	-0.0453 (0.0677)	**-0.0884** (0.0207)	**0.9129** (0.0865)	**0.5833** (0.1666)	**0.7836** (0.0482)	1.4959 (0.2962)	1.0229	**34.7**
Wet nighttime*	**-8.6417** (1.4905)	-0.4419 (0.2689)	-0.0800 (0.1021)	**-0.1039** (0.0321)	**0.7494** (0.1301)	**1.0403** (0.2471)	**0.8765** (0.0780)		1.0695	35.7
Single-vehicle	**-5.8930** (0.4684)	**-0.4616** (0.0832)	-0.0241 (0.0328)	**-0.0739** (0.0105)	**0.6185** (0.0426)	**0.6815** (0.0827)	**0.8286** (0.0250)	0.5598 (0.0646)	1.1010	**37.0**
Single-vehicle wet	**-7.7587** (1.0373)	**-0.3968** (0.1804)	-0.0037 (0.0702)	**-0.1279** (0.0226)	**0.6380** (0.0902)	**0.8635** (0.1790)	**0.8695** (0.0540)		1.1688	**32.8**
Single-vehicle nighttime	**-7.7545** (0.7084)	**-0.3492** (0.1208)	-0.0055 (0.0486)	**-0.0681** (0.0152)	**0.6964** (0.0629)	**0.9782** (0.1184)	**0.8996** (0.0376)	0.6547 (0.1307)	1.0685	**29.5**
Single-vehicle F+I	**-5.3920** (0.6376)	**-0.5479** (0.1201)	-0.0394 (0.0451)	**-0.0776** (0.0149)	**0.4844** (0.0590)	**0.9654** (0.1120)	**0.8644** (0.0359)	0.7124 (0.1295)	1.0939	**42.2**
Single-vehicle nighttime F+I*	**-8.2466** (0.9811)	**-0.4504** (0.1764)	-0.0455 (0.0669)	**-0.0524** (0.0206)	**0.5873** (0.0845)	**1.3439** (0.1553)	**0.9432** (0.0518)		1.0879	**36.3**
Older driver (≥ 55 years old)	**-10.7785** (0.7606)	**-0.2764** (0.1252)	-0.0699 (0.0507)	**-0.0404** (0.0146)	**1.1225** (0.0629)	0.1637 (0.1385)	**0.7074** (0.0337)		1.0552	**24.1**

Fixed object	**-6.4892** (0.5880)	**-0.3495** (0.1009)	-0.0307 (0.0408)	**-0.0889** (0.0130)	**0.6433** (0.0530)	**0.4572** (0.1079)	**0.7786** (0.0306)	0.6207 (0.1009)	1.1105	**29.5**
Lane departure	**-7.1562** (0.5283)	**-0.2429** (0.0875)	**-0.0845** (0.0365)	**-0.0674** (0.0114)	**0.8225** (0.0474)	**0.3958** (0.0967)	**0.7855** (0.0268)	0.5112 (0.0757)	1.1230	**21.6**

*These crashes were fitted by Poisson regression models because negative binomial regression models could not be fitted due to insufficient data. Poisson regression models do not have Dispersion parameters.

Note: Standard errors are provided in parenthesis. Results showing significant effects (at $\alpha = 0.05$) are in bold.

Table 43. Summary of Illinois crash data for 2001 through 2008.

Variable	Dataset With Animal Collisions				Dataset Without Animal Collisions			
	4 inches	5 inches	4 inches	5 inches	4 inches	5 inches	4 inches	5 inches
Number of segments	2,572	642	2,572	642	2,572	642	2,572	642
Total segment length (mi)	520.0	123.3	520.0	123.3	520.0	123.3	520.0	123.3
Mile-years	4,160.0	986.4	4,160.0	986.4	4,160.0	986.4	4,160.0	986.4
Average AADT	3,160.2	2,248.4	3,160.2	2,248.4	3,160.2	2,248.4	3,160.2	2,248.4
Crash Type	**Crash Counts**		**Crash Rates**		**Crash Counts**		**Crash Rates**	
Total	3,280	695	1.17	1.47	1,753	248	0.63	0.53
F+I	814	103	0.29	0.22	744	88	0.27	0.19
PDO	2,466	592	0.88	1.25	1,009	160	0.36	0.34
Daytime	1,472	247	0.53	0.52	1,134	171	0.41	0.36
Nighttime	1,534	362	0.55	0.77	541	64	0.19	0.14
Daytime F+I	488	55	0.17	0.12	468	52	0.17	0.11
Nighttime F+I	292	47	0.10	0.10	248	35	0.09	0.07
Wet	365	62	0.13	0.13	260	38	0.09	0.08
Wet nighttime	169	27	0.06	0.06	98	11	0.04	0.02
Single-vehicle	2,568	604	0.92	1.28	1,046	157	0.37	0.33
Single-vehicle wet	288	54	0.10	0.11	183	30	0.07	0.06
Single-vehicle nighttime	1,445	355	0.52	0.75	454	57	0.16	0.12
Single-vehicle F+I	551	77	0.20	0.16	483	62	0.17	0.13
Single-vehicle nighttime F+I	258	43	0.09	0.09	215	31	0.08	0.07
Older driver (≥ 55 years old)	707	147	0.25	0.31	369	49	0.13	0.10
Fixed object	654	105	0.23	0.22	654	105	0.23	0.22

Note: Crash rates are computed as crashes per million vehicle miles of travel per year.

Although the focus of the study was rural two-lane roadways, the research team also compiled the Illinois freeway crash data from 2001 through 2006 from 571 segments (708 mi), of which 514 segments (593 mi) have a standard line width (4-inch edge lines and 4-inch skip lines), 13 segments (21 mi) have 4-inch edge lines and 6-inch skip lines, and 44 segments (94 mi) have 5-inch edge lines and 5-inch skip lines. Appendix D provides a summary of crash rates for those 571 freeway segments. Table 93 in appendix D shows that the freeway crash rates associated with wider skip lines or edge lines are, in general, lower than those associated with 4-inch edge lines and skip lines. However, for single-vehicle and single-vehicle nighttime crashes, slightly higher crash rates were observed for wider lines compared to 4-inch edge lines. Unfortunately, available sample sizes did not allow the development of negative binomial or Poisson regression models, which take confounders into account.

Analysis of Kansas Rural Two-Lane Roadway Crash Data

The Kansas crash data consist of non-intersection/interchange crash counts during non-winter months from 2,767 rural two-lane road segments (2,178.2 mi) in districts 2 and 6 from 2001 through 2008. An EB approach was employed to analyze the Kansas crash data. The EB method accounts for the effect on crash frequencies of regression to the mean along with changes in traffic volume and other changes in crash frequencies not due to the treatment. It has been considered a statistically defensible safety evaluation tool in observational before-after studies for more than two decades. In the EB method, safety performance functions (SPFs) are used to estimate the expected crash frequencies at the treated sites had treatments not been applied. Generalized linear regression models, specifically negative binomial regression models, are often used to derive the SPFs. The steps of the EB procedure used for the Kansas data analysis in this project are described below. Note that SPFs were calibrated for each year of the before and after periods rather than just for each period.

1. Develop an SPF and estimate the regression coefficients and a negative binomial dispersion parameter (k) using data from the reference group.

2. Estimate the expected number of crashes $E\left(\kappa_{iy}\right)$ for each year in the before period at each treatment site using the SPF developed in step 1.

3. Compute the sum of the annual SPF predictions during the before period at each treatment site using the equation in figure 16.

$$P_i = \sum_{y=1}^{y_{0i}-1} \hat{E}\left(\kappa_{iy}\right)$$

Figure 16. Equation. Predicted number of crashes in before period.

Where y_{0i} denotes the year during which the countermeasure was installed at site i.

4. Obtain an estimate of the expected number of crashes (M_i) before implementation of the countermeasure at each treatment site and an estimate of variance of M_i. The estimate M_i is given by combining the sum of the annual SPF predictions during the before period (P_i) with the total count of crashes (K_i) during the before period using the equation in figure 17.

$$M_i = w_i P_i + \left(1 - w_i\right) K_i$$

Figure 17. Equation. Expected number of crashes in before period.

Where K_i is the total crash count during the before period at site i and the weight w_i is given by the equation in figure 18.

$$w_i = \frac{1}{1 + kP_i}$$

Figure 18. Equation. Weight.

Where k is the estimated dispersion parameter of the negative binomial regression model developed in step 1. An estimated variance of M_i is given by the equation in figure 19.

$$V\hat{a}r\left(M_i\right) = \left(1 - w_i\right) M_i$$

Figure 19. Equation. Estimated variance in expected number of crashes in before period.

5. Determine SPF predictions $\hat{E}(k_{iy})$ for each year in the after period at each treatment site and compute C_i, the ratio of the sum of the annual SPF predictions for the after period (Q_i) and the sum of the annual SPF predictions for the before period (P_i) using figure 20.

$$C_i = \frac{\sum_{y=y_{0i}+1}^{Y} \hat{E}\left(\kappa_{iy}\right)}{\sum_{y=1}^{y_{0i}-1} \hat{E}\left(\kappa_{iy}\right)} = \frac{Q_i}{P_i}$$

Figure 20. Equation. Ratio of the sum of the annual SPF predictions for the after period.

6. Obtain the predicted crashes ($\hat{\pi}_i$) and its estimated variance during the after period that would have occurred without implementing the countermeasure. The predicted crashes ($\hat{\pi}_i$) are given by the equation in figure 21.

$$\hat{\pi}_i = C_i M_i$$

Figure 21. Equation. Predicted number of crashes in after period with no countermeasure.

The estimated variance of $\hat{\pi}_i$ is given by the equation in figure 22.

$$V\hat{a}r\left(\hat{\pi}_i\right) = C_i^2 V\hat{a}r\left(M_i\right) = C_i^2\left(1 - w_i\right)M_i$$

Figure 22. Equation. Estimated variance of predicted crashes in after period.

7. Compute the sum of the predicted crashes over all sites in a treatment group of interest and its estimated variance by using the equations in figure 23 and figure 24.

$$\hat{\pi} = \sum_{i=1}^{I} \hat{\pi}_i$$

Figure 23. Equation. Sum of predicted crashes for all sites in a treatment group.

$$V\hat{a}r\left(\hat{\pi}\right) = \sum_{i=1}^{I} V\hat{a}r\left(\hat{\pi}_i\right)$$

Figure 24. Equation. Variance of total predicted crashes for all sites in a treatment group.

Where I is the total number of sites in a treatment group of interest.

8. Compute the sum of the observed crashes over all sites in a treatment group of interest by using the equation in figure 25.

$$L = \sum_{i=1}^{I} L_i$$

Figure 25. Equation. Sum of observed crashes for all sites in a treatment group.

Where L_i is the total crash counts during the after period at site *i*.

9. The index of effectiveness of the countermeasure is estimated by the equation in figure 26.

$$\hat{\theta} = \frac{L}{\hat{\pi}\left(1 + \text{var}\left(\hat{\pi}\right)/\hat{\pi}^2\right)}$$

Figure 26. Equation. Estimated index of effectiveness of a countermeasure.

The percent change in the number of crashes at site *i* is given by 100(1 – $\hat{\theta}$). If the index of effectiveness is less than 1, then the countermeasure has a positive effect on safety.

10. Compute the estimated variance and standard error of the estimated index of effectiveness and the approximate 95 percent confidence interval for θ, the index of effectiveness. The estimated variance and standard error of the estimated index of effectiveness are given by the equations in figure 27 and figure 28.

$$V\hat{a}r\left(\hat{\theta}\right) = \hat{\theta}^2 \frac{\left(1/L + V\hat{a}r\left(\hat{\pi}\right)/\hat{\pi}^2\right)}{\left(1 + V\hat{a}r\left(\hat{\pi}\right)/\hat{\pi}^2\right)^2}$$

Figure 27. Equation. Estimated variance in estimated index of effectiveness.

$$s.e.\left(\hat{\theta}\right) = \sqrt{V\hat{a}r\left(\hat{\theta}\right)}$$

Figure 28. Equation. Standard error of estimated index of effectiveness.

The approximate 95 percent confidence interval for θ is given by adding and subtracting 1.96 *s.e.*($\hat{\theta}$) from $\hat{\theta}$. If the confidence interval contains the value 1, then no statistically significant effect has been observed. This does not mean that a safety effect does not exist, so all indices that were estimated are presented in this report to provide a complete picture of safety effects. A confidence interval less than 1 (i.e., the upper limit of the interval was less than 1) implies that the countermeasure had a significant positive effect (i.e., a reduction in crashes) on safety. A confidence interval greater than 1 (i.e., the lower limit of the interval was greater than 1) implies that the countermeasure had a significant negative effect (i.e., an increase in crashes) on safety.

While the success of an EB approach largely depends on reliable estimation of SPFs, it is often hard to identify a reference group that is similar enough to the treatment group. Originally, the researchers considered sites untreated during the 8 years of the study period, 2001–2008, for Kansas. In Kansas, the wider lines were installed in 2005 through 2008. Table 44 summarizes the number of segments and the corresponding mileage for each implementation year. There were only 42.1 mi of roadways (90 segments) in the database that could be used as a reference group (without wider edge lines installed until the end of 2008). The limited length of comparable roadway made it difficult to develop reliable SPFs. Researchers decided to use the segments for wider edge lines that were installed in 2008 as additional sites for a reference group and restricted the study period to 7 years (2001–2007) instead. The number of segments and mileage for the resulting reference group are 261 and 158.1 mi, respectively. Because the segments implemented in 2007 (173 segments corresponding to 110.1 mi) do not have any after period data, 173 segments were excluded from the EB before-after evaluation, which left two treatment groups in the evaluation—group 1, implemented in 2005, consisted of 1,213 segments (803.8 mi) and group 2, implemented in 2006, consisted of 402 segments (361.5 mi). Also note that there are 718 segments in table 44 for which the implementation year is unknown. The only information researchers know about those segments is that wider lines were installed sometime after July 2005. Researchers conducted two sets of analysis for Kansas: one that excluded those 718 segments (analysis 1, which had 1,615 segments (1,165 mi) of rural two-lane roadways) and a second analysis that included them (analysis 2, which had 2,333 segments (1909.9 mi) of rural two-lane roadways). For analysis 2, the 718 included segments were placed in group 1 with an assumed implementation year of 2005 under the expectation that it would lead to more conservative safety effectiveness estimates (i.e., the effects of wider lines will be underestimated if the effects of wider lines are either null or positive and overestimated if the effects are negative, which is unlikely but possible).

Table 44. Number of segments and miles for each implementation year of wider edge lines in Kansas.

Implementation Year	Number of Segments	Miles
Unknown	718	744.7
2005	1,213	803.8
2006	402	361.5
2007	173	110.1
2008	171	116.0
Not implemented until 2008	90	42.1
Total	2,767	2,178.2

Types of crashes analyzed included the following:

- Total crashes.
- F+I crashes.
- PDO crashes.
- Daytime crashes.
- Nighttime crashes.
- Daytime F+I crashes.
- Nighttime F+I crashes.
- Wet crashes.
- Wet nighttime crashes.
- Single-vehicle crashes.
- Single-vehicle F+I.
- Single-vehicle nighttime crashes.
- Single-vehicle nighttime F+I crashes.
- Fixed object crashes.

The negative binomial regression models with indicator variables for district (2 and 6) and year (2001–2007) to control for general trends, shoulder width, log(AADT), and log(segment length) as independent variables were employed to develop SPFs. Although some other roadway characteristic variables, such as lane width and speed limit, were also available in the database, there was not much variation in those variables, so they were not included in the model. Due to an issue of the small sample size, the coefficients for SPFs could be directly estimated only for total, PDO, nighttime, single-vehicle, and fixed object crashes (recall that these crash types were all restricted to non-intersection/interchange crashes during non-winter months). SPFs for other crash types were obtained by applying a multiplier, α_f, (computed as the number of crashes of a specific type divided by the total number of crashes for the reference group) to the SPF for total crashes as in Bahar et al.(58) The estimated coefficients for SPFs for total, PDO, nighttime, single-vehicle, and fixed object crashes and the multipliers (α_f) for the crash types considered in this study are presented in table 45 and table 46, respectively.

Table 45. Estimates of coefficients for SPFs developed based on a reference group consisting of 263 segments (158.1 mi) on rural two-lane roadways in Kansas.

Variable		Total	PDO	Nighttime	Single-Vehicle	Fixed Object
District	2	-3.6538	-3.2213	-3.5047	-5.9793	-5.8683
	6	-4.3942	-4.2987	-4.5591	-5.6635	-6.1639
Year	2001	-0.2680	-0.3680	-0.4723	-0.0026	0.2467
	2002	-0.4696	-0.4754	-0.5300	-0.5760	-1.2433
	2003	-0.3080	-0.3020	-0.2082	-0.2770	-0.5571
	2004	-0.2427	-0.1521	-0.2027	-0.1425	-0.1167
	2005	-0.4324	-0.5194	-0.3902	-0.2484	-0.5254
	2006	-0.2561	-0.3073	-0.5010	0.0505	0.0216
	2007	0.0000	0.0000	0.0000	0.0000	0.0000
Shoulder width		-0.0483	-0.0138	-0.0552	-0.1569	-0.0808
Log(AADT)		0.5417	0.4355	0.4378	0.7190	0.6017
Log(length)		0.9344	0.9387	0.8666	1.0178	1.0476
Dispersion		0.2777	0.2913	0.4745	0.9151	0.2666
Pearson chi-square/DF		1.0700	1.1218	1.0759	1.1422	1.0663

Table 46. Ratio of the number of crashes of a specific type and the total number of crashes for the reference group.

Crash Type	α_f
Total	1.000
F+I	0.226
PDO	0.774
Daytime	0.375
Nighttime	0.493
Daytime F+I	0.127
Nighttime F+I	0.071
Wet	0.064
Wet nighttime	0.033
Single-vehicle	0.358
Single-vehicle F+I	0.167
Single-vehicle nighttime	0.108
Single-vehicle nighttime F+I	0.052
Fixed object	0.182

Table 47 and table 48 include the results of two EB before-after evaluations (analyses 1 and 2) based on the Kansas crash data. It can be observed from the tables that almost all crash types resulted in statistically significant (95 percent confidence level) crash reduction estimates with the exception of nighttime, nighttime F+I, wet nighttime, and single-vehicle nighttime F+I crashes. As expected, the percent crash reduction estimates were, in general, slightly smaller for analysis 2; however, the overall pattern stayed the same. It needs to be noted that single-vehicle road departure crashes were especially relevant target crashes for assessing the safety effects of wider edge lines. The results in table 47 and table 48 support consistent safety effects of wider edge lines for single-vehicle and associated disaggregate crash types (e.g., single-vehicle nighttime and single-vehicle F+I).

A sensitivity analysis that uses the yearly coefficients (as well as the coefficients for other variables) from the total crash SPF for PDO, nighttime, single-vehicle, and fixed object crashes (and applies the corresponding α_f to the calibrated model) to predict for those crash types was conducted. The results are also presented in table 47 and table 48. It can be observed that the results from the sensitivity analysis for PDO, nighttime, single-vehicle, and fixed object crashes did not change materially from those obtained by using their own SPF model coefficients in table 45.

Table 47. Results of EB before-after evaluations based on the Kansas crash data for analysis 1.

Crash Type	Crashes—Before Period: Observed (K)	Crashes—Before Period: EB Estimate (M)	Crashes—After Period: Observed (L)	Crashes—After Period: EB Estimate[a] ($\hat{\pi}$)	Estimated Index of Effectiveness (Standard Error)	95 Percent Confidence Interval for θ	Percent Crash Reduction[b]
Total	2,776	2,420.79	1,021	1,234.07	0.827 (0.028)	(0.772, 0.882)	**17.3**
F+I	474	481.37	156	242.01	0.644 (0.053)	(0.541, 0.748)	**36.6**
PDO	2,302	1,935.39	865	987.19	0.876 (0.032)	(0.813, 0.939)	**12.4**
PDO[c]	2,302	1,897.28	865	970.44	0.891 (0.033)	(0.827, 0.955)	**10.9**
Day	823	807.45	293	406.34	0.721 (0.044)	(0.635, 0.807)	**27.9**
Nighttime	1,610	1,258.77	589	614.95	0.958 (0.043)	(0.874, 1.041)	4.2
Nighttime [c]	1,610	1,212.16	589	619.53	0.950 (0.042)	(0.869, 1.032)	5.0
Daytime F+I	256	268.65	80	135.09	0.592 (0.067)	(0.460, 0.724)	**40.8**
Nighttime F+I	186	152.24	68	76.72	0.886 (0.109)	(0.673, 1.099)	11.4
Wet	178	137.49	54	69.45	0.777 (0.107)	(0.568, 0.987)	**22.3**
Wet nighttime	82	69.95	27	35.32	0.764 (0.148)	0.474, 1.054)	23.6
Single-vehicle	784	738.42	273	368.97	0.739 (0.048)	(0.644, 0.834)	**26.1**
Single-vehicle [c]	784	770.66	273	387.84	0.704 (0.044)	(0.617, 0.790)	**29.6**
Single-vehicle F+I	325	350.25	113	176.63	0.640 (0.061)	(0.519, 0.760)	**36.0**
Single-vehicle nighttime	299	235.32	98	118.77	0.825 (0.085)	(0.659, 0.991)	**17.5**
Single-vehicle nighttime F+I	126	110.87	46	55.87	0.823 (0.122)	(0.583, 1.063)	17.7
Fixed object	382	368.42	160	195.28	0.819 (0.067)	(0.688, 0.950)	**18.1**
Fixed object [c]	382	385.29	160	194.55	0.822 (0.067)	(0.691, 0.953)	**17.8**

[a]EB estimate is the predicted number of crashes during the after period where wider lines had not been installed.
[b]Percent crash reduction = $100(1-\hat{\theta})$.
[c]Indicates the results from the sensitivity analysis using the coefficients from the total crash SPF for prediction.
Note: Bold indicates statistically significant percent crash reductions at 95 percent confidence level.

Table 48. Results of EB before-after evaluations based on the Kansas crash data for analysis 2.

Crash Type	Crashes—Before Period Observed (*K*)	Crashes—Before Period EB Estimate[a] (*M*)	Crashes—After Period Observed (*L*)	Crashes—After Period EB Estimate ($\hat{\pi}$)	Index of Effectiveness (Standard Error)	95 Percent Confidence Interval for θ	Percent Crash Reduction[b]
Total	4,319	3,757.87	1,739	2,042.63	0.851 (0.022)	(0.807, 0.895)	**14.9**
F+I	820	757.23	311	408.68	0.761 (0.045)	(0.673, 0.848)	**23.9**
PDO	3,499	2,906.11	1,428	1,562.46	0.914 (0.026)	(0.862, 0.966)	**8.6**
PDO[c]	3,499	2,914.32	1,428	1,585.65	0.900 (0.026)	(0.849, 0.951)	**10.0**
Day	1,413	1,291.15	571	699.05	0.817 (0.036)	(0.746, 0.887)	**18.3**
Nighttime	2,426	1,834.85	959	938.24	1.022 (0.036)	(0.951, 1.093)	-2.2
Nighttime [c]	2,426	1,848.47	959	1,003.78	0.955 (0.033)	(0.890, 1.020)	4.5
Daytime F+I	450	420.57	176	226.93	0.775 (0.060)	(0.658, 0.892)	**22.5**
Nighttime F+I	315	235.66	121	127.08	0.952 (0.088)	(0.780, 1.124)	4.8
Wet	291	213.0	96	115.14	0.834 (0.086)	(0.665, 1.002)	16.6
Wet nighttime	135	107.80	44	58.19	0.756 (0.115)	(0.531, 0.981)	**24.4**
Single-vehicle	1,313	1,251.26	499	694.67	0.718 (0.035)	(0.649, 0.787)	**28.2**
Single-vehicle [c]	1,313	1,214.06	499	655.69	0.761 (0.036)	(0.691, 0.831)	**23.9**
Single-vehicle F+I	529	542.24	205	292.49	0.701 (0.050)	(0.602, 0.799)	**29.9**
Single-vehicle nighttime	486	363.77	170	196.32	0.866 (0.068)	(0.733, 0.999)	**13.4**
Single-vehicle nighttime F+I	209	170.67	74	91.97	0.804 (0.094)	(0.619, 0.989)	**19.6**
Fixed object	629	606.10	275	353.12	0.779 (0.049)	(0.683, 0.874)	**22.1**
Fixed object [c]	629	600.14	275	324.37	0.848 (0.053)	(0.744, 0.951)	**15.2**

[a]EB estimate is the predicted number of crashes during the after period where wider lines had not been installed.
[b]Percent crash reduction = $100(1-\hat{\theta})$.
[c]Indicates the results from the sensitivity analysis using the coefficients from the total crash SPF for prediction.
Note: Bold indicates statistically significant percent crash reductions at 95 percent confidence level.

Analysis of Michigan Rural Two-Lane Roadway Crash Data

The Michigan crash data consist of non-intersection/interchange crash counts during non-winter months obtained from 253 rural two-lane road segments (851.5 mi) from 2001 through 2007. In Michigan, the change from 4- to 6-inch edge lines was made on almost all State-owned systems in 2004. Table 49 shows the annual aggregated crash counts from the 253 segments for crash types considered in this study. Because 2004 was the installation year of wider lines, crashes from that year were excluded from the subsequent safety analysis.

Table 49. Annual aggregated crash counts over 253 segments (851.5 mi) of rural two-lane roadways in Michigan for 2001–2007.

Crash Type	2001	2002	2003	2004	2005	2006	2007
Total	1,012	1,068	1,188	1,202	980	1,096	1,115
F+I	146	166	144	158	134	113	139
PDO	866	902	1,044	1,044	846	983	976
Daytime	396	441	444	505	406	415	446
Nighttime	462	468	562	504	450	521	522
Daytime F+I	83	103	86	117	88	65	92
Nighttime F+I	42	44	48	35	40	38	39
Wet	110	103	134	115	50	96	72
Wet nighttime	48	54	65	47	20	51	41
Single-vehicle	832	879	1,009	1,014	838	968	978
Single-vehicle wet	88	84	114	98	37	82	61
Single-vehicle night	437	443	524	480	432	502	505
Single-vehicle F+I	80	99	90	95	92	70	88
Single-vehicle nighttime F+I	36	33	36	28	33	28	32

Originally, researchers attempted to conduct an EB before-after analysis on the Michigan data. However, the widespread switch from 4- to 6-inch edge lines on almost all State-owned roads (i.e., all facility types) in 2004 left almost no sites within Michigan as an available reference group/comparison group in the before-after safety evaluation. Although the SPFs could be developed based on the before period data, the general time trends in crash frequencies from before to after periods not due to wider lines could not be easily estimated. The researchers attempted to use the Illinois F+I data to estimate the change in underlying trends. Michigan intersection crashes were also tested as an alternative, but the trends of these crashes in the before period were opposite to those on Michigan rural two-lane highways. The lack of an appropriate reference group within the same state remained one of the main limitations of the EB analysis of the Michigan data.

Researchers employed an alternative approach to perform a safety evaluation of Michigan rural two-lane roadway crash data. The new approach was an interrupted time series design. (See references 59–63.) An interrupted time series design is a quasi-experimental method used to determine the impact of an intervention. Campbell and Ross indicated, “In the Interrupted Time-Series, the ‘causal’ variable is examined as an event or change occurring at a single time, specified independently of inspection of the data.” (p. 41)[59] In this instance, the causal variable (intervention) is the installation of wider lines that took place statewide in 2004. A generalized linear segmented regression analysis was used as a statistical method for analyzing the data from the interrupted time series design. Specifically, a negative binomial regression model that introduces time as a variable to control for overall trend and intervention (installation of wider lines) as a variable to estimate the effect of the wider lines was utilized. For time, the years prior to the installation of wider lines were coded as negative integers starting at -1 in descending order, and the years after the installation of wider lines were coded as positive integers starting at 1 in ascending order. For intervention, years corresponding to the after period were coded “1,” and years in the before period were coded “0.” An additional variable, time after intervention, which was coded “0” before the intervention and (time-t_0) where t_0 is the year of the intervention, can also be included in the model to estimate a possible change in the trend (not just in the level) in the expected number of crashes. At road segment *i*, the log of expected number of annual crashes in year t (μ_{it}) can be expressed as shown in figure 29.

$$\log \mu_{it} = \beta_0 + \beta_1 * \text{time}_t + \beta_2 * \text{Intervention}_t + \beta_3 * \text{time after intervention}_t + \beta_4 X_{i,4t} \cdots + \beta_k X_{i,kt}$$

Figure 29. Equation. Negative binomial regression model for interrupted time series.

Where $X_{i,kt}$ is the value of the *k*th predictor variable measured at road segment *i* in time *t*.

The underlying assumption for the above model is that the relationship between the log mean annual crash count and time is linear within each segment of time period (i.e., for the time period before the intervention and independently for the time period after the intervention). The intercept, β_0, represents the baseline level of the log mean annual crash count, and β_1 represents the baseline trend that corresponds to the change in the log mean annual crash count that occurs with each year before the intervention. The coefficients β_2 and β_3 represent the level change (i.e., the change in the intercept) in the log mean annual crash count immediately after the intervention and the change in the trend (i.e., the change in the slope) in the log mean annual crash count after the intervention, respectively. The key parameters of interest are β_2 and β_3, which can measure the effects of intervention, while β_0 and β_1 play the role of controlling for baseline level and trend.

In addition to time, intervention, and time after intervention, lane width, terrain, log(AADT), log(segment length), and log(number of rainy days) were included as predictors in the negative binomial regression model for Michigan crash data. GEEs were employed as an estimation method to account for correlation in crash counts obtained for multiple years from the same segment.

Table 50 contains the estimated coefficients for negative binomial regression models considered and the corresponding percent crash reduction estimates where the GEE approach was used as an estimation method. Originally, an additional variable, time after intervention, had been included in the negative binomial regression models to estimate a possible change in the trend (not just in the level) in the expected number of crashes. However, time after intervention was not statistically significant for any of the crash types considered in the study and was consequently dropped from the models to facilitate the interpretation of the results. It can be observed from table 50 that for total, PDO, nighttime, wet, wet nighttime, single-vehicle, single-vehicle wet, and single-vehicle nighttime crashes, statistically significant crash reductions at the 95 percent confidence level were found.

In addition to the crash types reported in table 50, opposite direction crashes and additional disaggregated F+I crashes such as wet F+I, wet nighttime F+I, and single-vehicle wet F+I were analyzed. However, due to insufficient data (there were very few crashes of those types), model coefficients could not be estimated, and reliable crash reduction estimates could not be obtained.

Table 50. Results of interrupted time series analysis applied to the Michigan crash data from 253 segments (851.5 mi) of rural two-lane roadways with 3 years (2001–2003) of pre-intervention and 3 years (2005–2007) of post-intervention data.

Crash Type	Intercept	Time	Intervention	Lane Width (inches)	Terrain	Log (AADT)	Log (Length)	Log (No. of Rainy Days)	Percent Crash Reduction*	95 Percent Confidence Interval for Percent Crash Reduction
Total	**-3.4846**	**0.0782**	**-0.3204**	-0.0977	**0.1721**	**0.5205**	**1.0980**	0.0769	**27.4**	(15.4, 37.7)
F+I	**-8.6073**	0.0050	-0.1668	-0.0379	0.1945	**0.8216**	**1.0277**	0.0056	15.4	(-21.5, 41.0)
PDO	**-3.3755**	**0.0953**	**-0.3633**	-0.1140	**0.1700**	**0.4981**	**1.1149**	0.1026	**30.5**	(18.1, 40.9)
Day	**-3.9724**	0.0512	**-0.2271**	-0.1008	**0.2735**	**0.5638**	**1.0141**	-0.0968	**20.3**	(0.2, 36.4)
Night	**-5.4095**	**0.0984**	**-0.3666**	-0.0474	0.1008	**0.5666**	**1.1596**	0.1228	**30.7**	(15.0, 43.5)
Daytime F+I	**-8.6123**	0.0031	-0.0860	-0.0801	0.2077	**0.9254**	**0.9238**	-0.1079	8.2	(-43.3, 41.2)
Nighttime F+I	**-10.7416**	0.0348	-0.2564	0.0780	0.1336	**0.6430**	**1.2491**	0.2353	22.6	(-50.3, 60.2)
Wet	**-11.2267**	**0.1715**	**-1.1140**	-0.0626	0.2183	**0.4813**	**0.9848**	**1.2745**	**67.2**	(45.2, 80.3)
Wet nighttime	**-11.8302**	**0.2715**	**-1.4633**	-0.0321	0.1819	**0.4009**	**1.0133**	**1.3551**	**76.9**	(57.2, 87.5)
Single-vehicle	**-2.9988**	**0.1004**	**-0.3566**	-0.1117	**0.1917**	**0.4313**	**1.1665**	1.1046	**30.0**	(17.7, 40.5)
Single-vehicle wet	**-9.9483**	**0.2313**	**-1.3394**	-0.1147	0.2328	**0.3202**	**1.0439**	**1.3670**	**73.8**	(55.8, 84.5)
Single-vehicle nighttime	**-5.2232**	**0.0987**	**-0.3476**	-0.0519	0.1062	**0.5438**	**1.1694**	0.1174	**29.4**	(13.4, 42.4)
Single-vehicle F+I	**-6.0126**	0.0062	-0.1056	-0.0671	0.1209	**0.5717**	**1.2009**	-0.1233	10.0	(-40.8, 42.5)
Single-vehicle nighttime F+I	**-8.1645**	-0.0016	-0.1023	-0.0382	0.1039	**0.5420**	**1.2847**	0.0835	9.7	(-85.7, 56.1)

*Percent crash reduction estimates are obtained by $\{1 - \mathrm{Exp}(\beta I)\} \times 100$ where βI represents the estimated coefficient of the intervention variable.

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

The researchers obtained crash data for rural two-lane roadways in Michigan for two additional years—2008 and 2009. Because of the changes on some road segments after 2007, the number of segments of which roadway characteristics stayed the same for the entire study period (2001–2009) was reduced to 238 segments (787.8 mi). Table 51 shows the annual aggregated crash counts from the 238 segments for crash types considered in this study. Because 2004 was the installation year of wider lines, crashes from 2004 were excluded from the subsequent safety analysis.

Table 51. Annual aggregated crash counts over 238 segments (787.8 mi) of rural two-lane roadways in Michigan for 2001–2009.

Crash Type	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total	943	981	1,106	1,119	905	1,010	1,034	1,006	1,007
F+I	127	149	127	146	125	99	121	124	115
PDO	816	832	979	973	780	911	913	882	892
Daytime	374	398	411	459	373	381	408	417	365
Nighttime	427	431	525	481	419	482	487	441	495
Daytime F+I	71	90	74	109	80	55	79	95	80
Nighttime F+I	38	41	43	33	39	35	35	25	30
Wet	101	100	129	105	46	89	67	67	97
Wet nighttime	43	52	63	44	19	47	39	31	50
Single-vehicle	778	811	946	953	775	894	915	890	891
Single-vehicle wet	81	81	109	90	34	76	56	55	83
Single-vehicle nighttime	403	409	493	458	401	463	472	428	479
Single-vehicle F+I	73	90	80	91	88	60	77	79	63

Researchers performed another interrupted time series analysis with 9 years of data as a sensitivity analysis. The number of rainy days could not be included in the models for the extended time period because the data for that variable were not available after 2007. Table 52 contains the results for the crash data obtained from 238 segments for 2001–2009 where a GEE approach was used as an estimation method. The results did not materially change from those in table 50, although the magnitude of crash reduction moderately decreased compared to the results based on 2001–2007 data (except for F+I, daytime F+I, and wet nighttime crashes). In addition to the crash types reported in table 52, opposite direction crashes and additional disaggregated F+I crashes such as single-vehicle nighttime F+I, wet F+I, wet nighttime F+I, and single-vehicle wet F+I were also analyzed. Due to the insufficient data, model coefficients could not be estimated, and reliable crash reduction estimates could not be obtained.

The research team also compiled the Michigan freeway crash data for 2001–2007 from 508 segments (1,067.4 mi). Appendix D provides the annual aggregated crash counts from those 508 freeway segments as well as the results of interrupted time series analysis on the freeway crash data. No consistent or statistically significant safety effects of wider lines were observed for the Michigan freeway crash data.

Table 52. Results of interrupted time series analysis applied to the Michigan crash data from 238 segments (787.8 mi) of rural two-lane roadways with 3 years (2001–2003) of pre-intervention and 5 years (2005–2009) of post-intervention data.

Crash Type	Intercept	Time (year)	Intervention	Lane Width (inches)	Terrain	Log (AADT)	Log (Length)	Percent Crash Reduction*	95 Percent Confidence Interval for Percent Crash Reduction
Total	**-3.0916**	**0.0451**	**-0.2151**	-0.1302	**0.1737**	**0.5542**	**1.1074**	**19.4**	(10.1, 27.6)
F+I	**-8.0168**	0.0132	-0.1754	-0.0118	0.1088	**0.7572**	**1.0270**	16.1	(-11.1, 36.6)
PDO	**-2.9525**	**0.0490**	**-0.2186**	-0.1399	**0.1806**	**0.5310**	**1.1199**	**19.6**	(9.8, 28.4)
Day	**-4.0554**	0.0264	-0.1277	-0.1296	**0.2397**	**0.5589**	**1.0106**	12.0	(-3.5, 25.2)
Night	**-4.7448**	**0.0489**	**-0.2081**	-0.0734	0.1138	**0.5801**	**1.1665**	**18.8**	(6.3, 29.6)
Daytime F+I	**-8.5857**	0.0560	-0.2617	-0.0150	0.1331	**0.7860**	**0.9419**	23.0	(-6.6, 44.4)
Nighttime F+I	**-9.1065**	-0.0490	0.0560	0.0072	0.0614	**0.6744**	**1.2300**	-5.8	(-86.8, 39.5)
Wet	**-5.2136**	**0.1185**	**-0.9847**	-0.0808	0.1628	**0.5140**	**0.9940**	**62.6**	(45.6, 74.4)
Wet nighttime	**-12.1894**	**0.2982**	**-1.5695**	0.0253	0.1669	**0.3807**	**1.0200**	**79.2**	(60.2, 89.1)
Single-vehicle	**-2.4692**	**0.0540**	**-0.2066**	-0.1425	**0.1984**	**0.4615**	**1.1610**	**18.7**	(8.9, 27.4)
Single-vehicle wet	**-3.4974**	**0.1386**	**-1.0768**	-0.1574	0.1754	**0.3824**	**1.0386**	**65.9**	(48.6,77.4)
Single-vehicle nighttime	**-4.5967**	**0.0511**	**-0.1983**	-0.0807	0.1234	**0.5624**	**1.1767**	**18.0**	(5.2, 29.0)
Single-vehicle F+I	**-5.8489**	-0.0190	0.0191	-0.0339	0.0916	**0.4476**	**1.1011**	-1.9	(-44.8, 28.3)

*Percent crash reduction estimates are obtained by $\{1-\mathrm{Exp}(\beta I)\} \times 100$ where βI represents the estimated coefficient of the intervention variable.

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

Consolidated Results

Table 53 presents consolidated results for estimations in the percent crash reductions from the six separate analyses. Note that while only the non-intersection/interchange non-winter crashes were considered for all three States, animal collisions were removed only from the Illinois data. Additionally, the animal collisions were excluded from the Kansas single-vehicle crash categories by default since the Kansas crash types were coded so that single-vehicle animal collisions were separated from other single-vehicle crash types in the raw data. Single-vehicle animal collisions were not removed from the crash categories in the Michigan dataset or from non-single-vehicle crash categories in the Kansas dataset. The overall effect of these crashes on the safety effectiveness estimates for Kansas and Michigan was minimal given the before-after observational study design for these two States (as opposed to the cross-sectional study design for Illinois where different numbers of animal collisions at different locations across the State could mask the effect of wider lines on other crash types). Overall, the results in table 53 support consistent safety effects of wider edge lines on the (relevant) crashes considered.

Table 53. Percent crash reduction estimates for wider edge lines on rural two-lane highways based on the crash data from three States.

Crash Type	Percent Crash Reduction					
	Illinois (With Animal Collisions)	**Illinois (Without Animal Collisions)**	**Kansas (Analysis 1)**	**Kansas (Analysis 2)**	**Michigan (Analysis 1)**	**Michigan (Analysis 2)**
Total	-0.8	**30.1**	**17.5**	**15.0**	**27.4**	**19.4**
F+I	**31.6**	**37.7**	**36.5**	**24.4**	15.4	16.1
PDO	**-11.9**	**23.9**	**12.3**	**8.6**	**30.5**	**19.6**
Daytime	**19.3**	**29.1**	**28.6**	**18.6**	**20.3**	12.0
Nighttime	-9.8	**29.9**	3.7	-2.4	**30.7**	**18.8**
Daytime F+I	**36.7**	**36.0**	**41.5**	**22.7**	8.2	23.0
Nighttime F+I	20.5	**34.2**	12.7	5.8	22.6	-5.8
Wet	**25.4**	**34.7**	**22.9**	**17.2**	**67.2**	**62.6**
Wet nighttime	28.1	35.7	24.3	**24.9**	**76.9**	**79.2**
Single-vehicle	-3.9	**37.0**	**27.0**	**28.7**	**30.0**	**18.7**
Single vehicle wet	21.7	**32.8**			**73.8**	**65.9**
Single-vehicle nighttime	**-12.5**	**29.5**	**18.4**	**14.1**	**29.4**	**18.0**
Single-vehicle F+I	**33.1**	**42.2**	**36.8**	**30.5**	10.0	-1.9
Single-vehicle nighttime F+I	19.5	**36.3**	18.7	**20.3**	9.7	
Older driver	1.7	**24.1**				
Fixed object	**29.5**	**29.5**	**19.0**	**22.4**		

Note: Statistically significant results at 95 percent confidence level are shown in bold. Blank cells represent inadequate data available to perform statistical testing.

CRASH SEVERITY ANALYSIS OF SINGLE-VEHICLE CRASHES

The results of the crash frequency analysis provided detailed evidence to suggest that wider edge lines are effective in reducing crashes on rural two-lane highways, especially with regard to relevant target crashes such as single-vehicle crashes and related disaggregate crashes (e.g., single-vehicle nighttime and single-vehicle F+I). The safety effects of wider edge lines, measured in terms of crash frequencies, were consistently positive and statistically significant using data from the three States. Crash severity is also an important component of road safety. Crash severity was partially addressed by the frequency analysis, with crash reductions estimated by severity level (e.g., F+I and PDO). This was still a frequency analysis. Confounding factors that influenced both frequency and severity may influence severity-related conclusions. The crash reduction parameters were also estimated independently. Estimated reductions in F+I and PDO crashes may not necessarily sum up to equal the estimated reductions in total crashes.(64) Finally, the levels of severity were highly aggregated. Crashes resulting in a fatality or any level of injury (i.e., incapacitating, non-incapacitating, or possible injury) were grouped into one severity category. Disaggregating the injury levels may provide additional insights to crash severity effects.

This research focused on an alternative approach to explore the impacts of wider lines on crash severity. The analysis estimated the effects of wider lines on crash severity given that a crash has occurred. The effects of traffic, roadway, and vehicle occupant factors that also influence severity are incorporated into the analysis. The data used for estimation were from the same rural two-lane highway segments in Illinois and Michigan used for the frequency analysis. The Kansas pavement marking data were not available until the final stages of this research project. Efforts focused on preparing the Kansas data for the EB analysis and executing the analysis; severity modeling of Kansas data was not conducted. The concentration was single-vehicle crashes, which was the focus of the following possible outcomes discussed by the research team, which ultimately became the motivation for conducting this research task:

- Wider lines appear to reduce the frequency of single-vehicle crashes on rural two-lane highways. The presence of wider lines may also reduce the severity of single-vehicle crashes that occur. This may be due to drivers having a clearer view of the roadway alignment. While a single-vehicle crash was not completely avoided, the severity was lower due to a smaller roadway departure angle or lower selected speed.

- Wider lines may not have any effect on the severity of single-vehicle crashes on rural two-lane roads. An overall safety benefit is still realized according to the frequency analysis.

- The presence of wider lines is associated with an increase in crash severity. There is evidence that some safety-related treatments may actually have an adverse safety effect at some locations.(58) Driver adaptation has been proposed as one reason for the counterintuitive findings. For example, improved visibility leads to increased driver comfort and higher operating speeds. This adaptive effect has been identified as a focus of future safety research, and it is becoming clear that safety effects cannot be deduced purely from human factors theory alone.(65)

The severity effects of wider lines were empirically modeled in order to explore these potential outcomes. Published research exists on the application of discrete choice models to explore crash severity.[66] Their use in applied safety research is relatively limited. The methodologies in the *Highway Safety Manual* are frequency-based.[55] Methods to predict changes in crash frequency by severity are included in some chapters. Default distributions for crash severity are also used in the *Highway Safety Manual* algorithms. Since the use of discrete choice models has been relatively limited, the research team conducted a literature review on the application of such models to explore crash severity (see appendix I).

Modeling Approach

The logit model is the most widely used discrete choice model because the choice probabilities take a closed form and are readily interpretable. In the multinomial logit model, the probability that crash *n* will have severity *i* is given by the equation in figure 30.

$$p_n(i) = \exp(\beta_i X_n) / \sum_I \exp(\beta_I X_n)$$

Figure 30. Equation. Probability of a given crash having a specified severity using multinomial logit model.

Where X_n is a set of variables that will determine the crash severity, and β_i is a vector of parameters to be estimated. Utility functions defining the severity likelihoods are defined in figure 31.

$$S_{in} = \beta_i X_n + \varepsilon_{in}$$

Figure 31. Equation. Function for severity likelihood.

Where ε_{in} is a set of error terms that account for unobserved variables. The error terms for each choice should follow independent extreme value distributions (also called Gumbel or type I extreme value). The key assumption is that the errors are independent of each other. This independence means that the unobserved portion of utility for one severity alternative is unrelated to the unobserved portion of utility for another severity alternative. If the unobserved portion of utility is correlated over alternatives, then there are three options: (1) use a different model that allows for correlated errors, such as nested logit or mixed logit model, (2) respecify the representative utility so that the source of the correlation is captured explicitly and thus the remaining errors are independent, or (3) use the logit model under the current specification of representative utility, considering the model to be an approximation.

This independence of irrelevant alternatives (IIA) assumption is an important issue for the application of the multinomial logit model. If IIA holds, the ratio of probabilities for any two alternatives is entirely unaffected by the systematic utilities of any other alternatives. Tests of IIA were developed by McFadden et al.[67] Under IIA, the ratio of probabilities for any two alternatives is the same whether or not other alternatives are available. As a result, if IIA holds in reality, then the parameter estimates obtained on the subset of alternatives will not be significantly different from those obtained on the full set of alternatives. A test of the hypothesis that the parameters on the subset are the same as the parameters on the full set constitutes a test of IIA.[68] The null hypothesis of the test is that the coefficients of variables are equal for full set alternatives and subset alternatives (i.e., IIA holds). The test statistic has a chi-square distribution with the degrees of freedom equal to the number of coefficients estimated in the constrained (subset) model. If the null hypothesis is not rejected, then the IIA assumption holds, and the multinomial logit model is appropriate. The researcher should explore the three options stated above if the null hypothesis is rejected (i.e., the IIA assumption does not hold). As shown in the following sections, the IIA assumption was confirmed for the severity models in this report, indicating that the multinomial logit model was appropriate.

The likelihood ratio index is used to assess the goodness of fit of the logit model. The statistic measures how well the model, with its estimated parameters, performs compared to a model in which all the parameters except for the constant are zero (which is usually equivalent to having no model at all). The likelihood ratio index is defined in figure 32.

$$\rho = 1 - \frac{LL(\beta)}{LL(0)}$$

Figure 32. Equation. Likelihood ratio index.

Where $LL(\beta)$ is the value of the log-likelihood function at the estimated parameters and $LL(0)$ is its value when all the parameters are set equal to zero.

Description of Data

The data used for model estimation were crashes occurring on the same rural two-lane highway segments as those used for the Illinois cross-sectional analysis and the Michigan interrupted time series analysis. The database consisted of all 2002–2006 Illinois single-vehicle crashes occurring on these segments, except those that were animal collisions, and all Michigan single-vehicle crashes from 2001–2003 (i.e., the before period) and 2005–2007 (i.e., the after period). The 2001 Illinois crashes were not used because there was a significant amount of missing occupant-related data, which is important information for the severity model specifications. The final datasets consisted of 4,061 rural two-lane highway single-vehicle crashes in Illinois and 2,483 rural two-lane highway single-vehicle crashes in Michigan. Many of the same variables were available for both datasets. Detailed information on vehicle occupants other than the driver was only available for Illinois. Table 54 and table 55 provide definitions of the variables used in the model specifications for Illinois and Michigan, respectively.

Table 54. Illinois variable definitions.

Variable	Description
Male occupants	The number of male occupants (not including the driver) in the vehicle
Female occupants	The number of female occupants (not including the driver) in the vehicle
Back restraint use	Indicator variable for back restraint use (1 = there is at least one occupant in the back seat that is not wearing a seatbelt)
Front restraint use	Indicator variable for front restraint use (1 = there is at least one occupant in the front seat, other than the driver, who is not wearing a seatbelt)
Max occupant age: back	Maximum age of occupants in the back seat (equals zero if no occupants)
Max occupant age: front	Maximum age of occupants in the front seat (equals zero if no occupants)
Driver age	Driver age
Alcohol use	Indicator variable for driver alcohol use (1 = alcohol use is suspected)
Driver sex	Indicator variable for driver sex (1 = male)
Driver restraint use	Indicator variable for driver restraint use (1 = not wearing seatbelt)
Fixed object collision	Indicator variable for collision type (1 = fixed object; 0 = rollover)
Wet road	Indicator variable for road condition (1 = road surface is wet)
Snow road	Indicator variable for road condition (1 = road surface has snow)
Rainy weather	Indicator variable for weather (1 = raining)
Snowy weather	Indicator variable for weather (1 = snowing)
Foggy weather	Indicator variable for weather (1 = foggy)
Road debris	Indicator variable for road condition (1 = road surface has debris)
Lane width	Lane width (ft)
Shoulder width	Shoulder width (ft)
Speed limit	Speed limit (mi/h)
5-inch line width	Indicator variable for pavement marking width (1 = 5 inches)
Sharp curve	Indicator variable for horizontal curve presence (1 = horizontal curve sharper than 2.5 degrees)
AADT	Average annual daily traffic (thousand vehicles per day)

Table 55. Michigan variable definitions.

Variable	Description
Driver age	Driver age
Driver restraint use	Indicator variable for driver restraint use (1 = not wearing seatbelt)
Driver sex	Indicator variable for driver sex (1 = male)
Alcohol use	Indicator variable for driver alcohol use (1 = alcohol use is suspected)
Fixed object collision	Indicator variable for collision type (1 = fixed object; 0 = rollover)
Foggy weather	Indicator variable for weather (1 = foggy)
Rainy weather	Indicator variable for weather (1 = raining)
Snowy weather	Indicator variable for weather (1 = snowing)
Other weather condition	Indicator variable for weather (1 = other/unknown)
Daylight	Indicator variable for light condition (1 = daylight)
Wet road	Indicator variable for road condition (1 = road surface is wet)
Icy road	Indicator variable for road condition (1 = road surface has ice)
Snow road	Indicator variable for road condition (1 = road surface has snow)
Other road condition	Indicator variable for road condition (1 = other/unknown)
Speed limit	Speed limit (mi/h)
Shoulder width	Shoulder width (ft)
Lane width	Lane width (ft)
6-inch edge line width	Indicator variable for edge line width (1 = 6 inches)
AADT	Average annual daily traffic (thousand vehicles per day)

Results and Conclusions

General model specifications were used since this was an exploratory analysis of crash severity. Table 56 and table 57 provide the model estimation results using the Illinois and Michigan data, respectively. The PDO crash was set as the base outcome for both models. Generally, positive parameters indicate that the respective level of severity became more likely as the value for the variable increased. For example, the parameters for the driver restraint use indicator variables were positive, indicating that higher levels of severities become more likely if the driver was not wearing a seat belt. As expected, this variable is highly associated with crash severity in both the Michigan and Illinois models. Parameters for ADT were negative, indicating that higher levels of severities were less likely as traffic increased, likely due to slower travel speeds. Crash severity increased with driver age. The increased likelihood of injuries to older drivers likely offset the lower impact speeds that are more likely for those drivers. This is consistent with findings that sometimes show a U-shaped curve for driver fatalities per vehicle miles of travel by age, with an increasing trend from age 50 and above. This trend reflects an increased likelihood that crash involvement proves fatal more than an increase in crash frequencies. The signs are mixed for some variables. For example, the probability of a possible injury crash is lower, and the probabilities of non-incapacitating, incapacitating, and fatal crashes are higher as the number of male occupants in the vehicle increases. The findings for posted speed limit are also mixed. Increased severity is associated with higher posted speeds for all severities except fatalities in the Illinois model. The parameter estimate signs are not as consistent in the Michigan model. None of the parameters for posted speed limit are statistically significant in either model, likely reflecting that the impact speed of the crash as opposed to the posted speed is the most important speed-related variable.

Table 56. Multinomial logit model estimation results for severity of single-vehicle crashes on rural two-lane highways in Illinois.

Variable	Possible Injury		Non-Incapacitating		Incapacitating		Fatal	
	Coefficients	*p*-value	Coefficients	*p*-value	Coefficients	*p*-value	Coefficients	*p*-value
Constant	**-2.462**	0.06	-0.279	0.716	-1.296	0.205	-2.565	0.219
Male occupants	-0.394	0.113	0.049	0.66	0.086	0.568	0.313	0.25
Female occupants	0.107	0.527	**0.160**	0.097	0.151	0.266	0.348	0.158
Back restraint use	1.185	0.194	-0.003	0.995	**1.196**	0.043	1.037	0.235
Front restraint use	**1.329**	0.073	**1.34**	0.002	**1.459**	0.002	**2.409**	0
Max occupant age: back	-0.024	0.532	0.016	0.212	-0.006	0.756	-0.073	0.23
Max occupant age: front	0.005	0.540	0.006	0.173	**0.012**	0.037	0.014	0.131
Driver age	0.001	0.789	0.002	0.419	**0.016**	0	**0.034**	0
Alcohol use	-0.178	0.565	**0.816**	0	**0.883**	0	**1.46**	0
Driver sex	**-0.391**	0.017	**-0.329**	0.001	**-0.244**	0.065	0.033	0.911
Driver restraint use	0.262	0.564	**1.526**	0	**2.574**	0	**2.708**	0
Fixed object collision	**-0.625**	0	**−0.5**	0	**-0.519**	0	0.252	0.36
Wet road	**0.573**	0.081	-0.091	0.669	0.209	0.431	-0.598	0.34
Snow road	0.175	0.525	**-0.368**	0.054	**-0.579**	0.058	-1.696	0.114
Rainy weather	-0.228	0.533	-0.036	0.877	-0.483	0.123	-0.319	0.67
Snowy weather	**-0.448**	0.087	**-0.714**	0	**-1.091**	0	-1.017	0.121
Foggy weather	**-1.756**	0.088	-0.187	0.554	-0.079	0.84	1.054	0.121
Road debris	-0.578	0.181	**-0.626**	0.013	-0.46	0.162	-0.549	0.47
Lane width	0.074	0.481	-0.008	0.902	-0.025	0.758	-0.211	0.214
Shoulder width	0.025	0.46	**-0.037**	0.065	**-0.062**	0.022	-0.02	0.723
Speed limit	0.174	0.554	0.207	0.207	0.144	0.497	-0.3	0.444
5-inch line width	-0.043	0.879	0.205	0.19	-0.099	0.659	**-1.048**	0.095
Sharp curve	0.289	0.225	0.174	0.235	-0.02	0.919	0.422	0.24
AADT	**-0.141**	0.001	**-0.084**	0	**-0.061**	0.026	-0.01	0.835

Note: Significant (α = 0.10) effects are shown in bold.

Table 57. Multinomial logit model estimation results for severity of single-vehicle crashes on rural, two-lane highways in Michigan.

Variables	Possible Injury		Non-Incapacitating		Incapacitating		Fatal	
	Coefficients	*p*-Value	Coefficients	*p*-Value	Coefficients	*p*-Value	Coefficients	*p*-Value
Constant	-1.236	0.359	-0.321	0.824	-0.572	0.722	-60.637	0.993
Driver age	0.002	0.73	0.002	0.772	**0.015**	0.069	**0.04**	0.044
Driver restraint use	0.747	0.179	**1.403**	0.003	**3.267**	0	**4.352**	0
Driver sex	**-0.329**	0.065	-0.261	0.233	-0.419	0.173	-0.544	0.46
Alcohol use	-0.483	0.217	**1.071**	0	0.035	0.94	**1.506**	0.096
Fixed object collision	**-0.666**	0.001	**-0.767**	0.001	**-0.99**	0.002	-1.155	0.145
Foggy weather	-0.245	0.316	-0.119	0.665	-0.193	0.607	0.276	0.758
Rainy weather	-0.424	0.333	-0.144	0.792	0.717	0.293	2.836	0.148
Snowy weather	-0.072	0.83	-0.16	0.716	0.393	0.549	**2.894**	0.076
Other weather condition	0.283	0.525	-0.165	0.813	-13.85	0.989	-10.663	0.995
Daylight	-0.023	0.903	-0.149	0.511	-0.209	0.512	0.2	0.809
Wet road	-0.238	0.496	-0.516	0.223	-0.789	0.173	-1.622	0.302
Icy road	**-0.765**	0.01	**-1.277**	0.002	**-1.631**	0.007	-16.552	0.98
Snow road	**-1.366**	0.001	**-1.401**	0.009	**-2.793**	0.003	**-3.275**	0.079
Other road condition	-0.519	0.197	-0.348	0.48	**-1.807**	0.053	-16.365	0.988
Speed limit	0.008	0.967	-0.055	0.795	-0.271	0.201	9.654	0.994
Shoulder width	0.086	0.266	0.042	0.644	0.094	0.457	-0.213	0.436
Lane width	0.046	0.804	0.033	0.881	0.124	0.695	0.285	0.706
6-inch edge line width	-0.016	0.934	**-0.495**	0.024	-0.223	0.49	-0.619	0.421
AADT	-0.004	0.914	-0.049	0.256	-0.07	0.236	-0.347	0.11

Note: Significant (α = 0.10) effects are shown in bold.

The IIA assumption for all severity levels held true for both the Illinois and Michigan models, indicating that the multinomial logit model was appropriate. The signs of the parameters for edge line width were negative (except for non-incapacitating injury crashes in Illinois), indicating that crashes were less severe on road segments with wider lines. The only edge line parameters that were statistically significant ($\alpha = 0.1$) were the parameters for fatal crashes in Illinois (indicating that the probability of a fatality, given that a crash occurred, was lower with wider lines) and for non-incapacitating injury crashes in Michigan (indicating that the probability of a non-incapacitating injury, given that a crash occurred, was lower with wider lines). Overall, the level of confidence was not high enough to make conclusive remarks on the effect of edge line width on crash severity. The patterns and signs of the marking width parameters do indicate either a reduction in severity or no severity effect, which supports an overall safety benefit of wider lines given the results of the frequency analysis. Table 58 and table 59 provide the severity distributions with and without wider markings in Illinois and Michigan, respectively. These distributions are predicted using the logit model results, so they are more powerful than a simple univariate comparison.

Table 58. Single-vehicle crash severity distributions with and without wider pavement markings on rural two-lane highways in Illinois.

Crash Type	4-Inch Lines (percent)	5-Inch Lines (percent)
Fatal	1.25	0.42
Incapacitating injury	10.34	9.08
Non-incapacitating injury	22.32	26.58
Possible injury	5.23	4.86
PDO	60.87	59.06

Table 59. Single-vehicle crash severity distributions with and without wider edge lines on rural two-lane highways in Michigan.

Crash Type	4-Inch Lines (percent)	6-Inch Lines (percent)
Fatal	0.00	0.00
Incapacitating injury	2.14	1.81
Non-incapacitating injury	12.03	7.75
Possible injury	13.38	13.91
PDO	72.44	76.53

SUMMARY

Prior to this research, the results of work on the safety benefits of wider edge lines were inconclusive. The research reported herein provided a unique opportunity to explore the safety benefits of wider edge lines in the most comprehensive study on the topic to date.

Consolidated results for estimations in the percent crash reductions (six total analyses) support consistent safety effects of wider edge lines on the non-intersection/interchange non-winter crashes considered. Crash frequency analysis suggests that wider edge lines are effective in reducing crashes on rural two-lane highways, especially with regard to relevant target crashes such as single-vehicle crashes and related disaggregate crashes.

Generally, positive parameters indicated that the respective level of crash severity became more likely as the value for the variable increased, but results were mixed based on parameter. Statistically conclusive remarks on the effect of edge line width on crash severity cannot be made, but the patterns and signs of the marking width parameters support an overall safety benefit of wider lines given the results of the frequency analysis.

CHAPTER 5. ENVIRONMENTAL HEALTH AND SAFETY CONSIDERATIONS

INTRODUCTION

Identifying environmental health and safety considerations associated with the application and removal of pavement marking materials is important to workers, employers, and Government agencies involved with pavement marking. Pavement marking materials contain a variety of chemical compounds and physical characteristics that pose potential risks to human health and the environment during their application, presence in the roadway environment, removal, and disposal. The environmental health and safety risks involved with pavement markings are caused by the marking product chemical composition; equipment used for handling, applying, and removing; and roadway operations associated with application and removal procedures.

This chapter identifies environmental health and safety consideration for handling, applying, removing, and disposing pavement markings. The chapter addresses the following topics:

- Pavement marking product composition, application, and removal techniques.
- Environmental health and safety considerations concerning pavement markings.
- Federal environmental and safety regulations pertaining to pavement markings.
- Life-cycle assessment (LCA)-based frameworks that can foster environmental health and safety considerations during product selection.
- Best management practices (BMPs) to address environmental health and safety considerations for pavement marking products.

Pavement marking application and removal techniques have been summarized based on field observations and personal experience of the authors. Material safety data sheets (MSDSs), product-specific factsheets, and/or vendor information provided with products were collected and screened as part of the composition evaluation to formulate a complete list of chemicals and chemical mixtures used in pavement marking products. Environmental health and safety considerations were evaluated based on existing research available in published literature and through the experience of the authors.

Federal environmental and occupational safety regulations pertaining to the pavement markings industry were reviewed to provide regulatory context within the chapter. The following Federal regulations are discussed:

- National Environmental Policy Act (NEPA).
- Toxic Substances Control Act (TSCA).
- Clean Air Act (CAA).
- Clean Water Act.
- Resource Conservation and Recovery Act (RCRA).

- Occupational Safety and Health Act.
- Federal Hazardous Materials Transportation Law.
- MUTCD.[3]

The provided discussion is meant to act as an overview of existing regulatory frameworks that pertain to the industry and not as a comprehensive overview. The process of using LCA to inform decisionmaking is described, and an outline for creating an LCA specific for pavement marking systems is given. In addition to an LCA approach for selecting products, BMPs aimed at reducing environmental health and safety considerations are discussed.

BMPs for reducing exposures during storage, handling, application, and removal of pavement marking products are discussed. Included within the BMP discussion are recommendations for standardizing MSDS reporting practices for pavement marking products and a need for technical specifications for the pavement markings industry. Development of technical specifications for the storage, handling, transfer, application, and removal of marking products will reduce worker exposures and minimize product loss/release to the environment.

PAVEMENT MARKING PRODUCT COMPOSITION, APPLICATION, AND REMOVAL TECHNIQUES

Pavement Marking Composition Overview

Pavement marking materials are either liquid or premanufactured materials that are applied to pavement surfaces to provide pavement markings as defined in "Part 3, Markings" of the MUTCD (23 Code of Federal Regulations (CFR) 655, Subpart F).[3] While the MUTCD calls for pavement markings, the diversity of pavement marking technologies currently in commerce causes difficulty when trying to determine marking products or application processes that offer the highest value in terms of durability and performance.[69,70] Often, the most important consideration in selecting a pavement marking is durability. *Durability* is defined as how long materials retain their daytime and nighttime visibility. In addition to durability, environmental health and safety issues are important considerations when selecting pavement markings.

The basic components of a pavement marking material are a binder and a reflective element. The binder provides the pavement marking physical presence (day and night) and its color. It also serves as a holder of reflective elements. The binder can be a liquid or a preformed solid that is glued to a surface or melted into a surface. The most important and most prevalent components of a binder are the pigment, resin, and filler. Pigment gives the material color, opacity, and body, as well as the ability to provide retroreflection. A pavement marking typically needs to be white or yellow. How well a pigment accomplishes this task and how it wears is important. However, some of the most effective and durable yellow pigments contain lead and other heavy metals that can create potential environmental and occupational safety issues. The filler is a cost effective measure that supplements the performance gained from the more expensive pigment. Resin is the glue that holds the marking together and gives it durability. For some paints, the resin also allows the markings to be applied in less-than-ideal weather or pavement conditions.

Reflective elements are necessary to improve pavement marking visibility at night. The reflective elements enable the pavement marking to reflect light from a vehicle head light back to the driver. This process is called retroreflection. Retroreflection returns the light back to the light source rather than bouncing the light off the reflective surface and away from the light source. The retroreflective elements are either dropped on a liquid-applied pavement marking (such as paint) or embedded in the material as it is made (such as preformed tape).

TRAFFIC PAINT

Traffic paints are water- or solvent-based paints that are typically sprayed as lines on the surface of pavement. Traffic paints are the oldest and most widely used pavement marking materials in existence. Paint is the most inexpensive of all pavement marking materials, although its cost has increased slightly as new formulations have been introduced and the market has narrowed. Paint is almost exclusively used for long-line applications. The traffic paint market has changed alongside the architectural paint market due to regulatory impacts caused by VOC limits and regulation regarding the use of lead-based pigments.

The primary components of traffic paint are finely ground pigments that are mixed into a resin or binder system. Additives provide additional desired properties. Pigments are mixed with water or solvent in order to apply the paints. Prime pigments within the paint introduce chemical properties such as ultraviolet (UV) stability or physical properties such as color and hiding (the ability of a paint to cover or block out the surface beneath it). Extender pigments or fillers are also commonly used to bring the pigment level up to the required point. Fillers help reduce cost and give the paint consistency, durability, permeability, and scrubability.

Paint pigments and retroreflective elements are held together and to the road surface by a resin. The most common resin in water-based traffic paints are synthetic polymer acrylic-based resins (often referred to as latex paints). Latex paint systems are utilized for their ability to dry quickly following application, which is known as “fast dry.” Fast dry is an important characteristic for traffic paint because it allows the traffic paint to be placed on the road with minimal traffic disruption, paint splashing or tracking caused by vehicles, and water washout risk. Paint with a fast drying resin will dry within 1.5 h under a relative humidity of 90 percent; whereas normal resin does not dry under such conditions.

In waterborne paint, water is primarily a diluting agent. It holds the resin emulsion in solution with the other components until the paint has been applied. The drying time may be reduced by adding ammonia or methanol to the paint. Methanol is also an antifreeze and can be added to protect the paint from freezing in its container and storage tanks.

Traffic paint is most commonly applied with a paint spray gun. A conventional spray gun uses air jets in the tip of the paint gun and operates at pressures from 60 to 140 lbf/inch^2. Air spray application is commonly called air atomizing. Airless sprayers force the paint through an orifice into the tip of the spray gun at very high pressure (1,500–3,000 lbf/inch^2). Airless spraying has become the most common method of applying traffic paint. It has proven to be faster and less troublesome than air atomize spraying, hence its popularity. However, the high pressures associated with airless spraying present additional occupational safety risks. Figure 33 depicts paint application with a truck sprayer.

Figure 33. Photo. Applying paint with a truck sprayer.

THERMOPLASTIC PAVEMENT MARKINGS

Thermoplastic pavement marking uses a block and granular material and melts it so that it can be sprayed, gravity extruded, or pressure extruded (often called ribbon extruded) onto pavement as a line. Thermoplastic is a blend of solid ingredients that become liquid when heated and melted. Reflective elements are mixed into the material by the manufacturer and can be applied to the surface following application. Thermoplastic systems become homogenized when heated and agitated. Thermoplastic adheres to hot mix asphalt concrete (HMAC) by forming a thermal bond. When thermoplastic markings are used on PCC, the PCC must first be treated with a liquid-applied primer where the thermoplastic is to be applied. The elements of thermoplastic paints include pigments, reflective elements, fillers, binders, additives, and primer.

Pigment within thermoplastic paints provides color and chemical properties such as UV stability and hiding. Pigments are heat stable, as thermoplastic is often heated to temperatures in excess of 420 °F. Heating does not present a problem for white pigment like titanium dioxide, but it has proven difficult for yellow organic pigments. Yellow pigments containing lead chromate are very effective with respect to heat stability, UV durability, and color. However, organic yellow pigments are less effective than lead chromate yellow pigments in thermoplastic markings. Fillers, such as calcium carbonate, are added to the thermoplastic paints to provide additional volume, improving durability without the higher cost of the additional pigments.

Thermoplastic markings use either hydrocarbon-based polymers or plant- and vegetable-based alkyd (a modified polyester) as a binder. Thermoplastic is usually named for the type of resin used. The hydrocarbon thermoplastics are typically used for long lines along roadways, and alkyd thermoplastics are most often used for short lines (crosswalks, stop lines, legends, and symbols). In order to enhance product application, plasticizers are also added.

Three common methods for applying thermoplastic traffic markings are a spray gun, an extrusion shoe, and a ribbon gun. The spray gun operates much like a traffic paint spray gun. The extrusion process forces the thermoplastic material through a die or shoe riding on the pavement surface. With the ribbon gun, the thermoplastic material is forced through the system, into the gun, and onto the pavement.

Profiled Thermoplastic

Another variation of thermoplastic pavement markings is called profile thermoplastic, which offers improved durability and better visibility in wet pavement conditions. Profiled thermoplastic pavement markings can also be used as a longitudinal rumble strip. Profiled thermoplastic markings are a variation of normal extruded thermoplastic line markings created by providing a bump or an inversion to give the line a "profile" during application.

The profile, if configured at a height of around 0.5 inches, can result in a rumble effect if vehicle wheels come into contact with the line. Profile thermoplastic is often called rumble line. The line, in effect, also becomes a longitudinal rumble strip. Longitudinal rumble strips are used to provide a run-off-the-road crash reduction technique that is in wide use on rural highways in the United States.

The two most common types of profiled thermoplastics are inverted profile markings and raised profile markings. Inverted profile markings are created by rolling a patented rack and pinion wheel over wet (or cooling) thermoplastic. Profiling gives the line a corrugated appearance. Raised profile markings are created by extruding a thermoplastic marking of normal thickness with a raised thermoplastic "bump" at a uniform spacing.

Melt-In-Place Preformed Thermoplastic Tape

Melt-in-place preformed thermoplastic tape is a preassembled thermoplastic laminate, which is placed on the pavement surface and then melted into the surface via a heat source such as a propane torch. Preformed thermoplastic markings are manufactured in shapes ready to use on pavement and are typically used for symbols at intersections or other pavement identification uses. Preformed tapes do not have any preapplied adhesive, and bonding to the pavement is achieved thermally. There are two basic types of preformed thermoplastic markings: one does not require preheating the road surface, while the other does require preheating the road surface prior to application. The materials used in preformed thermoplastic traffic markings are the same as regular thermoplastic, except they have already been combined into a preformed tape that does not require application equipment. Preformed thermoplastic markings are typically shipped with some reflective elements within the laminate material. Additional reflective elements are normally added to the surface of the material during application.

Application of thermoplastic traffic markings requires that the marking be heated once it is placed on the pavement. Applying the marking to HMAC requires heat only. Applying preformed thermoplastic to PCC requires the use of a primer as well as heat on the PCC. Figure 34 shows a thermoplastic application.

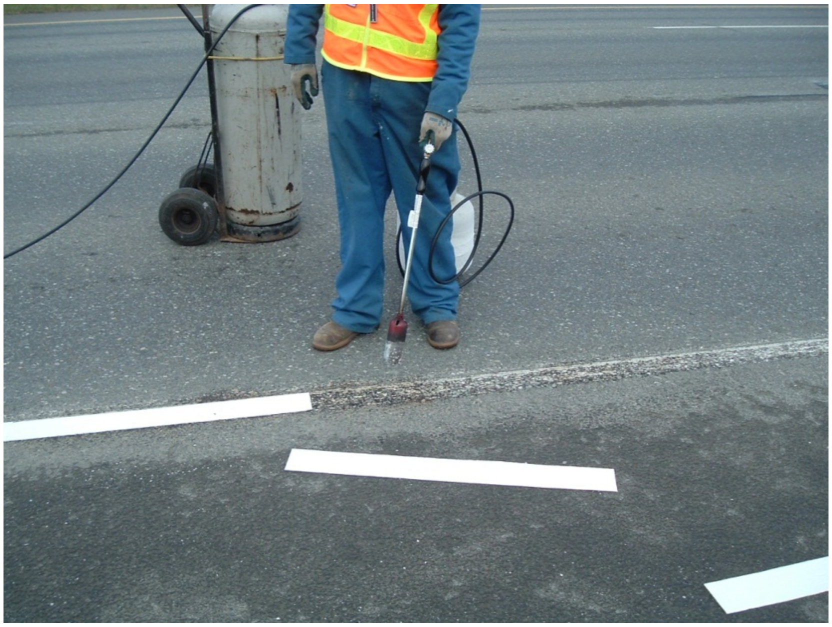


Figure 34. Photo. Applying preformed thermoplastic.

TWO-COMPONENT PAVEMENT MARKINGS

Two-component pavement markings are pavement marking systems that form a solid when mixed together and sprayed or extruded onto the pavement. The most common examples of two-component pavement marking systems are thermosets (i.e., epoxy, polyester, and modified epoxy), polyurea, and MMA.

Epoxy Paints

Epoxy paints are used as pavement marking materials to increase durability. As a two-component material consisting of a pigmented resin base and a hardener, epoxy paints are cured by an exothermic thermoset chemical reaction. Reflective elements are easily added during application. Epoxy paint pavement markings use pigments to impart color to the marking. The pigments are ground and mixed into the resin material. Color stability under UV exposure is often difficult to achieve with epoxy markings. Because of this characteristic, the pigment loading has to be much higher than with most other types of pavement marking technologies. The high pigment loading increases the cost of epoxy markings in comparison to other markings. The amount of yellow pigment used in epoxy is also often three to four times more than yellow traffic paint or yellow thermoplastic, which is a concern if lead-based yellow pigments are incorporated into the marking.

The hardener is mixed with the epoxy resin in a mixing tube or an impingement chamber. It is then sprayed to form a durable pavement marking. Proper mixing of the two components requires adherence to product-specified volume and temperature requirements. Mixing the two components can be complex and expensive in terms of equipment and materials. Reflective elements are incorporated into the epoxy marking by spraying the elements onto the epoxy as the epoxy is being sprayed onto the roadway. The element application spray gun is located behind the epoxy spray gun on the striping truck. During application, the two components (resin and catalyst) are mixed together prior to installation. The material is then sprayed, with the reflective elements, onto the roadway. A limitation to epoxy paint is that epoxy should not be applied to a wet surface.

Polyurea

Polyurea markings are two-component durable pavement marking materials that are sprayed. Polyurea materials are marketed as fast-curing systems. Some polyurea materials must be applied by a special striping apparatus, while others can be applied by a standard epoxy truck.

Modified Epoxy or Urethane

Modified urethane is a two-component durable marking material with similar performance characteristics to those of polyurea and epoxy. The product is marketed as being slightly more durable than epoxy but with quicker cure times and better UV color stability. Modified epoxy and urethane can be sprayed from any standard epoxy truck.

MMA

MMA is a two-component durable pavement marking material. It is manufactured in two basic mix configurations: (1) an impingement process (forced together by pressure in a mixing tube or chamber) or (2) a static mixer immediately prior to application. MMA can be sprayed or extruded onto pavement. The material forms a strong bond to the pavement surface by an exothermic reaction (release of heat) that occurs during the mixing process and is finished once applied. MMA was originally marketed primarily as an environmentally friendly alternative to solvent-borne paints in areas where lower temperatures are an issue (i.e., Alaska or northern States in the continental United States). However, MMA has been shown to provide a much longer service life than standard traffic paint and is now considered to be as durable as thermoplastics and tapes.

MMA pavement markings are designed to be resistant to oils, antifreeze, and other common chemicals found on roadway surfaces. MMA reportedly bonds well to concrete pavements, and it requires special equipment for application. Figure 35 shows structured MMA application with a hand striper.

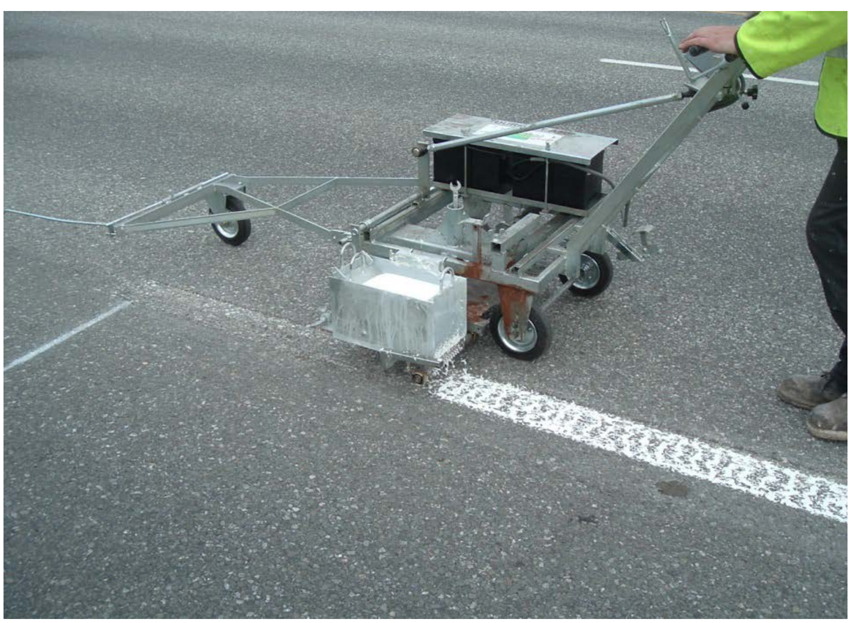


Figure 35. Photo. Applying structured MMA.

COLD-APPLIED PREFORMED TAPE

Cold-applied preformed tape is a preassembled laminate that has a pressure-sensitive adhesive. The tape is rolled out and glued to the pavement surface. Some tapes are flat, while others have structure that enhances the durability and wet pavement performance of the tape's retroreflection. Preformed tapes consist of pigments, resins, liquid primer or contact cement, and reflective materials and can be provided with or without adhesive. Preformed tapes are delivered in rolls and are designed for lane lines, legends, symbols, and transverse markings.

There are three types of preformed tape markings: permanent, temporary removable, and temporary non-removable. Permanent pavement marking tapes can be either flat or patterned and may require the use of a primer or sealer as part of the installation (based on vendor instructions). Permanent tapes are generally used for longitudinal edge lines, skip lines, stop lines, crosswalks, legends, and symbols. Two of the most common types of plastics binders used for permanent tapes are urethane and pliant polymer. Temporary tapes are typically used for construction or other short-term traffic management situations.

Pigments used in preformed tape pavement markings impart color to the marking and are ground and mixed into the resin tape during fabrication. The tape is held together with prereacted resins that hold the reflective elements and pigments in place. Some tapes provide an adhesive backing on the bottom side of the resin for adhesion to the roadway surface. Others require that a primer or additional adhesive be applied in the field. Because preformed tapes are manufactured with reflective elements built into the tape, no additional reflective elements are added in the field.

Tape is applied directly on the surface and bonded with an adhesive. Pressure-sensitive adhesives work best when overlaying permanent tapes on new asphalt pavement surfaces. Contact cement or primer is often used when installing the tape on concrete or over older markings. Markings are initially bonded with a light hand roller or vehicle tire and permanently bonded by traffic wear. Figure 36 shows an installed preformed pavement marking tape.

Figure 36. Photo. Marking tape in recessed pavement groove.

REFLECTIVE ELEMENTS

Glass Beads

Glass beads are the most commonly utilized reflective elements used in pavement markings. Glass beads are used to provide improved visibility of traffic markings at night. Beads are embedded into the traffic marking material and reflect light from a vehicle's headlights back to the driver. Spherical reflective beads are retroreflective when embedded in a traffic paint material to a depth of approximately 50–60 percent of their diameter. When light strikes a bead, it is refracted and reflected. The refractive index (R.I.) represents how much a bead bends the light. The bedding for the bead (paint, thermoplastic, etc.) acts as a mirror and allows the light to be reflected. Therefore, the depth of embedment in the marking material has a significant effect on the retroreflective properties of the bead.

Beads used for pavement markings are typically made with an R.I. of 1.50, 1.65, or 1.90. The amount of embedment in the marking material depends on the size of the glass bead, the thickness of the dry marking material, and the application process. Some pavement marking manufacturers use two sets of beads, each with a different R.I. One bead is designed for dry retroreflectivity and the other for retroreflectivity in wet weather. Water on a marking material will change the R.I. of the bead. Therefore, using one bead with an R.I. for dry weather and another with an R.I. for wet weather can result in a marking material that maintains its retroreflective performance in both wet and dry conditions.

Glass beads used as reflective elements in pavement marking systems are commonly grouped into three types following AASHTO M247 and FHWA's *Standard Specification for Construction of Roads and Bridges on Federal Highway Projects* (FP-03 Section 718-19).[33,71] Type 1 beads are the smallest and are used only as intermix beads for thermoplastic. Type 2 beads are commonly referred to as standard beads because they have historically been the typical drop-on beads used by transportation departments. Type 3 beads (and higher) are drop-on beads of a larger gradation. They are relatively new to the market and are marketed for their ability to provide wet-nighttime visibility under certain conditions. Type 2 beads (and higher) are sometimes coated with a moisture-proof adhesion or floatation coating to help them properly embed in the marking material and avoid clumping together. Type 1 beads are typically not coated when used in an intermix thermoplastic application.

During bead application, it is essential to control the amount and dispersion of beads reaching the marking material and the depth of embedment in the marking. The bead amount, dispersion, and embedment are affected by the bead drop rate, speed of the striping truck, temperature, and viscosity of the binder material. Figure 37 shows a bead gun with a bead shroud dropping beads on ribbon-extruded thermoplastic pavement markings. Figure 38 shows a two-component pavement marking material with a double drop of glass beads applied with standard flare nozzle guns.

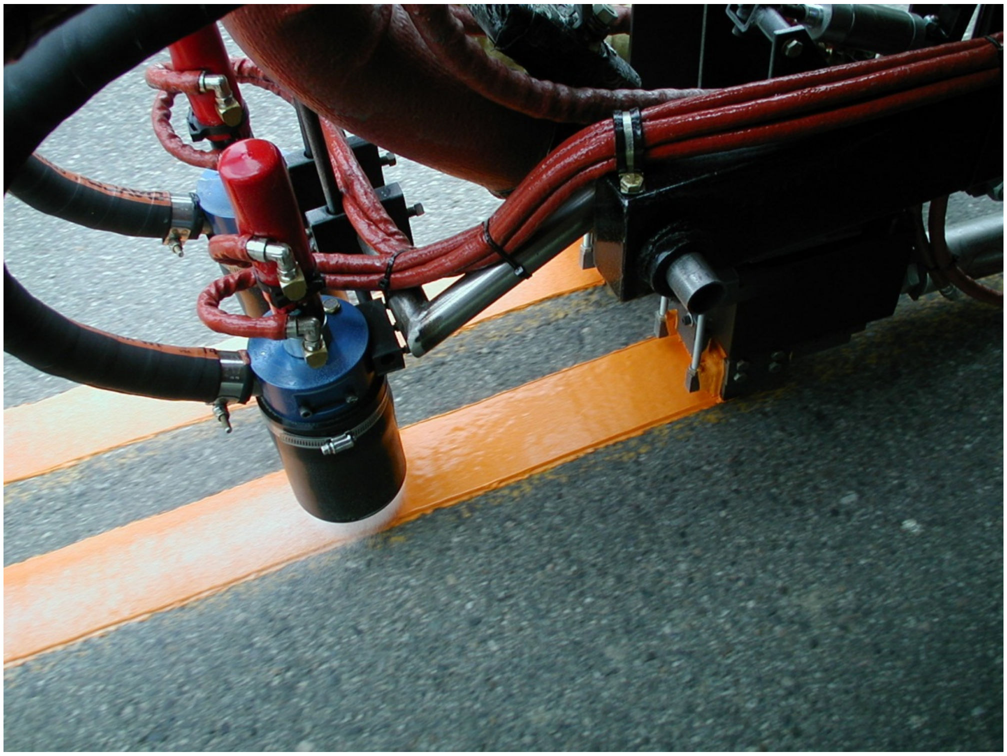


Figure 37. Photo. Glass beads applied with bead gun on thermoplastic.

Figure 38. Photo. Double bead drop with flare nozzle guns on a liquid material.

A typical glass bead application requires significant excess bead applications in order to create the correct bead density in the pavement marking. Bead drop rates usually range from 6 to 12 lb per 100 ft^2 for thermoplastics and are often higher for paints and epoxies. Figure 39 shows “clouds” of excess beads created during a bead drop application. Most of the pavement marking glass beads that run off the roadway are associated with application process overspray and excess beads that do not embed in the marking material.

Figure 39. Photo. Glass bead application on a highway on the Tennessee test deck.

The chemical and physical properties of glass beads are controlled during the manufacturing process. The most important properties for beads used in pavement markings include bead size, R.I., clarity, and roundness. Factors that affect these properties include the type, quality, and clarity of the virgin or recycled glass used to create the bead; furnace type and temperature; and sieve size. The size of a glass bead affects retroreflective performance, especially under wet conditions, but has no effect on R.I. Instead, the large beads have better performance under wet conditions because their higher profile can protrude through a thin film of water better than small beads. If the layer of water becomes thick enough, large beads will also be ineffective.

Glass bead retroreflective performance is also related to the materials used to manufacture the glass. The primary compound for manufacturing glass is silica, but other substances are often added to simplify the manufacturing process and improve the qualities of the produced glass (including carbonates, oxides, industrial by-products, and recycled glass). While beneficial reuse of recycled or by-product materials can save raw materials and energy, the added components may also introduce impurities into the product. Figure 40 shows glass beads embedded in an MMA pavement marking.

Figure 40. Photo. Glass beads in MMA.

Proprietary Reflective Elements and Bead Clusters

While glass beads dominate the market for reflective elements in pavement markings, several companies have developed alternatives to glass beads. One company has developed a microcrystalline ceramic bead that serves as a reflective element. Others have developed “bead clusters.” Alternatives will likely continue to penetrate the reflective element market in the near future.

PAVEMENT MARKING REMOVAL (ERADICATION)

The most common methods of pavement marking eradication (or removal) include blasting (hydro, sand, or shot), grinding, and masking (using paint, black tape, slurry, or a surface treatment that covers or encapsulates the marking). These eradication techniques can be used individually or in combination. The technique used to remove pavement markings is chosen based on the type of marking to be removed, the pavement surface type, the location of the marking to be removed (as it pertains to the needed path of travel for traffic), and past experiences with eradication techniques.

Removing pavement markings presents unique challenges based on each marking pavement surface scenario. For instance, abrasive blasting or high-speed grinding does not work well on thermoplastic markings on most surfaces because heat produced from the blasting or grinding will sometimes melt the thermoplastic rather than remove it. Grinding is not a particularly good choice for PCC because it removes the texturing of the pavement surface and can lead to major pavement scarring. Preformed marking tape removal is also a challenge when using blasting or grinding, as the tape can break up into small flakes that contain enough adhesive to adhere to the removal equipment or the pavement. Hydro-jetting or hydro-blasting, if used, results in slick pavements in the wintertime, and application of heat can make HMAC slick. When masking is used, the process can sometimes scar the pavement in a fashion that appears to be a traffic marking under certain viewing conditions.

Waste production during eradication techniques also presents a challenge. A significant amount of waste material can be produced when removing markings. Solid debris must be collected from the roadway surface and properly disposed when removing thicker applications of thermoplastic and MMAs. Chemical concerns from stripping agents and some marking products themselves may also be realized when the markings are removed. Marking eradication can also result in significant dust generation, which can impact roadway visibility and can be an occupational safety concern.

While no individual eradication method is free from challenges, the need for pavement marking eradication will continue. Additional research into pavement marking eradication based on pavement marking chemistry or manufactured degradability over time is warranted. New eradication techniques also offer opportunities within the current market.

ENVIRONMENTAL HEALTH AND SAFETY CONSIDERATIONS CONCERNING PAVEMENT MARKINGS

Environmental health and safety considerations during the application, use, and removal of pavement markings include reducing occupational exposure to the chemical components of the pavement markings and to fugitive emissions of vapors and particulate matter (PM) generated during application and removal of the products. Methods to reduce occupational exposures to the marking products should be taken into account when developing a health and safety program and can easily be accommodated in existing programs that aim to reduce occupational exposures to traffic, which remains a greater acute risk to workers than the products themselves. However, enough evidence exists to support putting into place protective measures that will reduce long-term chronic exposures to marking products.

Occupational exposure to pavement marking chemicals or emissions can occur during the storage, handling, and application of markings; during cleanup of the application devices; and from waste produced throughout the process. Exposures will increase in the event of spilled materials, emergency situations caused by equipment failures or traffic crashes, or poor personal protective equipment (PPE) use.

Potential environmental health and safety concerns include chronic exposures to several chemicals present in pavement marking systems as declared on MSDSs provided by vendors along with the pavement marking products used during the Tennessee and Alaska field demonstration projects. Table 60 presents a summary of chemicals within pavement marking products acquired for the field demonstration project. Appendix E includes a full list of products reviewed.

Table 60. Representative list of chemicals in pavement marking products used in Tennessee and Alaska field demonstration projects based on MSDS review.

Chemicals from MSDS Information	Hazardous	Hazard Listing and Applicable Regulation
Acetone	Yes	F-003, 40 CFR 261.31; U-002, 40 CFR 261.33
Acrylated urethane	No	Not hazardous
Alkyl glycidyl ether	No	Not hazardous
Barium sulfate	No	Not hazardous
Bisphenol-A-(epichlorhydrin) epoxy resin	No	Not hazardous
Dibenzoyl peroxide	No	Not hazardous
Dicyclohexyl phthalate	No	Not hazardous
Diethylenetriamine	No	Not hazardous
Diglycidyl ether of bisphenol	No	Not hazardous
1,6-diisocyanatohexane homopolymer	No	Not hazardous
Butyl methacrylate	No	Not hazardous
Hexamethylene diisocyanate	No	Not hazardous
2-ethylhexylacrylate	No	Not hazardous
Limestone	No	Not hazardous
Methanol	Yes	F-003, 40 CFR 261.31; U-154, 40 CFR 261.33
MMA	Yes	U-162, 40 CFR 261.33
4-nonylphenol	No	Not hazardous
Modified polyamine	No	Not hazardous
Polyurethane	No	Not hazardous
Silica (quartz/crystalline)	No	Not hazardous
Titanium dioxide	No	Not hazardous
2,2,4-trimethylpentane-1,3-diol monoisobutyrate	No	Not hazardous
Trimethylolpropane triacrylate	No	Not hazardous
Urethane acrylate	No	Not hazardous
Xylene	Yes	F-003, 40 CFR 261.31; U-239, 40 CFR 261.33

The primary concerns revealed through the evaluation of the MSDS include dermal and inhalation exposures of solvents (including acetone, methanol, and xylene), bisphenol-A, nonylphenol, phthalates, and MMA. Long-term exposures to solvents at low to moderate exposure levels is known to cause eye, skin, and respiratory system irritation, headaches, dizziness, and nausea. Long-term exposure to endocrine-disrupting compounds, including bisphenol-A, nonylphenol, and phthalates, is documented for environmental endpoints, but it is less understood for humans. Exposure to MMA causes similar symptoms to exposure to solvents, with additional concerns for impact on the nervous system of an exposed individual. While there is potential risk associated with the materials used in product formulations, the actual level of risk is not characterized.

Additional environmental health and safety concerns have recently been raised due to the heavy metals content in recycled glass beads used as reflective elements. Two existing studies highlight the loss of heavy metals, including arsenic, lead, and antimony, from the surface of the beads under laboratory conditions. The reported concentrations of total arsenic and lead in the beads are significantly high enough to raise concern. The two primary studies concerning the presence of heavy metals in recycled glass beads include the New Jersey Department of Transportation (NJDOT)-funded New Jersey Institute of Technology/Rowan University (NJIT/RU) heavy metals leaching study and the American Glass Bead Manufacturing Association (AGMBA)-funded TTI/ Texas A&M University glass beads leaching study.[(72,73)] Both the NJDOT and TTI studies observed elevated arsenic concentrations in the glass beads and in leaching solutions mixed with the beads. A summary of both studies is included in this section, along with a summary of a subsequent study performed at FHWA that aimed to contextualize the NJDOT study. An overview of additional research being carried out on this topic at TTI with Texas A&M University, Scientific Applications International Corporation (SAIC), Chalmers Engineering, and the Environmental Protection Agency (EPA) aiming to assess the risk of the metals within the glass beads is also provided.

NJDOT GLASS BEAD STUDY OVERVIEW

Research sponsored by NJDOT and FHWA was conducted by NJIT/RU to study the environmental implications of using glass beads containing elevated concentrations of metals and metalloids on roadways. The study reviewed applicable literature, evaluated laboratory analytical procedures for measuring metals in the glass beads, and reported on leaching of metals from glass beads. The NJDOT study identified the following summarized technical objectives as the basis for the research:

- Review specifications for glass beads used in pavement markings for all U.S. States.
- Prepare a list of State standards with given levels of acceptable metals content.
- Evaluate analytical techniques to measure metals in glass beads.
- Evaluate metals content in glass beads with high metals content.
- Perform batch experiments to determine metal leaching due to factors including solution salinity and pH, along with contact duration.

The report introduced AASHTO standard M247-09, *Standard Specification for Glass Beads Used in Pavement Markings,* and the State-adopted standards in accordance with the first two objectives of the study.[72,33] The report continued with an extended review of the glass bead manufacturing process and metals leaching for reference.

The report evaluated two procedures for measuring metal concentrations in glass beads. It compared the total metal concentrations in the beads measured using findings between bead digestion with hydrofluoric acid followed by measurement with inductively coupled plasma mass spectroscopy versus measurement with a field-portable x ray fluorescence (FP-XRF) detector. The authors determined that the total metals concentrations using both methods were comparable and promoted using FP-XRF because of the method's rapid use and lower safety risk. Results of the bulk bead metal analysis showed a wide range of metal concentrations in the beads tested, ranging from 0.07 parts per million (ppm) for beryllium to 1,120 ppm for barium. Antimony, lead, and arsenic concentrations ranged from 54–192, 19–204, and 92–823 ppm, respectively.

The report also highlights findings from three individual leaching procedures applied to the beads. The procedures included the fractional factorial method, the toxicity characteristic leaching procedure (TCLP), and the synthetic precipitation leaching procedure (SPLP). For the factorial study, the researchers investigated factors affecting leaching, including pH, chemical (salt) application, ionic strength, and time. The tests simulated the type and amount of salt typically used on roadways. The factorial study also simulated weathering and wear and tear of roads by grinding the beads to smaller sizes. TCLP was used to determine whether the beads would be classified as hazardous waste under Federal regulations. SPLP was used to assess the risk of groundwater contamination posed by land application of solid wastes. SPLP extracts were interpreted to represent the leachate potential leaving the applied material and were gauged against criteria for assessing risk to groundwater.

The results of the leaching studies show that 2 to 3 percent of total metal within the glass beads leaches from the beads into the leaching solutions over 160 days. Concentrations within the leaching solutions ranged from non-detectable (nd) to 6,200 micrograms per liter (µg/L) for arsenic, nd to 520 µg/L for lead, and nd to 130 µg/L for antimony (note: 1 g = 0.0353 oz and 1 L = 0.908 quarts). The factorial study results show an effect of pH, ionic strength, and particle size on metals content observed in leaching solutions. Comparison of the leaching procedures revealed that two orders of magnitude lower metals leaching occurs with the 18 h TCLP and SPLP tests than with the 160-day factorial leaching studies.

The study postulates that glass beads may leach metals under field conditions even though significant amounts of metals were not detected in leaching solutions when TCLP or SPLP methods were used. The study also reports that metals concentrations within evaluated batches were very variable. Variability may partly explain why the study did not find a correlation between initial metals concentrations and concentration of the same metals in leaching solutions. Finally, leaching results were compared to the New Jersey groundwater quality standards. Based on statistical analysis and extrapolation of the data, recommended levels of metals within the beads that would result in a leachate metals concentration below the groundwater quality standards were provided.

TTI HEAVY METALS IN GLASS BEADS STUDY

Concerned over the presence of heavy metals in recycled glass bead pavement marking products, AGBMA sponsored research at TTI to determine the composition and leaching potential of heavy metals in recycled glass beads. The TTI study evaluated the presence of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), and lead (Pb) in three separate batches of type I AASHTO M247 beads and leachate from column studies conducted under laboratory conditions.[33]

The bead total metals content was determined by digesting the beads using Pacific Northwest Laboratory's KOH fusion method and analyzing the resulting solutions for metals according to EPA Method 6020A.[74] Mean ± standard deviation metals contents for the provided samples are shown in table 61 and illustrated in figure 41.

Table 61. Mean ± standard deviation metals contents measured in glass beads ($\mu g_{metal}/g_{bead}$).

Bead	As	Cd	Cr	Cu	Pb	Ni	∑Metals
Batch 1	83.3 ±1.42	5.92	35.8 ±1.32	8.88 †	21.7	31.1 ±5.85	186 ±3.56
Batch 2	308 ±23.6	nd	nd	nd	77.4 ±27.7	76.4 ±4.17	462 ±18.3
Batch 3	393 ±6.53	nd	23.7	nd	81.0 ±7.98	nd	497 ±7.29

† = Not all replicates were detectable.

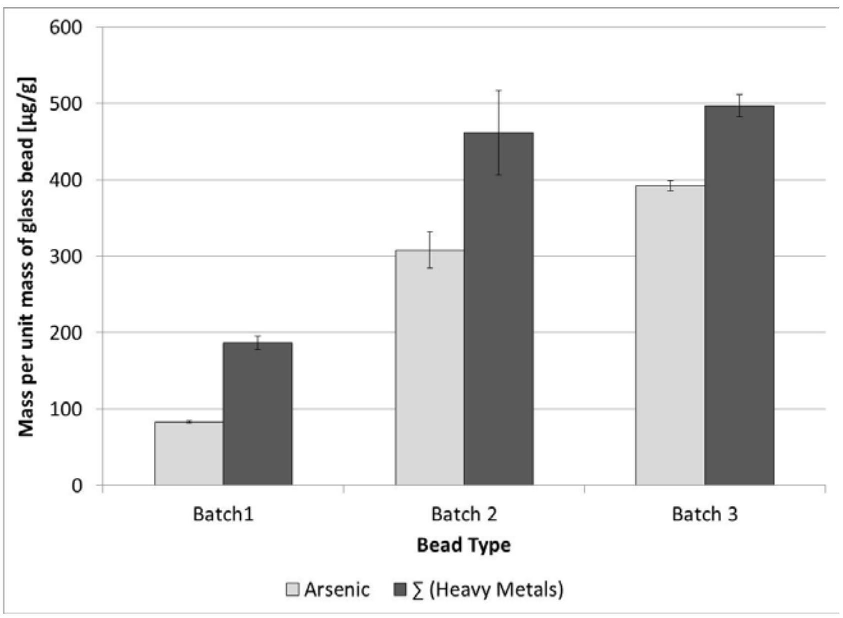


Figure 41. Graph. Mean ± standard deviation arsenic and total metals contents for the samples provided by AGBMA.

Arsenic content in the beads accounted for 45 percent of the total measured metals content of batch 1 beads up to 79 percent of the total measured metals content of batch 3 beads. The lowest measured arsenic content (83 µg/g in batch 1 beads) was higher than the metals content of any other metal analyte in all the measured samples. Only nickel in batch 2 and lead in batches 2 and 3 had contents above 50 µg/g. All other metal contents observed for the other analyses were below this level.

Following the composition study, a column leaching system was used to investigate the effect of column eluent solution pH, UV light exposure, temperature exposure, and abrasion on metal release from the beads. The experimental factors and the examined values used in the leaching study are presented in table 62. A complete summary of the experimental study design is available in the TTI project report.[73]

Table 62. Experimental design for the column leaching experiments.

Experimental Factor	pH	UV Exposure (h)	Temperature (°F)	Particle Size (μm)
Evaluated levels	4	12	70 (ambient)	< 149
	7	24	100	149–250
	10	48	150	> 250
Bead batch evaluated	1,2,3	1 and 3	1 and 3	1 and 3

1 μm = 0.039 mil.

Results of one-way ANOVA and Tukey's multiple comparison testing indicate that solution pH and abrasion affect the mean amount of arsenic and total metals leached into solution. However, no effect on the mean amount of arsenic or total metal leached was observed due to temperature or UV exposure. The overall amount of total metal released during the 48-h column studies under each experimental condition evaluated was less than 0.2 percent of the total metal content of the beads. However, arsenic concentrations in the column effluent samples were ≥ 100 μg/L for batch 1 and ≥ 3,500 μg/L for batches 2 and 3 during the first hour of collection. After 1 h, observed metal concentrations in the column effluent decreased rapidly. The amount of leaching observed was also greater for smaller particle size fraction samples. Therefore, the fast initial metals release coupled to the finding that smaller particle size fraction releases more metal into solution indicates that leaching is occurred from the surface layer of the bead and not the bead's interior in the experimental setup used in this work.

The TTI study established the presence of heavy metals in recycled glass beads used in pavement marking systems and their potential for leaching. Based on the observed metals content in the beads and in the leaching solutions, additional research was advised. The study recommended that special attention be focused on arsenic due to the magnitude of arsenic content observed in the beads and the high arsenic concentrations observed in the resulting leaching solutions.

FHWA STUDY

The FHWA study established correction factors for heavy metal leaching from glass beads in order to apply laboratory leaching study results to roadside environments. Specifically, the FHWA study was formulated to put the recommendations of the NJDOT laboratory leaching study into a broader context. The study examined the overall size distribution of glass particles in roadside soils and the overall mean percentage of glass as a constituent of the soil.

FHWA obtained roadside soil samples from nine highways, three each in Iowa, Texas, and Virginia. The sampling sites were located adjacent to two-lane two-way highways with edge lines and centerlines marked on an annual basis with paint and glass beads. Three non-overlapping sampling sites 164 to 328 ft long that extended 1.64 to 6.56 ft from the edge of the paved area were established for each highway. Samples of 3.5 oz were collected from 30 10.764-ft^2 sampling spots randomly selected from each sampling site. Soil was collected from the top 5.91-inch soil layer and particles greater than 1.57 inches were discarded. The 30 samples collected from each sampling site were mixed together, air dried, sieved through a 0.19-inch sieve, and homogenized in 1.75-oz subsamples using a sample splitter. The glass particles were separated from the homogenized samples and weighed to determine the overall mean percentage of glass as a constituent of the soil. The particle size distribution of the glass beads in the homogenized samples was determined using a series of sieves. The correction factor was calculated based on the overall distribution of glass particle size in roadside soils and the overall mean percentage of glass as a constituent of the soil.

Based on the results of the roadside evaluations in Texas, FHWA proposed a correction factor of 0.002. Multiplying the NJDOT leaching study results by the FHWA correction factor resulted in an arsenic leachate concentration that was more than 20 times below the allowable criterion (in this case, the criteria for ground water). The leachate lead concentration was lower than the allowable criterion for lead in groundwater before applying the correction factor. The FHWA study also recommended that leaching procedures be conducted on roadside soil and not on individual components of the soil (in this case the glass beads) as glass beads comprise less than 0.3 percent of roadside soil.

FHWA EPA STUDY

In response to an FHWA request, TTI proposed a study aimed at supporting decisionmaking concerned with regulating the presence of heavy metals (specifically arsenic and lead) in recycled glass beads used in pavement marking systems. The study is funded by FHWA but has oversight and input from EPA. The study is now being carried out at TTI and Texas A&M University with support from EPA, SAIC, and Chalmers Engineering Services Company. The first objective of the study was to develop a conceptual risk assessment model identifying exposure scenarios likely to occur under occupational and residential conditions. A parameters list formulated from existing exposure assessment models will be refined through field observations related to bead storage, handling, and application procedures on the roadway environment in order to develop a conceptual model. A screening level risk assessment based on the conceptual model of exposure, available literature data, and some base assumptions will be performed utilizing SAIC software and databases.

The second objective of the study examines the relationships between total, extractable, and bioavailable metals content in samples of glass beads. Fifteen batches of AASHTO M247 type I glass beads were under evaluation.[(33)] Heavy metals in the glass beads were extracted using three separate and independent methods. The total metals fraction in the beads was extracted according to the Pacific Northwest Laboratory’s KOH fusion method. The extractable fraction was extracted according to EPA Method 3050B.[(75)] The bioavailable fraction was extracted with a solution of 0.4 M glycene adjusted to pH 1.5 with hydrochloric acid. The extracts will be analyzed for arsenic and lead following EPA Method 6020A.[(74)] The results will be compared using corollary statistics (e.g., Pearson’s product-moment correlation coefficient) and inferential statistics (e.g., ANOVA followed by multiple comparison testing) to evaluate the likelihood of predicting the bioavailable content in glass beads through analysis of total or extractable metals.

The final objective of the study was to investigate whether the retroreflectivity of the beads was correlated to the metal content of the bead. TTI created pavement marking draw-downs (18-inch pavement marking samples created in the lab under controlled conditions) for the evaluation. The draw-downs are identical except for the beads used. The beads were the same 15 batches of type I beads used to accomplish the second objective as previously described. Three replicate draw-downs were produced. The retroreflective performance of the draw-downs were measured at the standard 98-ft geometry.

The combined results of the three objectives will inform the decisionmaking process regarding maximum allowable concentration of heavy metal in recycled glass beads intended for use in pavement marking systems.

HEAVY EQUIPMENT AND TRAFFIC HAZARDS

While considerations should be taken into account for reducing handling and exposure to pavement marking products, it is important to note that the environment for workers involved in pavement marking poses significant hazards. In addition to possible chemical exposure, installation and removal of pavement markings requires the use of heavy equipment and heating devices.

Equipment used can include the following:

- Large striping trucks.
- Manually operated striking carts.
- Heated thermoplastic applicator.
- Heating elements to apply thermoplastic markings.
- High-pressure spray applicators.
- High-pressure water-blasting equipment.
- Sand or soda shot-blasting equipment.
- Milling or grinding equipment.

Traffic hazards also pose a significant hazard when working with traffic markings. By nature, traffic markings are used on traveled roadways. Work zone hazards on roadways are well documented. Even with lane closures and speed limit reductions, workers are often close to high-speed traffic when installing or removing traffic markings. Heavy equipment and traffic hazards are as much of a concern to worker safety as is chemical exposure.

FEDERAL ENVIRONMENTAL AND SAFETY REGULATIONS PERTAINING TO PAVEMENT MARKINGS

Due to potential health and safety considerations posed by the storage, handling, and use of pavement marking products, a review of existing Federal and State environmental laws and regulations is included in this chapter. The information is not meant to be an comprehensive review of all Federal acts, regulations, or policies that may pertain to glass beads. Rather, it is meant to provide background material to put potential proposed regulations into context. This section reviews primary environmental acts as they pertain to pavement markings, including NEPA, TSCA, RCRA, CAA, the Clean Water Act. This section also provides information concerning the Occupational Safety and Health Act and the Federal Hazardous Materials Transportation Law.

NEPA

NEPA became a law in 1970. Among its provisions is the requirement for environmental reviews of all major Federal actions and decisions. Regulation 23 CFR 771, *Environmental Impact and Related Procedures*, addresses FHWA actions under NEPA.(76) Section 23 CFR 771.101, "Purpose," states the following:(76)

> "This regulation prescribes the policies and procedures of the FHWA and the Federal Transit Administration (FTA) for implementing the National Environmental Policy Act of 1969 as amended (NEPA), and supplements the NEPA regulation of the Council on Environmental Quality (CEQ), 40 CFR parts 1500 through 1508 (CEQ regulation). Together these regulations set forth all FHWA, FTA, and DOT requirements under NEPA for the processing of highway and public transportation projects."

Section 23 CFR 771.117 sets forth the FHWA categorical exclusions under NEPA, and pavement marking projects are typically given an exclusion from environmental review. Subsection 23 CFR 771.117 (c)(8) provides a categorical exclusion for the "Installation of fencing, signs, pavement markings, small passenger shelters, traffic signals, and railroad warning devices where no substantial land acquisition or traffic disruption will occur."(76) In most circumstances, pavement markings would not trigger an environmental assessment under NEPA. However, the applicability of NEPA to a project must be considered for each project, and pavement markings may be involved in an environmental assessment if some other aspect of the project triggered an environmental assessment requirement.

NEPA requirements come into play when Federal agencies are involved in funding, permitting, licensing, or making decisions that can affect the environment. The primary tools under NEPA are the environmental assessment and environmental impact statements, which include processes designed to assess the likelihood of impacts from alternative courses of action.

TSCA

TSCA provides a mechanism for EPA to identify, list, and categorize new and existing chemicals used in manufacturing and commerce. The primary purpose of TSCA is to identify potentially dangerous products or product uses that should be subject to Federal control. Because of their inorganic and organic chemical composition, pavement marking products are required to meet compliance with inventory listing requirements established in TSCA.

RCRA

RCRA provides EPA with the authority to control the generation, transportation, treatment, storage, and disposal of hazardous waste. Under the current regulatory framework within the act, it is unclear whether or not pavement marking products or waste from pavement marking products would be considered hazardous wastes. Table 96 through table 103 in appendix F list chemicals contained in pavement marking materials, including chemicals that also are considered hazardous waste upon disposal such as acetone, methanol, MMA, and xylene. In addition to these solvents, the reported levels of lead and arsenic observed in glass beads used as pavement marking reflective materials are characteristic of a hazardous waste under 40 CFR 261.21–24.(77) Cleaning application devices or removing pavement marking materials also creates waste products with potentially hazardous properties. In order to determine whether or not a waste is hazardous, EPA calls on subjecting the waste to TCLP (as defined in 40 CFR 261.24).[77]

CAA

The Federal CAA affects pavement marking use, application, and eradication due to the potential release of PM, lead, and VOCs to the air. PM and lead are directly regulated under the National Ambient Air Quality Standards (NAAQS), while VOCs are indirectly regulated because of their role in the formation of ozone (a criteria air pollutant along with PM and lead). Under CAA, as amended in 1990, each State must develop a plan describing how it will attain and maintain NAAQS. This plan is called the State Implementation Plan (SIP) and is required under section 110 of the CAA (40 CFR 51, subparts F and G).[78]

In general, SIP is a collection of programs (monitoring, modeling, emission inventories, control strategies, etc.) and documents (policies and rules) that States use to attain and maintain NAAQS. States must engage the public in approving their plans prior to sending them to EPA for approval. Instating engineering controls to limit the release of PM, lead, and VOCs from pavement marking products could be considered within SIPs. For instance, the use of blasting or other removal procedures that produce PM may be restricted in SIP non-attainment areas. Also, the 2008 changes to the lead air quality standard may affect the pavement markings industry if detectable quantities of lead are identified in air emissions from either applying or removing the markings.

Under CAA, the Federal government also gave EPA the ability to identify a list of hazardous air pollutants not currently listed as criteria pollutants. Several components of pavement markings, including arsenic and VOCs, are found on the hazardous air pollutants list. The list is currently regulated under the National Emission Standards for Hazardous Air Pollutants (NESHAP), which requires air pollution sources to utilize maximum achievable control technologies to limit emissions. Within NESHAP, EPA regulates activities such as paint stripping. However, pavement marking removal activities are not covered under the NESHAP's regulations, likely due to the mobile and low-frequency nature of pavement marking removal operations.[79]

VOC emission from pavement markings was found to be minimal compared to other sources. A report published by EPA in 1989 examined the VOC emissions from various types of pavement markings, and the results of the report are included in table 63.[80]

Table 63. Comparison of estimated VOC emissions.[80]

Marking Materials	Emissions (lb/lane mi-year) Estimated VOC*
Solvent-based (non-aerosol)	69
Water-based (non-aerosol)	13
Thermoplastic	Negligible
Field-reacted polyester	Negligible
Field-reacted epoxy	0.25
Preformed tapes without adhesive primer	0
Preformed tapes with adhesive primer	58
Permanent markers	0

*Lane mile refers to a 4-inch-wide solid stripe that is 1 mi long. The average VOC content for water-based paints is 0.76 lb/gal.

Clean Water Act

Pavement markings are considered non-point sources under the Clean Water Act. The Nonpoint Source Management Program with the CAA provides grant money for States, territories, and Indian tribes to support a variety of activities to control nonpoint sources of water pollution. These activities may include technical assistance, financial assistance, education, training, technology transfer, demonstration projects, and monitoring.

Because storm water management from roadway surfaces is achieved on a local project level and because transportation departments are actively involved in construction projects, many State transportation departments have developed guidance to control point and nonpoint source water pollution associated with construction and maintenance activities. Examples of State programs include the following:

- AKDOT's *Alaska Storm Water Pollution Prevention Plan Guide*.[81]
- California Department of Transportation's *Statewide Storm Water Management Plan*.[82]
- TDOT's *Statewide Storm Water Management Plan*.[83]
- Texas Department of Transportation's (TxDOT) *Storm Water Management Guidelines for Construction Activities*.[84]
- MnDOT's *MnDOT Metro District's MS4 Stormwater Program*.[85]
- Ohio Department of Transportation's *Storm Water Management Program*.[86]
- Virginia Department of Transportation's (VDOT) *VDOT Manual of Practice for Stormwater Management*.[87]
- New York State Department of Transportation's *Memorandum of Understanding Between the Department of Transportation and the Department of Environmental Conservation Regarding the SPDES General Permit for Stormwater Discharges from Construction Activity*.[88]
- Colorado Department of Transportation's (CDOT) *Stormwater Programs* and *Water Quality Program: Illicit Discharges Program*.[89,90]

HAZARDOUS MATERIALS TRANSPORTATION

The U.S. Department of Transportation has the authority to control the transportation of hazardous materials through the Hazardous Materials Transportation Law. Regulations promulgated from this law potentially affect manufacturers and striping crews transporting pavement marking materials if the products are considered hazardous. Regulation 49 CFR 171–180 lists the hazardous materials covered within the Hazardous Materials Transportation Law, including identification of a compounds hazard class and shipping information requirements.[91] Some of the chemicals found in the pavement marking products used on the Tennessee and Alaska test decks include acetone, butyl methacrylate, epichlorhydrin, diethylenetriamine, hexamethylene diisocyanate, methanol, MMA, modified polyamine, and xylene. The law also requires incident reporting and emergency response during spills of hazardous materials during transportation. In addition, under 49 CFR 172.504, "General Placarding Requirements," vehicles used for transporting and applying pavement marking materials are subject to Federal vehicle placarding requirements.[(91)]

OCCUPATIONAL SAFETY AND HEALTH ACT

The Occupational Safety and Health Act founded the Occupational Safety and Health Administration (OSHA) with the goal of protecting the health and safety of workers employed in private and public sectors. Under 29 CFR 1910, OSHA identifies information that must be available to workers and the public regarding the chemical constituents of products.[(92)] Regulation 29 CFR 1910.1200(g)(1) requires that "chemical manufacturers and importers shall obtain or develop a material safety data sheet for each hazardous chemical they produce or import."[(92)] This information is typically provided in the format of an MSDS. The format for MSDS reporting has evolved over time and most companies follow American National Standards Institute (ANSI) standard Z400.1**,** *Hazardous Industrial Chemicals—Material Safety Data Sheets—Preparation*, which is a voluntary consensus standard for the preparation of MSDSs.[(93)] Pavement marking products are supplied with an MSDS, and employees working with the products need to be aware of the MSDS and any health and safety considerations of working with the products that are identified.

In addition to requiring MSDSs, OHSA regulations pertain to reducing exposures to particular components commonly found in pavement markings, including lead, hexavalent chromium, silica, and respirable dust. Worker exposure to lead is regulated under 29 CFR 1926.62, and subsection 29 CFR 1926.62(c)(1) establishes a permissible exposure limit (PEL) for lead at a maximum of 50 $\mu g/m^3$ of air averaged over an 8-h period.[(94)] OSHA regulation 29 CFR 1910.1026 regulates worker exposure to chromium (VI) and establishes a PEL not to exceed 0.5 $\mu g/m^3$ as an 8-h time-weighted average under any expected conditions of use.[(92)]

OSHA regulation 29 CFR 1926.55 also establishes threshold limit values for airborne contaminants for construction activities, including limit values for seven silica compounds and six silicates.[(95)] Because workers handling, applying, and eradicating pavement marking may be exposed to lead, chromium (VI), or silica, monitoring and worker protection measures should be considered.

In addition to chemical exposures, OSHA also sets requirements for noise protection. Applying and removing traffic markings may require noise protection for exposed workers. The OSHA requirements for noise control and hearing conservation are set forth in 29 CFR 1910.95, "Occupational Noise Exposure."[(92)] This regulation establishes permissible noise exposures for short time periods (15 min or less) up to a full 8-h day. Noise levels that exceed the permissible noise exposure levels require hearing protection, noise reduction, and, in certain instances, hearing conservation programs.

ENVIRONMENTAL LCA OF PAVEMENT MARKINGS

The choice between two pavement marking products should be made based on the performance of the marking materials and the chemical constituents (determined through reporting requirements, including MSDS). However, if the two products have similar performance characteristics and chemical composition, a review of the product life cycle may be beneficial to reducing environmental health and safety considerations indirectly related to the pavement markings industry prior to making decisions concerning product selection. LCA offers decisionmakers with tools and information to gain a higher level of understanding of the environmental trade-offs associated with a product or process by following a product through production, use, disposal, or reuse. Examples of factors considered during LCA include energy use and consumption, water use, greenhouse gas production, waste and wastewater production, hazardous pollutant generation, toxicity endpoints, and carbon footprinting.

The Organization for Standardization (ISO) provides a framework for LCA through two guidance documents: ISO 14040:2006, *Environmental Management—Life Cycle Assessment—Principles and Framework*, and ISO 14044:2006, *Environmental Management—Life-Cycle Assessment—Requirements and Guidelines*.(96,97) Collectively, these two documents describe the principles and framework for conducting LCAs. While the ISO standards provide broad guidance on LCAs, other groups have taken guidance on LCAs significantly further. Table 64 provides existing additional guidance used for LCAs along with the program country of origin.

Table 64. LCA methodologies.(98)

Methodology	Developer	Country of Origin
ILCD	European Commission Joint Resource Centre	European Union
CML2002	Centre of Environmental Science at Leiden University (CML)	Netherlands
Eco-indicator 99	PRé	Netherlands
EDIP97 – EDIP2003	DTU	Denmark
EPS 2000	IVL	Sweden
Impact 2002+	EPFL	Switzerland
LIME	AIST	Japan
LUCAS	CIRAIG	Canada
ReCiPe	RUN + PRé + CML + RIVM	Netherlands
Swiss Ecoscarcity 07	E2+ ESU-services	Switzerland
TRACI	EPA	United States
MEEuP	VhK	Netherlands

Note: Reference information for each methodology is provided in *ILCD Handbook, International Reference Life Cycle Data System*. (See reference 99.)

The first step in an LCA for pavement marking products is to define the goal. A typical goal for an LCA is to compare two materials and determine which has the least overall impact on the environment. For pavement markings, the impact on the environment will arise from extraction of the raw materials used to make the product (commonly including petroleum products as well as inorganics). Transforming the extracted or recycled raw materials into pavement marking products requires energy and water. The production process results in the formation of waste streams that could escape in wastewater and air. Additional impacts are associated with packaging and distributing pavement marking materials and applying pavement marking materials to roadways. Waste products also include not only the original manufacturing materials but also road surface and equipment cleaning wastes.

Potential impacts become part of a life-cycle inventory (LCI). LCI is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity. In the LCI phase of an LCA, data are collected and organized. The collected data are necessary to evaluate comparative environmental impacts or potential improvements. LCI documents the quantities of pollutants released to the environment and the amount of energy and material consumed. The four steps in an LCI process are as follows:

1. Develop a flow diagram of the processes being evaluated.

2. Develop a data collection plan.

3. Collect data.

4. Evaluate data and report results.

Figure 42 shows a schematic of a pavement marking LCA model.

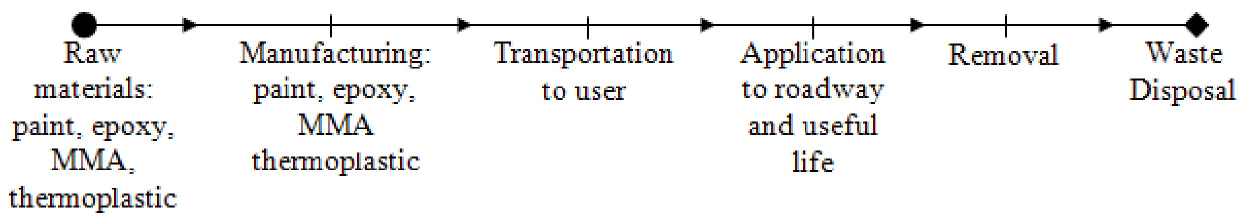


Figure 42. Illustration. Pavement marking LCA model.

The life-cycle inventory assessment (LCIA) phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI. An LCIA does not necessarily attempt to quantify any specific actual impacts associated with a product, process, or activity. Instead, it seeks to establish a linkage between a system and potential impacts. LCIA models are based on the models within each of the impact categories using assumptions. The models provide an overview of the relative risk and are not intended to provide specific predictions of risk.

After the LCI and LCIA are completed, the results are subjected to a life cycle interpretation. ISO 14040:2006 defines life cycle interpretation as follows:(96)

> "Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together or, in the case of LCI studies, the findings of the inventory analysis only. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations, and provide recommendations."

LCIA models are typically simplified versions of more comprehensive models used in the impact category analyses. These simplified models are suitable for relative comparisons of the potential to cause human or environmental damage but are not indicators of absolute risk or actual damage to human health or the environment. Finally, the interpretation step considers findings from the inventory analysis and the impact assessment together. The interpretation should reflect the relative approach used for LCIA, indicating potential environmental effects rather than predicting actual impacts on category endpoints. The interpretation phase may also be an iterative process of reviewing and revising the scope of the LCA as well as the nature and quality of the data collected in a way that is consistent with the defined goal.

An accurate LCA for a pavement marking material requires detailed information from the manufacturer. A list of ingredients in the marking material and their concentrations is a starting point. The processes used to produce these ingredients must be determined, and their environmental impacts should be factored into the assessment. For example, energy and waste material associated with producing a resin in a marking material becomes part of the analysis. The energy, emissions, and waste products associated with producing the marking material from the ingredients is another step. Transporting the marking materials to a user also requires energy, typically petroleum fuel products, and generates additional emissions. Applying the pavement marking material usually involves some waste material, emissions, and energy (for vehicles or heating requirements). Finally, removing the marking material also requires energy and produces additional emissions and waste products. Quantifying and calculating these elements are the essential tasks in developing a pavement marking environmental LCA.

As of the writing of this report, LCIs for pavement marking products do not exist. However, their development is a potential future focus of research in academics, government, and industry. Developing LCAs for pavement markings is an important step forward and will become a necessary tool to make sound decisions regarding product selection for pavement marking installations.

BMPS

Reducing Exposure Risks

When the total environmental impact of a pavement marking product is unknown but sufficient concern exists to warrant minimizing exposure to products, implementation of BMPs will help reduce potential adverse outcomes. Occupational exposure to traffic conditions, heavy metals and silica through dermal contact, accidental injection, and inhalation of product dust is potentially significant. If there are concerns that the exposure limits for heavy metals or silica may be exceeded, OSHA procedures for sampling and monitoring the potential exposure should be followed. Additionally, BMPs may be implemented to reduce worker exposure to pavement markings. BMPs for pavement markings are associated with the storage, handling, application, and removal of pavement markings.

Proper storage, handling, application, and removal of pavement markings will minimize the possible release of pavement marking contaminants to the environment and include preventative measures for managing accidental spills of pavement marking materials.

BMPs for minimizing environmental exposures to pavement marking products that can be adopted include the following:

- Storage.
    - Storing materials in containers that prevent water and UV light penetration.
    - Monitoring and mitigating leaking storage containers.

    - Ensuring available MSDSs are read and understood by work crews and that PPE measures identified within the MSDS are utilized when moving products into or within storage.
    - Labeling of all materials.
    - Maintaining a clean storage environment that is free from product spills and dust.

- Handling.
    - Using equipment suitable to move containers of a given container type.
    - Using appropriate PPE to minimize contact of product.
    - Minimizing dust release from products.
    - Identifying individual products that require additional special handling.
    - Having a plan in place to manage and clean up materials spills.

- Application.
    - Understanding the application system.
    - Using handling BMPs for all products transferred into the application device.
    - Minimizing spillage during application.
    - Having a plan in place to manage materials spills.
    - Capturing wash solutions used to clean application equipment.

- Removal.
    - Selecting appropriate removal methods for pavement marking on a given surface.
    - Assessing potential VOC, lead, chromium, silica, or other chemical hazards caused by product removal and addressing such hazards in accordance with regulatory requirements.
    - Developing a plan to manage the removal of waste products that complies with environmental regulatory requirements.
    - Minimizing worker exposure to removal waste products during and after the physical removal of the marking by dust suppression, water vapor release suppression, vacuum collection of all removed materials, or similar engineering controls.
    - Understanding evaluation practices for determining if removal product wastes are non-hazardous or hazardous materials.

In addition to the BMPs identified to reduce environmental exposures to workers from pavement marking products, reducing hazards associated with the use of heavy equipment and traffic hazards is also important. Hazards associated with pavement marking application from equipment and traffic are similar to hazards faced within roadway construction or maintenance operations. Considerations specific to traffic marking application or removal include worker exposure to roadway environments. Some of the equipment is operated at very high temperatures (above 250 °F) and pressures.

MSDS RECOMMENDATIONS

A need for standardizing and improving the information listed on product MSDSs became apparent based on the review of 41 pavement marking product MSDSs (listed in appendix E and summarized in appendix F). Products reviewed were shipped with either ANSI- or OSHA-formatted MSDSs. Within each format, there were significant differences in the information provided. Therefore, developing improved standardization of MSDS information for pavement marking materials will facilitate comparison of the materials and assist with managing environmental risks and impacts.

At a minimum, the following recommended changes should be adopted:

- Follow the ANSI Z400.1 MSDS format for all pavement marking product MSDSs (see table 65).
- Enter information or a comment in all categories to insure information is not inadvertently omitted.
- Include PPE discussion for storing, handling, transferring materials, applying, and removing products.

Training pavement marking work crews and managers to read and understand the provided MSDSs is also necessary. Marking crews know that MSDSs are available and are carried along with the team; however, the value of the MSDS in regards to reducing environmental health and safety is not appreciated. There is also confusion regarding what to actually do about the information listed on the MSDS. Training of PPE and BMPs used to reduce exposure to pavement marking products would benefit the industry. These practices should be specified in technical specifications on pavement marking storage, handling, application, and removal that are set through AASHTO or ASTM.

Table 65. MSDS ANSI format.[93]

Section 1. Chemical Product and Company Identification: Names the material and links MSDS to the label and shipping documents. Includes the name, mailing address, and telephone number for the manufacturer or distributor.
Section 2. Hazards Identification: Descriptions of the material's appearance, odor, and health, as well as physical and environmental hazards that may be of concern for emergency response personnel. Includes four subsections: emergency overview, OSHA regulatory status, potential health effects, and potential environmental effects.
Section 3. Composition Information on Ingredients: Identifies the hazardous components of the material. Non-hazardous ingredients are listed separately. Chemical Abstracts Service (CAS) numbers are included, as well as percentages or ranges of percentages.
Section 4. First Aid Measures: Includes two subsections, emergency and first aid procedures, and a note to physicians regarding additional information on antidotes, specific treatments, and diagnostic procedures intended for use by healthcare professionals.
Section 5. Fire-Fighting Measures: Describes fire and explosive properties of the material, extinguishing media to be used, and fire-fighting instructions.
Section 6. Accidental Release Measures: Information regarding preventing or responding to spills, leaks, or releases. Information on personal protective equipment, containment equipment, cleanup equipment and techniques, environmental precautions, and specific reporting requirements may be included.
Section 7. Handling and Storage: Guidelines on safe handling and storage practices.
Section 8. Exposure Controls, Personal Protection: Discusses exposure guidelines, such as the OSHA PELs, American Conference of Governmental Industrial Hygienist's Threshold Limit Values, and Biological Exposure Indices. Engineering controls and personal protective equipment are also covered in this section.
Section 9. Physical and Chemical Properties: The material's physical and chemical properties. Properties typically include appearance, odor, odor threshold, physical state, pH, melting/freezing point, initial boiling point and boiling range, flash point, evaporation rate, flammability (solid, gas), upper/ lower flammability or explosive limits, vapor pressure, vapor density, specific gravity or relative density, solubility, partial coefficient: n-octanol/water, auto-ignition temperature, and decomposition temperature.
Section 10. Stability and Reactivity: Describes hazards associated with stability and reactivity of the materials.
Section 11. Toxicological Information: Presents toxicological information such as acute dose effects, repeated dose effects, irritation, corrosivity, skin and respiratory sensitization, carcinogenicity, neurological effects, genetic effects, reproductive effects, developmental effects, and target organ effects.
Section 12. Ecological Information: Provides information regarding potential environment impacts associated with releasing the material to the environment or in evaluating waste treatment practices.
Section 13. Disposal Considerations: Recommends disposal methods, including recycling or reclamation.
Section 14. Transport Information: Classifies information and special precautionary information for shipping the material. Includes U.S. Department of Transportation classifications or an indication that transporting the material is not regulated.
Section 15. Regulatory Information: Provides information regarding the regulatory status of the material. Addresses regulations under OSHA, EPA, and other relevant regulatory agencies, including State agencies, if appropriate.
Section 16. Other Information: Lists other material that may be useful and not covered in the preceding 15 sections. May include label information, hazard ratings, revision dates, and references to other related information.

SPECIFICATION GUIDELINES FOR STORAGE, HANDLING, APPLICATION, AND REMOVAL PRACTICES

The creation of technical specifications for work practices concerning pavement marking products is recommended to address environmental health and safety considerations. Currently, tremendous variation within the pavement markings industry exists regarding how products are stored in contractor, city, or State yards. Product spillage is a concern due to the content and cost of pavement marking products. Standard specifications would allow for better control of pavement marking products in storage and result in fewer spills.

The process for handling product materials and transferring product materials from storage to the application devices is also variable. The technical specifications would be dependent on the type of application (long-line versus short-line applications) and the type of marking being applied. PPE measures could be specified within a guidance document to standardize measures put in place to reduce exposures to products. Similarly, the actual methods of application should be specified to achieve an industry standard of quality across crews applying markings. Currently, quality assurance is a mostly qualitative measure, and the resulting quality of applied markings is highly variable. However, technical specifications could be followed to help standardize the applied marking quality. The specifications, based on the best practices currently available in the industry, would result in fewer environmental health and safety concerns and less product loss/wastage.

Finally, the process for removing marking products must be specified. Currently, State guidance and regulations regarding removal methods is variable. Because the amount of exposure to the products is based on the type of removal occurring, technical specifications requiring vacuum recovery and identifying the appropriate disposal method for the removed materials will be valuable to the industry.

SUMMARY

This chapter identifies and highlights important environmental health and safety considerations for the application and use of pavement marking products. Pavement marking product compositions, application techniques, and removal procedures are introduced. Worker health and environmental considerations for paints, thermoplastics, epoxies, tapes, and reflective elements are discussed. Included within the discussion is a summary of existing research seeking to understand the impact of heavy metals present in glass beads used to impart retroreflectivity of pavement markings. The chapter also provides an overview of existing Federal environmental and safety regulations pertaining to pavement markings.

LCA is introduced in order to suggest a framework that can be used to include environmental health and safety considerations into the process of selecting pavement marking products for application. BMPs for storage, handling, application, and removal of pavement marking materials are also introduced in this chapter. The chapter ends with recommendations to standardize the information present on the MSDS accompanying the products and develop specification guidelines for the storage, handling, application, and removal of pavement markings. The appendices provide additional resources, including a summary of the products used within the pavement marking demonstration project.

CHAPTER 6. STATE BIDDING AND PROCUREMENT

INTRODUCTION

The procurement of pavement markings is often a source of conflicting demands placed on agencies. Procurement is not just the purchase of the materials, but rather a more holistic view of a contracting mechanism that provides for the purchase, application, and maintenance of pavement marking materials at locations determined by the contracting agency.

As with any contract, a basic question is, "How does an agency ensure they are getting what they have 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 the 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 has proposed 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.[100]

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 agencies 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, etc.).

A root question pertaining to these differing specifications is, "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 that would ensure the desired quality. This, in turn, could provide for better roadway information being supplied to drivers, potentially decrease crashes, and save money.

RECIPE OR COMPONENT SPECIFICATION

In general, the performance of pavement markings varies significantly from one location to the next. In order to achieve a consistent level of service across the roadway system, road agencies have developed recipe or component specifications for the installation and final inspection of pavement markings. A recipe or component specification defines the materials and application parameters for the components of the pavement marking system. A significant advantage of this type of specification is that the agency knows exactly what it is paying for because the provisions of the material and placement are all tightly defined—the type of equipment to be used, the rate for the application of the material, the ambient conditions during the installation, and the testing methods for final acceptance are described in the specification.

The main attributes of pavement marking are retroreflectivity, thickness, and durability. Thickness and retroreflectivity are predetermined before the installation of the markings. Durability is mostly dictated by the installation process. In general, road agencies will accept newly installed markings based on these three characteristics.

Different road agencies propose different initial levels of retroreflectivity to accommodate their road systems' needs. For example, the Alabama Department of Transportation (ALDOT) specifies an initial retroreflectivity value of 450 mcd/lux/m^2 for white thermoplastic pavement markings. Table 66 shows examples of wet paint and thermoplastic pavement marking retroreflectivity values indicated in component specifications.

Table 66. Component specification—initial retroreflectivity values. (See references 101–109.)

Agency	Paint Markings (mcd/lux/m^2)	Thermoplastic Markings (mcd/lux/m^2)
ALDOT	300 (white) and 200 (yellow)	450 (white) and 300 (yellow)
Florida Department of Transportation (FDOT)	300 (white) and 250 (yellow)	450 (white) and 350 (yellow)
North Carolina Department of Transportation (NCDOT)	225 (white) and 200 (yellow)	375 (white) and 240 (yellow)
KDOT	Apply glass beads at a rate of 10 lb per gallon of paint (white-yellow)	300 (white) and 225 (yellow)
Delaware Department of Transportation	Minimum rate of 5 lb of beads per gallon of paint to obtain a minimum average retroreflectivity of 125 mcd/lux/m^2 (white-yellow)	300 (white) and 200 (yellow)
Georgia Department of Transportation (GDOT)	Minimum rate of 6 lb of beads per gallon of paint (white-yellow)	Minimum rate of 14 lb of beads per 100 ft^2 (white-yellow)
CDOT	Minimum rate of 5 lb of beads per gallon of paint and a maximum rate of 6 lb of beads per gallon of paint (white-yellow)	Minimum rate of 10 lb of beads per 100 ft^2 (white-yellow)

As shown in table 66, some road agencies do not indicate a retroreflectivity value for pavement markings; instead, they indicate the minimum or acceptable rate at which glass beads should be incorporated to the base material. For example, GDOT specifies a minimum rate of 6 lb of glass beads per gallon of paint for painted pavement markings. The amount of glass beads incorporated to the base material combined with the physical properties of the base material provides the expected retroreflectivity.

Most component specifications prescribe the type of inspection for final acceptance of the pavement markings at the end of the proving period. The proving period ranges between 15 and 180 days of installation. The prevailing method for testing new installed markings is a direct measurement of the retroreflectivity using a handheld or mobile retroreflectometer. In general, agencies use an average retroreflectivity per line per sample unit to compare against the initial value specified.

TxDOT utilizes an alternative method for inspecting the markings. It has adopted a visual method for testing and accepting new pavement markings (Tex-828-B).[110] Testing is performed during the day and at night. The method consists of counting the number of visible stripes from a vantage point and comparing the count against a predetermined number. If marking defects are minimal, then the new markings are accepted. Otherwise, the new markings are rejected, and they have to be replaced at the contractor's expense.

PERFORMANCE-BASED SPECIFICATION

In direct contrast to the recipe specification, a performance-based specification does not define the specifics of the materials and their placement but, rather, the overall goal that must be met by the markings. This goal, typically a minimum level of retroreflectivity within a prescribed number of days of placement, seeks to establish a sufficiently high peak, or starting point, of the pavement marking material.

While 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. However, not enough is known about marking performance over time in different locations and applications to accurately set initial performance metrics to produce repeatable end-of-life cycles.

One advantage of this type of specification is that it requires less manpower from the agency to inspect markings at the time of application, since a reduced number of performance indicators, such as retroreflectivity, are inspected. Another advantage of this type of specification is that it provides flexibility to innovate and use alternative materials. For example, in 2007, VDOT solicited a proposal for a statewide performance-based contract for the installation of wet reflective pavement markings. The solicitation package indicated that installed wet reflective pavement markings should perform at a minimum in conformance with applicable VDOT standards, but the specifications related to material composition, installation methods, and material performance measures were to be proposed by the contractor.

Table 67 shows an example of performance criteria for evaluating the quality of installed pavement markings based on the KDOT performance specification.[111] To assess compliance with reflectivity and width requirements, the agency measures the pavement marking at predetermined locations. All other performance requirements are assessed based on the extent of the marking defects. The most common unit for the performance inspections is 1 mi of highway.

Table 67. Performance measures for installed pavement marking.

Measure	Performance Criteria
Reflectivity	Average retroreflectivity above the minimum value.
Width	Maximum of 0.25 inches above the specified plan width.
Color	Each color shall meet the chromaticity limits. Less than 10 percent of the markings have discolored areas.
Alignment	Lines should not deviate laterally from the intended alignment more than 2 inches in 200 ft.
Appearance	Less than 10 percent of the markings have drag marks, gashes, foreign covering, or railroad tracking.
Presence	Less than 10 consecutive feet is missing from the solid lane line, edge line, or gore line.

Reflectivity requirements can be specified by indicating an initial value and assuming degradation over time or by indicating a minimum value for the estimated life of the pavement markings. For example, the Maryland Department of Transportation specifies the initial retroreflectivity value at the moment of installation, 500 mcd/lux/m^2, for white striping tapes and the minimum retroreflectivity values for years 1–4, which are 400, 300, 200, and 150 mcd/lux/m^2, respectively.[(112)] The contractor will be directed to replace the marking if the average retroreflectivity value is below the corresponding minimum value at the moment of the evaluation. The Wisconsin Department of Transportation defines a minimum retroreflectivity value of 125 mcd/lux/m^2 for white paint markings and directs contractors to repair or replace all markings that fall below the threshold value after 1 year of installation.[(113)]

Performance-based specifications are not only used for purchasing and installing pavement markings but also for contracting maintenance services. Damaged pavement markings negatively affect the purpose of the markings and ultimately affect safety. Since the early 1990s, performance-based specifications have been used for directing pavement marking maintenance services. Table 68 shows examples of contract performance criteria for evaluating the quality of maintenance service with regard to pavement markings.

Table 68. Performance measures for pavement marking maintenance.

Agency	Outcome	Performance Criteria
FDOT	90 percent of the length and width of each line functions as intended	(1) Less than 10 percent of the length of any line is less than 5.4 inches wide during daylight inspection, (2) less than 10 percent of the length and width of any line is not visible for a distance of 160 ft at night, (3) less than 10 percent of the length of any line is missing, and (4) less than 10 percent of the length of any line is covered by soil, grass, or debris.
NCDOT	95 percent of markings are visible	(1) No edge lines, centerlines, or skip lines are worn, missing, or obliterated, (2) lines must be present, visible, and reflective at night, and (3) lines must be replaced when damaged/lost during pavement repair or winter weather events, regardless of who performs the snow and ice removal.
VDOT	Present	(1) Less than 15 percent of lines should be covered by debris, (2) less than 25 percent of lines should be damaged or missing due to snow removal operations, and (3) less than 15 percent of lines should be damaged or missing due to incidents or patching operations.

FDOT specified that pavement markings have to be visible at a distance of 160 ft at night.(114) To verify compliance with the performance specifications, FDOT staff evaluate the pavement markings using a testing method similar to the visual inspection method developed by TxDOT.(110) NCDOT does not include a minimum distance for the evaluation; it only specifies that the marking has to be present, visible, and reflective at night.(115) This omission may affect the repeatability and reproducibility of the assessment, which is one of the main characteristics of a performance assessment. VDOT does not include reflectivity in its performance criteria.(116) The intention is to direct routine maintenance only. Newly installed pavement marking are managed separately and in accordance with VDOT *Road and Bridges Specifications*.(117)

WARRANTY SPECIFICATION

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 marking's life cycle. This life cycle may vary greatly depending on the application and type of material. Some warranty specifications are up to 5 years in length. 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.

SURVEY ON STATE BIDDING AND PROCUREMENT PROCESSES

As stated previously, a fundamental question is, "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 DOT Pavement Marking Task Force investigated the use of performance-based specifications across other State transportation departments. 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 varied in terms of what types of materials are procured by a performance specification. A number of responses indicated a mix of specification types, with paint using a recipe specification but more advanced types of markings, such as thermoplastics and tape, utilizing performance characteristics. In most cases, the performance metric was initial retroreflectivity. Of the 23 responses, only 5, or approximately 22 percent, used a performance specification across all marking types.

There were no additional follow-up questions related 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 observation that can be drawn is that while performance specifications are in use, in some respect, their wholesale application to all material types is much smaller in roughly 50 percent of the States. Many States are still using recipe or component specifications, especially for paint, which is the most common pavement marking material.

In order to obtain additional information concerning the effect of State bidding and procurement processes on the quality of pavement marking material, the research team conducted a national survey in 2008 to gather information from the States regarding the impacts of State bidding and procurement processes. The survey was sent out along with a similar survey conducted as part of the National Cooperative Highway Research Program project 39-13, *Pavement Marking Warranty Specifications*.[118] While the survey had a number of questions, the first question was directly comparable to the 2007 survey previously described (see figure 43).

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 43. Chart. Survey question 1—procurement process.

Figure 44 shows a 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 immediately 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 29 respondents indicated the use of both a recipe and a performance-based specification. Four respondents indicated on overlap for thermoplastics, four for multicomposite, and seven for preformed tapes. This indicates that agencies are not limiting themselves to a single procurement mechanism for a specific marking material. It may also indicate that agencies are using composite specifications, such as a recipe specification with some performance requirements, such as initial retroreflectivity. Because this result was somewhat unexpected, there is insufficient detail in the later questions to explore this issue in more depth.

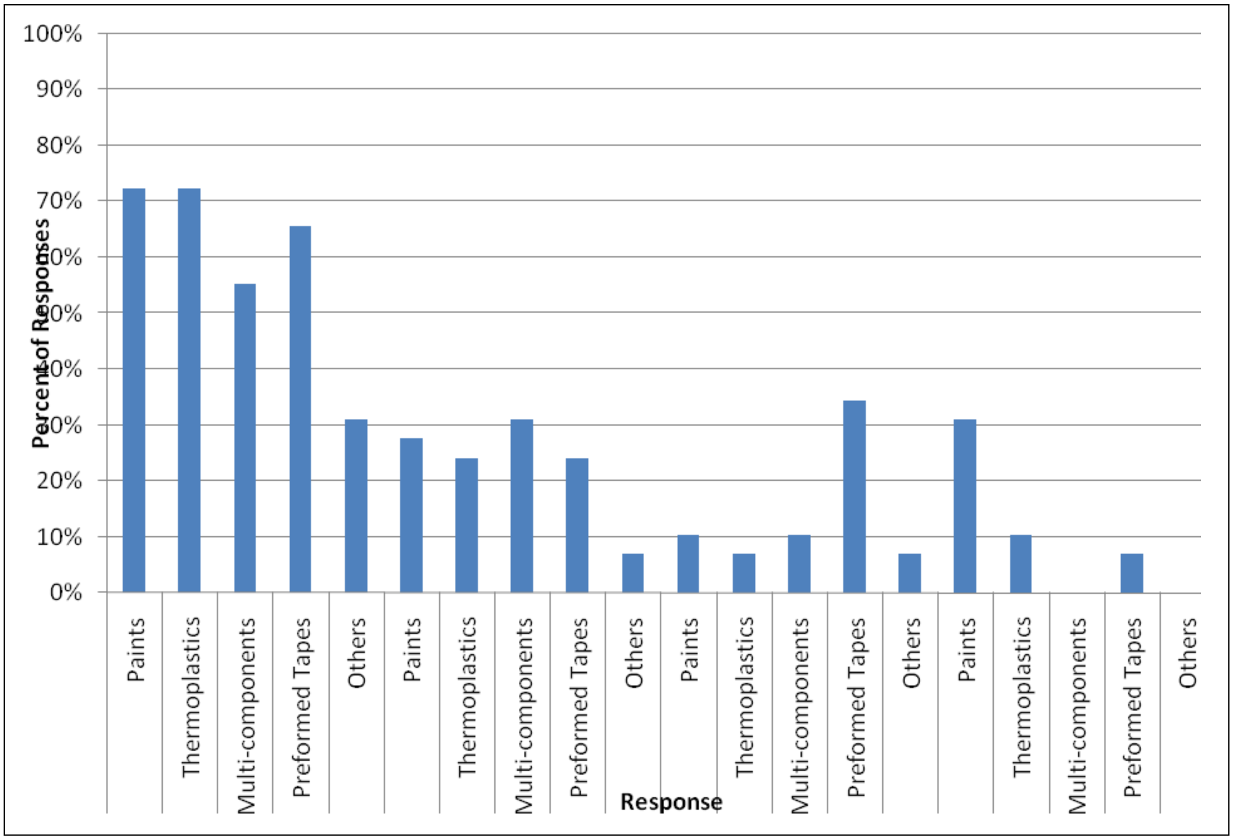


Figure 44. Graph. Survey responses: type of specification versus material.

Comparison of the responses by agencies that participated in both the 2007 and 2008 surveys are 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 the same use in 2007. Four agencies that had reported the use of a performance-based specification in 2007 did not indicate the use of such a specification in 2008. However, the second question of the 2008 survey (see figure 45), 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-based specification. Therefore, differences in responses between 2007 and 2008 may be due to differences in how the questions were asked and the answers 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 45. Chart. Survey question 2—procurement process change.

Fourteen respondents indicated "Yes" to question 2, while 15 answered "No." There was no timeframe mentioned with regard to the change in specification, so there is no direct comparison 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 test deck."

Questions 3 through 6 of the 2008 survey focused on ascertaining the reasons for the change as well as any benefits or consequences. Question 3, shown in figure 46, listed several common reasons for changing from a recipe to a performance-based specification and asked respondents to identify all reasons that were applicable.

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 46. Chart. Survey question 3—reasons for process change.

Many agencies responded with more than one reason, so the total number of responses represented in figure 47 is significantly greater than the number of agencies (14) that indicated a switch in their specifications.

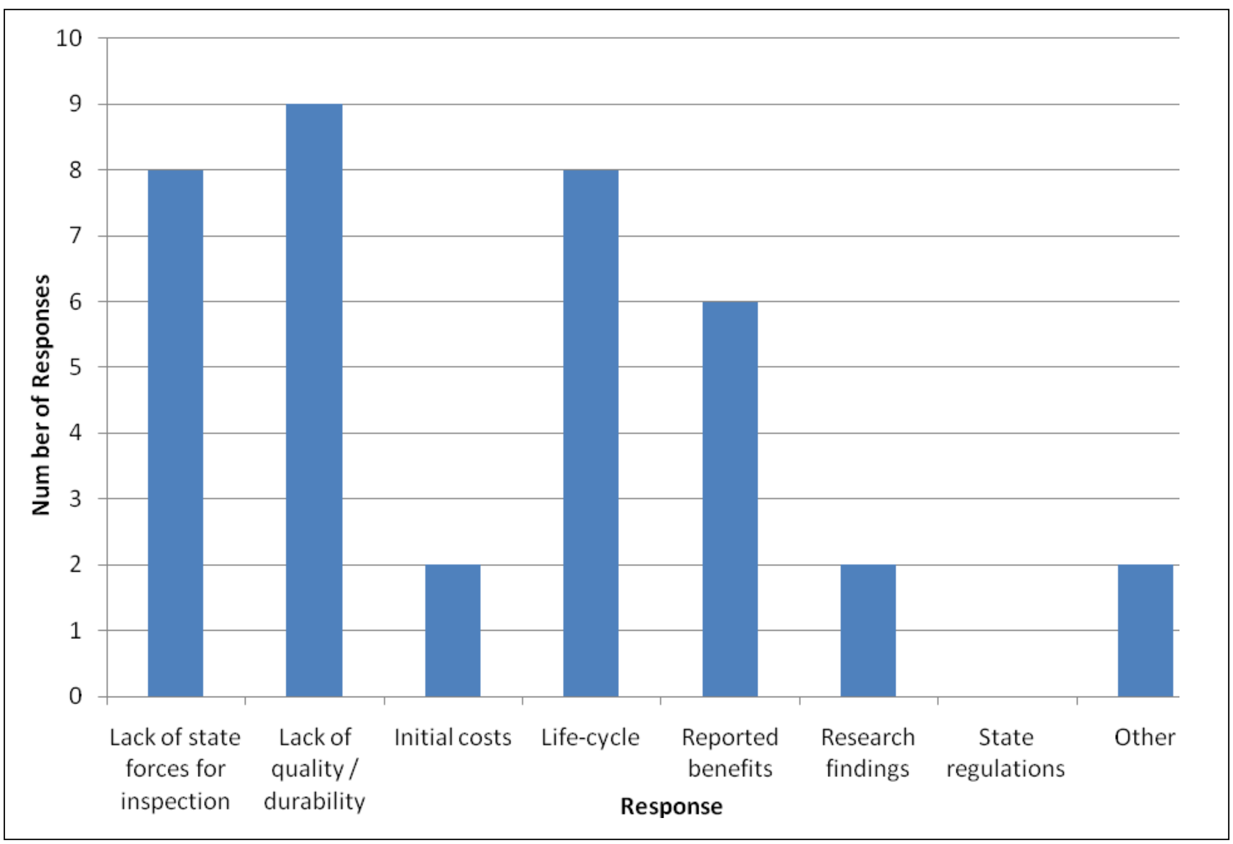


Figure 47. Graph. Survey responses: reasons for switching to performance-based specification.

The four most common answers were as follows:

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

"Lack of State forces for inspection" is a significant answer because it points to a particular onus or disadvantage of the recipe specification. Because individual components are detailed in a recipe specification, a significant amount of 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 fewer performance indicators, such as retroreflectivity, are inspected.

The answer "lack of quality/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 48). Although the format of the question provided no mechanism to differentiate between expected and realized benefits, respondents were asked to check all 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 48. Chart. Survey question 4—expected and realized benefits.

Figure 49 identifies that the highest number of responses was associated with a desire to lower the life-cycle costs and obtain more durable markings. This is a clear indication that agencies recognize, or are investigating, the use of performance- or warranty-based specifications to improve the quality of the pavement markings.

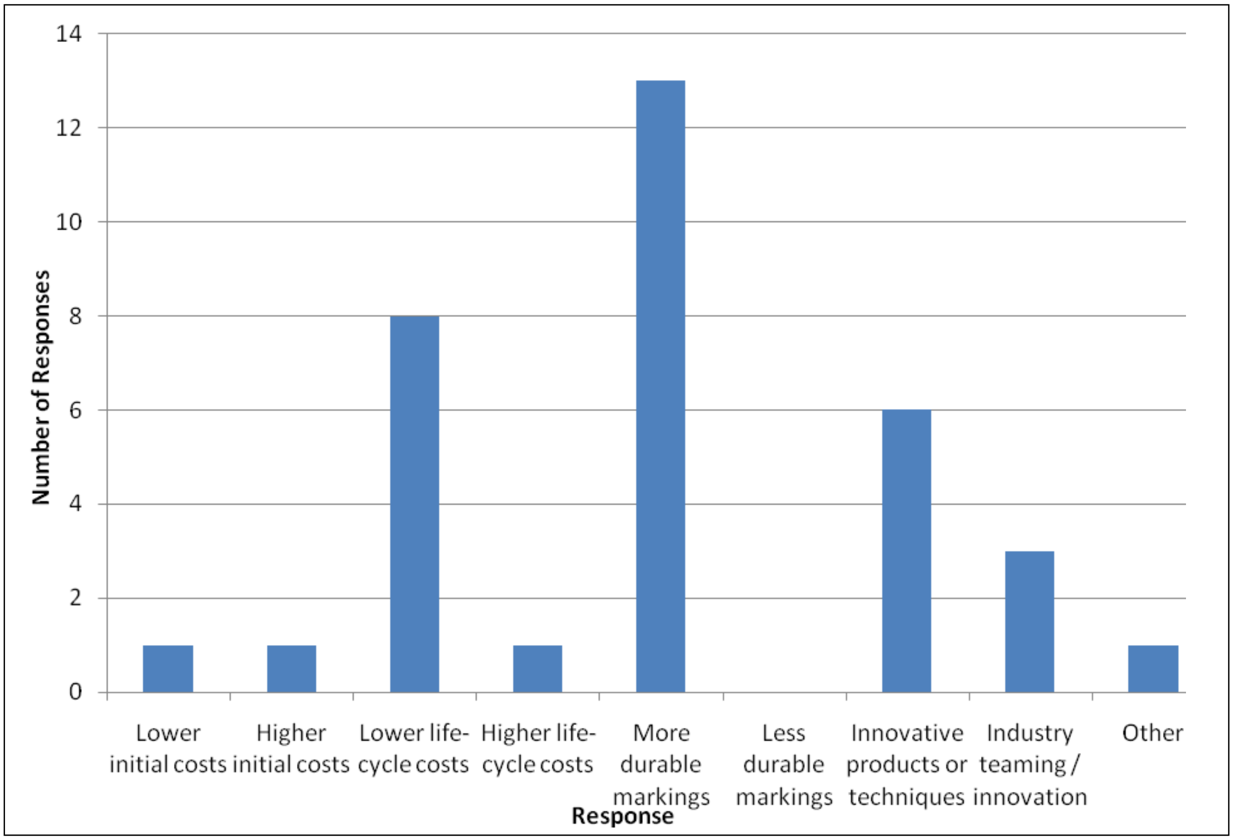


Figure 49. Graph. Survey responses: benefits of switching to a performance- or warranty-based specification.

Question 5 of the 2008 survey investigated if there were any unintended circumstances of the switch in specification type (see figure 50). Respondents were again asked to check all answers that applied. Because of this, the tally of the number of responses to the individual items in question 5 is 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 50. Chart. Survey question 5—unintended consequences.

Figure 51 shows a fairly even distribution across all responses. Therefore, the expectation is that a switch to a performance- or warranty-based specification should hold no hidden trouble spots.

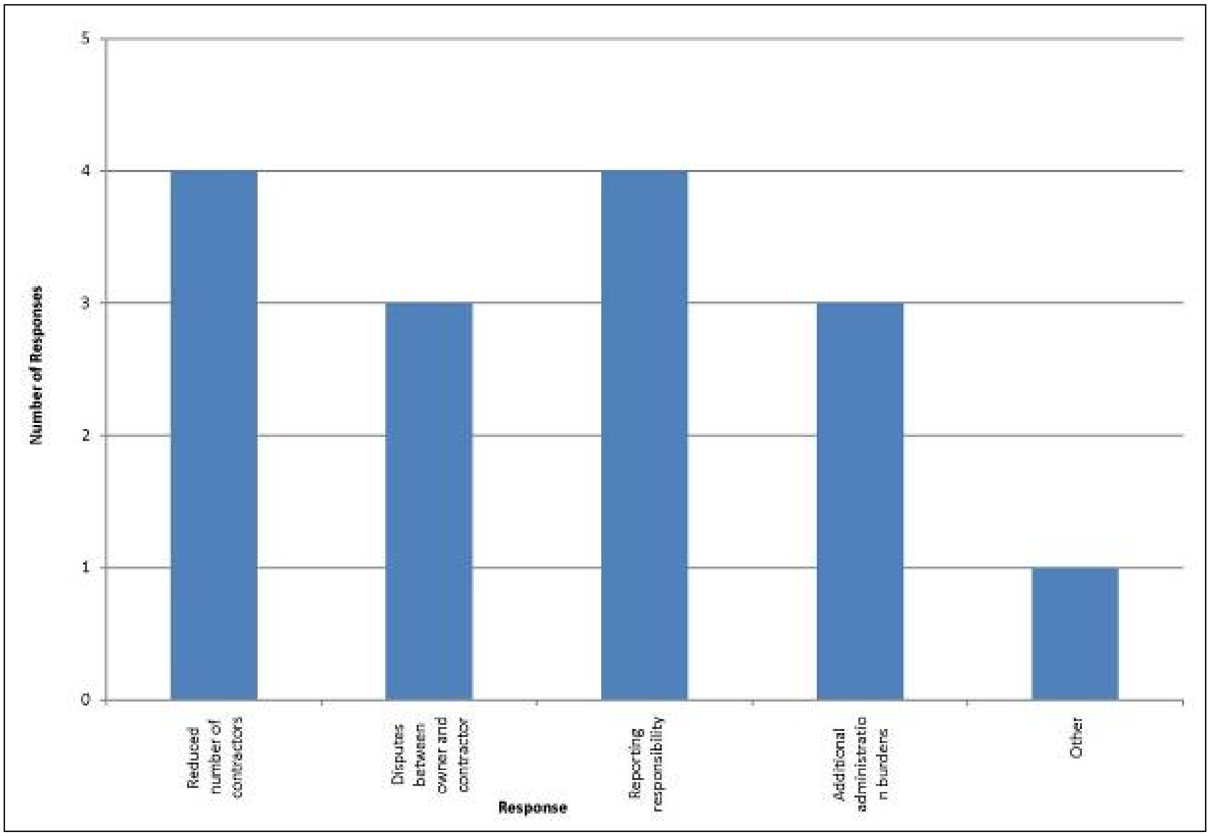


Figure 51. Graph. Survey responses: unintended consequences of switching to a performance- or warranty-based specification.

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

- "It's too early to tell. We've only been using the warranty spec 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, 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 approx. 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."

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.

However, the surveys 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 indicates a widespread national interest in improving the quality of pavement markings. The procurement process is certainly one area where quality could reasonably be affected by moving to a mechanism that prescribes expected results, regardless of the makeup of the materials.

One important obstacle to the utilization of performance-based specifications is the lack of true maintenance responsibility geared to the overall performance of the product or installation. Most installations are performed by local and small contractors that prefer component specifications rather than a performance-based approach. Bundling pavement marking installation with other road services, such as routine maintenance or pavement rehabilitation, is a viable alternative for the utilization of performance-based specifications; however, this type of contract may be attractive only to large contracting firms.[3]

[3] Based on information obtained from VDOT Traffic Engineering Division.

CHAPTER 7. RESEARCH SUMMARY AND FINDINGS

This chapter provides a summary of findings regarding a pavement marking demonstration project carried out in Alaska and Tennessee. The findings of the four major elements of the project are provided in the following sections.

COST EFFECTIVENESS OF PAVEMENT MARKINGS

Findings on cost effectiveness of pavement markings are as follows:

- Three pavement marking test decks (one in Alaska and two in Tennessee) were installed to evaluate the durability of various pavement marking materials, including advanced acrylic pavement markings. The results of the test decks, combined with pavement marking material and installation costs, were used to study the cost effectiveness of the pavement marking materials studied.

- Using key pavement marking degradation factors, a framework for a PMST was developed. The PMST was populated with data from the test decks in Tennessee to demonstrate the usefulness of such a tool.

- The test deck in Alaska 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 is responsible for the accelerated degradation of the tape product. The markings that maintained adequate retroreflectivity the longest were the structured MMA (not the splatter pattern but a longitudinal raised dual rib pattern) and the tape on the edge line.

- One strategy that AKDOT uses effectively is to apply a durable MMA marking in a groove and then remark 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 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.

EFFECTS OF WIDER EDGE LINE PAVEMENT MARKINGS

Operational effects include the following:

- Earlier operational effect studies conducted on wider pavement markings have been inconclusive, showing inconsistent and/or insignificant findings.

- The crash surrogate study results are not different from previous research findings. After converting edge lines from 4 to 6 inches, small differences were detected in the mean and variance of vehicle speeds and lateral position (and of speed change from the beginning to the midpoint of curves). However, these changes were subtle and based on previous research and are not practically significant.

Safety effects include the following:

- Earlier crash studies conducted with wider pavement markings have shown no particular benefit, partly because of a lack of adequate data.

- This study provided a unique opportunity to obtain the data needed to conduct a methodical examination of the safety benefits of wider edge lines. Two different approaches were used. One was based on crash frequency, and another was based on crash severity. The results are as follows:

    - Crash frequency analyses for two-lane rural highways: Because of the different nature of data from each State, a different statistical analysis approach was employed for each State—an EB, before-after analysis of Kansas data, an interrupted time series analysis of Michigan data, and a cross-sectional analysis of Illinois data. Although it is well known that causation is hard to establish based on observational studies, the results from three extensive statistical analyses all led to the same findings that wider edge line pavement markings on two-lane rural highways lead to lower crash frequencies.

    - Crash frequency analyses for multilane highways: Interrupted time series analyses of Michigan data and cross-sectional analyses of Illinois data were performed. The findings from these analyses do not support the use of wider edge line pavement markings for multilane highways.

    - Crash severity on two-lane rural highways: This innovative analysis approach found positive safety effects for wider edge line pavement markings for two-lane rural highways, supporting the findings from the crash frequency analyses. More specifically, the findings demonstrate a shift from more to less severe crashes for two-lane rural highways with wider edge line pavement markings.

ENVIRONMENTAL CONCERNS

Environmental concerns are as follows:

- A review of past and ongoing research includes a description of a study aimed at supporting decisionmaking concerned with regulating the presence of heavy metal (specifically arsenic and lead) in recycled glass beads used in pavement marking systems.

- A discussion of LCA is included to suggest a framework that can be used to include environmental health and safety considerations in the process of selecting pavement marking products for application.

- BMPs for storage, handling, application, and removal of pavement marking materials are described.

- Recommendations are included to standardize the information present on the MSDSs accompanying products and develop specification guidelines for the storage, handling, application, and removal of pavement markings.

STATE PROCUREMENT AND BIDDING PRACTICES

Information on State procurement and bidding practices includes the following:

- In a review of State transportation department practices, it was discovered that there is a wide disparity in how 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 will result in higher-quality installations.

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

RECOMMENDATIONS FOR FUTURE RESEARCH

Despite having several objectives, this study allowed researchers to thoroughly analyze various aspects of pavement marking, including performance, safety, environmental concerns, State bidding practices. The results of the environmental portion of this study have already spurred additional research pertaining to the human health risks associated with glass beads used for pavement markings. Additional recommendations for research are as follows:

- One of the most interesting findings from this study is the estimated safety benefit, measured by expected reductions in expected crash frequency, of using wider edge lines on RTLTW highways. It is interesting because the safety surrogate study (i.e., the operational effects study) resulted in subtle differences in driver behavior when 4-inch edge lines were converted to 6-inch edge lines. Additional research is needed to better understand how the use of wider edge lines can have such a significant safety impact while not influencing traditional measures of driver behavior. Ideally, this study would involve real-time coordination between the research team and State agencies to develop a study design that includes locations of wider lines implementation, reference site locations, and real-time monitoring of other characteristics (e.g., retroreflectivity) during the course of the study. While the study would take 3 years or more to compile adequate after data, the benefits would include safety estimates with fewer caveats than the current study.

- An opportunity exists for additional research to better understand how different types of low-cost safety treatments affect different crash types and severities. This will result in more precise considerations when prioritizing their use at specific locations. For instance, it is unlikely that one could experience an additive safety impact by installing both rumble strips and wider edge lines. Do these low-cost safety treatments impact all crashes similarly, or are there some crash types that are more affected by one treatment than the other?

- This study focused primarily on the use of wider edge lines and not on wider centerlines (the Illinois data did provide the opportunity to look at 5-inch edge lines and centerlines, but within a cross-sectional study). A follow-up question that has already surfaced is, “What would be the result of increasing both the edge line and centerline width?” Similarly, would the impact on rural two-lane highways be even greater if 8-inch edge lines were used?

APPENDIX A. 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 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 office, the study sites were carefully selected so that they were representative, similar, and on newly installed pavements that would not need major maintenance during the life of this study. All 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. All test sections were applied along tangent sections.

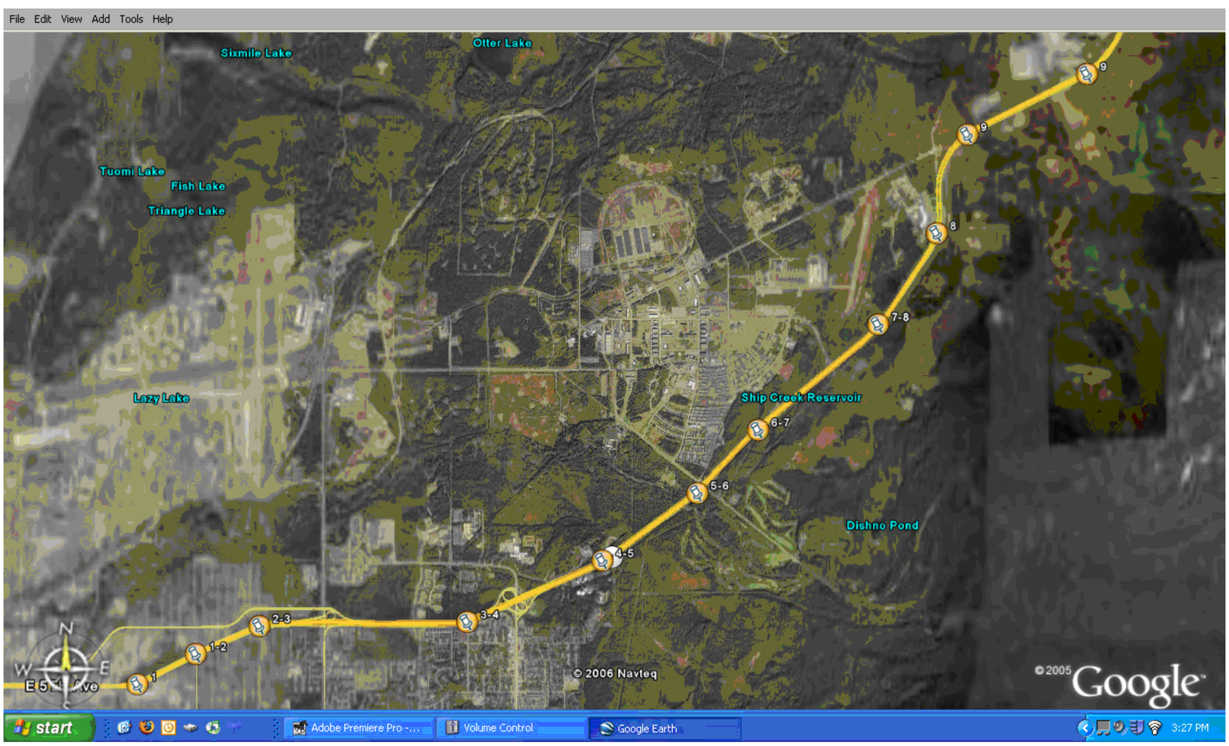
PAVEMENT MARKING PREPARATION FOR INLAID MARKINGS

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 (inlaid). This required that within each test section, half of the section needed the current markings to be eradicated, leaving a clean surface for installation. The second half of the test section needed to be grooved to an adequate depth so that the marking would be inlaid (recessed) below the road surface. The specific parameters of the grooving for the inlaid 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 inlaid marking section. The grooving machines would typically go somewhat 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 PAVEMENT MARKING TEST DECK AREA

Figure 52. Photo. Glenn Highway (SR 1 in Anchorage, AK).



©Navteq and Google

Figure 53. Screenshot. Proposed pavement marking installation sites (Anchorage, AK).[119]

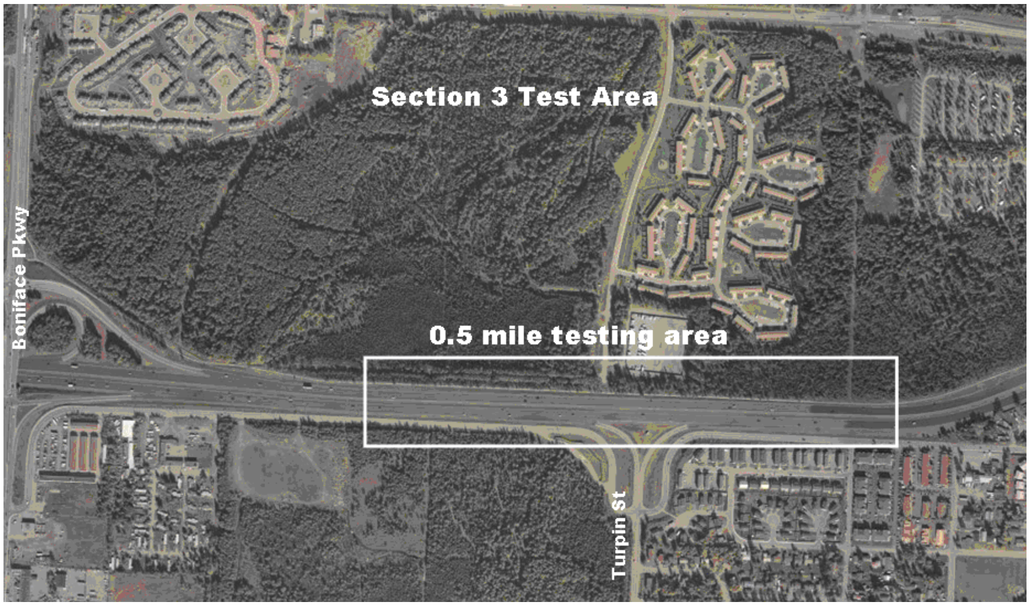


Figure 54. Photo. Test section 3 (Anchorage, AK).

Figure 55. Photo. Test section 5 (Anchorage, AK).

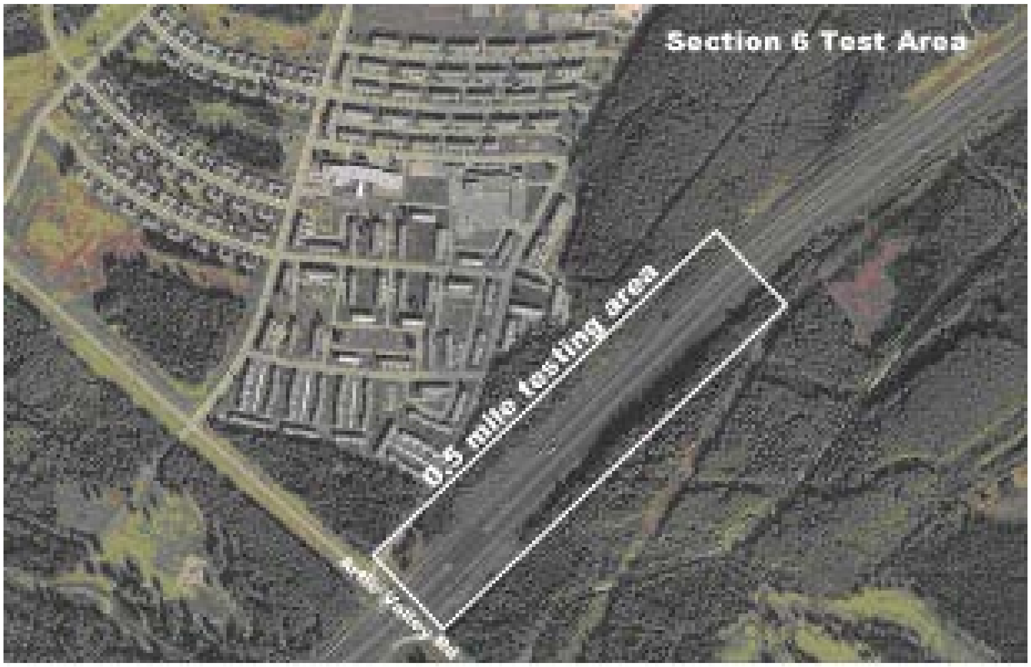


Figure 56. Photo. Test section 6 (Anchorage, AK).

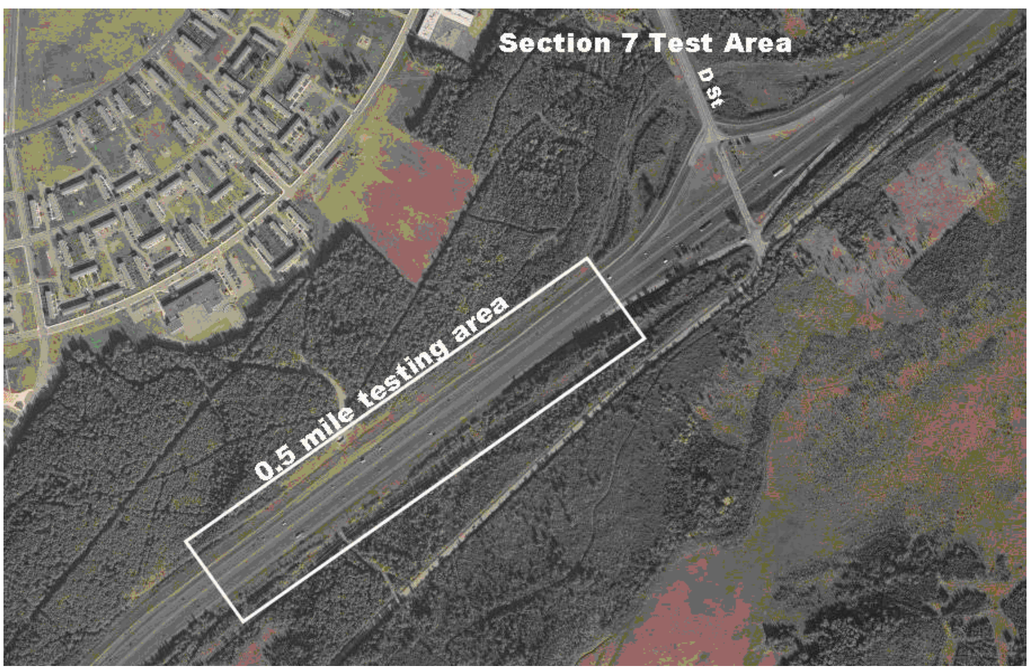


Figure 57. Photo. Test section 7 (Anchorage, AK).

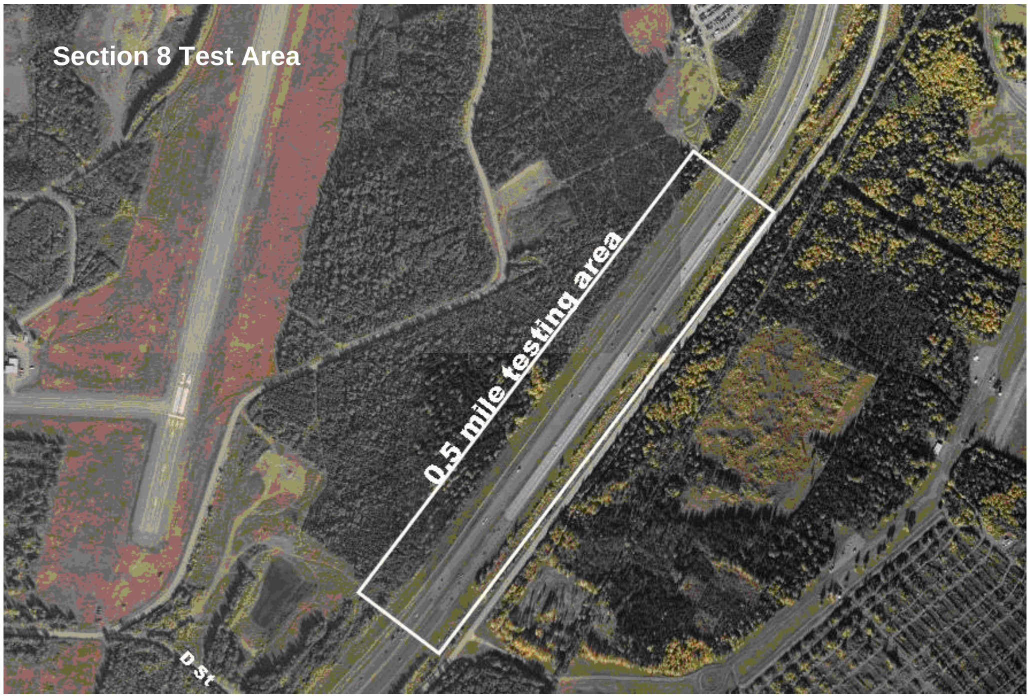


Figure 58. Photo. Test section 8 (Anchorage, AK).

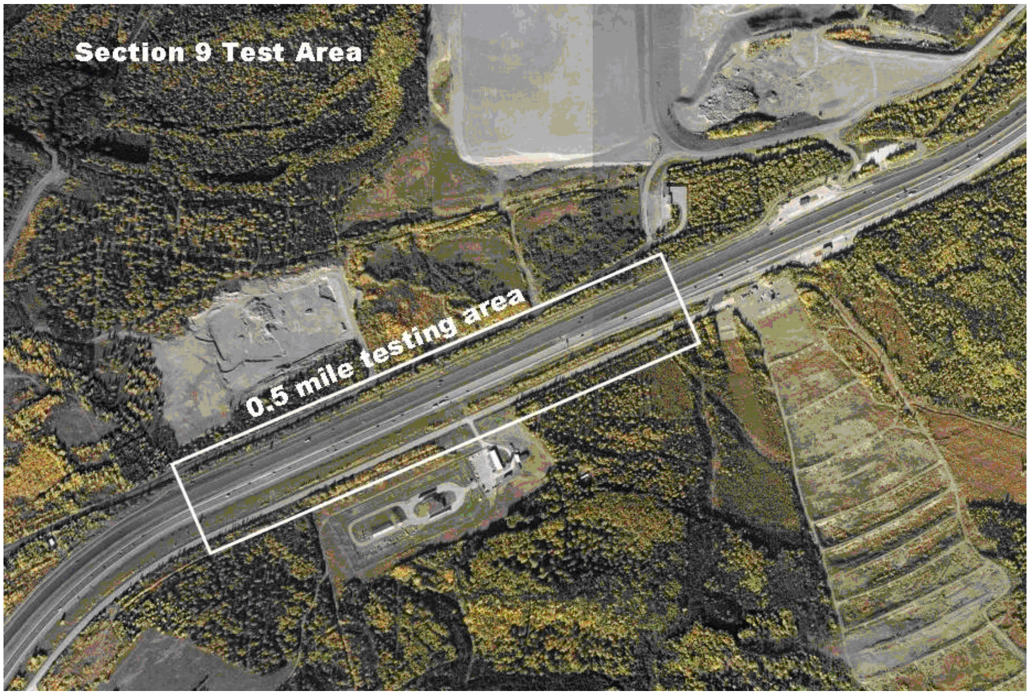


Figure 59. Photo. Test section 9 (Anchorage, AK).

ANCHORAGE PAVEMENT MARKINGS

Table 69. Initially installed pavement marking in Anchorage, AK.

Test Section	Marking Type	Application Type	Placement	Groove Depth (mil)	Material Thickness (mil)	Bead Type
1 AK a	AKDOT low-VOC paint	Spray	Surface	0	12	AASHTO M247[33]
			Shallow (inlaid)	65	12	
			Deep (inlaid)	160	12	
2 AK a	3M all-weather paint	Spray	Shallow (inlaid)	65	30	Swarco type 2 and 3M elements
			Deep (inlaid)	160	30	
3 AK a	MMA 98:2 (Stirling Lloyd)	Extruded	Shallow (inlaid)	70	100	Type 2
			Deep (inlaid)	175	100	
4 AK a	MMA 98:2 (Stirling Lloyd)	Agglomerate	Shallow (inlaid)	90,	200	Type 2
			Deep (inlaid)	275	200	
5 AK a	3M pavement marking tape 380IES	Rolled	Deep (inlaid)	175	100	N/A
5 AK b	3M pavement marking tape 380WR	Rolled	Deep (inlaid)	175	100	N/A
6 AK a	MMA 4:1 (Ennis)	Extruded	Shallow (inlaid)	60	100	30/50 Mesh Swarco Megalux T13 coated
			Deep (inlaid)	120	100	
6 AK b	Modified urethane (IPS)	Spray	Surface	0	20	Potters type 1 AC110 coating and type 4 Visibead plus 2
			Shallow (inlaid)	70	20	
			Deep (inlaid)	120	20	
7 AK a	Low-temperature acrylic waterborne paint (Ennis)	Spray	Surface	0	12	Swarco AASHTO M247[33]
			Shallow (inlaid)	140	12	
			Deep (inlaid)	175	12	
8 AK a	MMA 4:1 (Degussa—Pathfinder™)	Agglomerate	Shallow (inlaid)	120	200	Swarco AASHTO M247[33]
			Deep (inlaid)	320	200	
9 AK a	High-build acrylic waterborne paint (Ennis)	Spray	Shallow (inlaid)	60	30	Swarco Megalux type 3
			Deep (inlaid)	145	30	
10 AK a	Polyurea (IPS)	Spray	Shallow (inlaid)	65	20	Potters type 1 AC110 coating and type 4 Visibead plus 2
			Deep (inlaid)	155	20	

N/A = Not applicable.
Note: The installation of edge lines and outside lane lines occurred on August 7, 2006. Section 1 AK a was applied with long-line striping equipment; all other sections were hand cart applied.

Table 70. Pavement markings installed after the first winter in Anchorage, AK.

Date	Test Section	Marking Type	Application Type	Placement	Groove Depth (mil)	Material Thickness (mil)	Bead Type
6/21/2007	All	AKDOT low-VOC paint	Spray	Over existing	Existing	12	AASHTO M247[33]
9/24/2007	1 AK b	Flint Trading Premark preformed thermoplastic	Heat in place	Deep (inlaid)	160	125	N/A
10/2/2007	2 AK b	Standard AKDOT MMA	Spray	Shallow (inlaid)	85	60	AASHTO M247[33]
				Deep (inlaid)	180	60	

N/A = Not applicable.
Note: Paint and MMA were applied with long-line striping equipment; preformed thermoplastic was hand cart applied.

Table 71. Pavement markings installed after the second winter in Anchorage, AK.

Date	Test Section	Marking Type	Application Type	Placement (Inlaid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type
8/5/2008	9 AK b	MMA (Ennis), paint (Pervo)	Extruded with raised edges, double spray	Shallow (inlaid)	60	10,	30/50 Mesh, 30-30-40 Swarco mega blend
				Shallow and deep (inlaid)	60 and 145	40	
8/5/2008	7 AK b	MMA (Ennis), paint (Pervo)	Extruded with raised edges, spray	(Deep)	175	100	30/50 Mesh, 30-30-40 Swarco mega blend
					175	20	

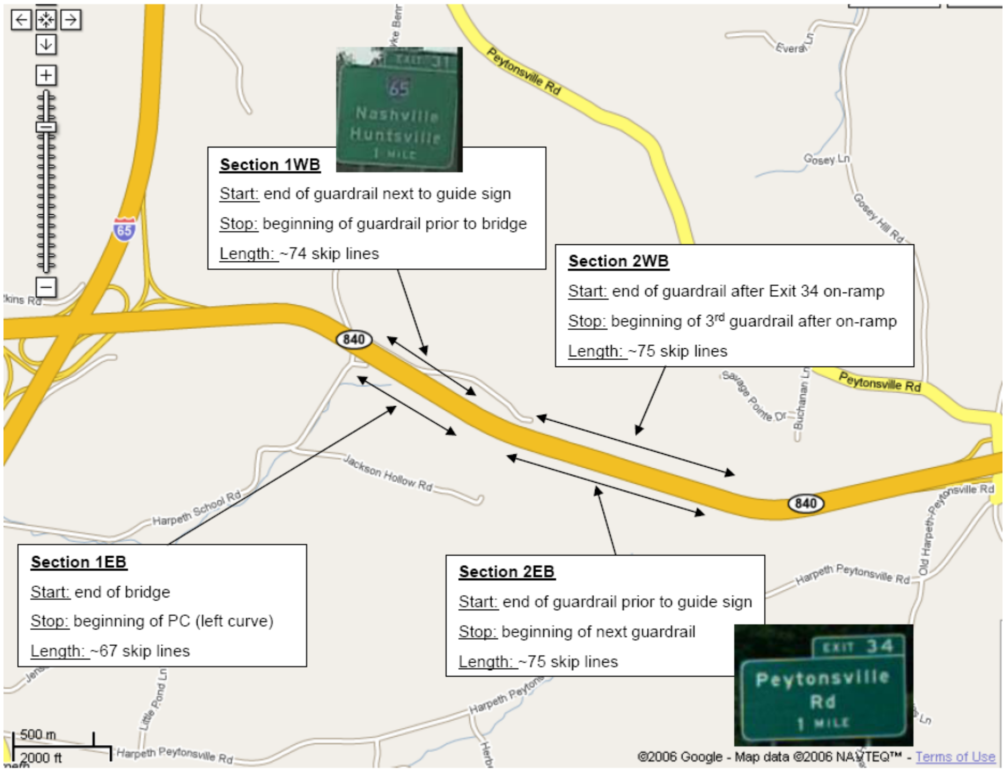
Note: Paint was applied with long-line striping equipment; MMA was hand cart applied.

NASHVILLE PAVEMENT MARKING TEST DECK AREA

Figure 60. Photo. SR 840 (Nashville, TN).

©Google and Navteq

Figure 61. Illustration. Proposed pavement marking installation sites (Nashville, TN).[120]

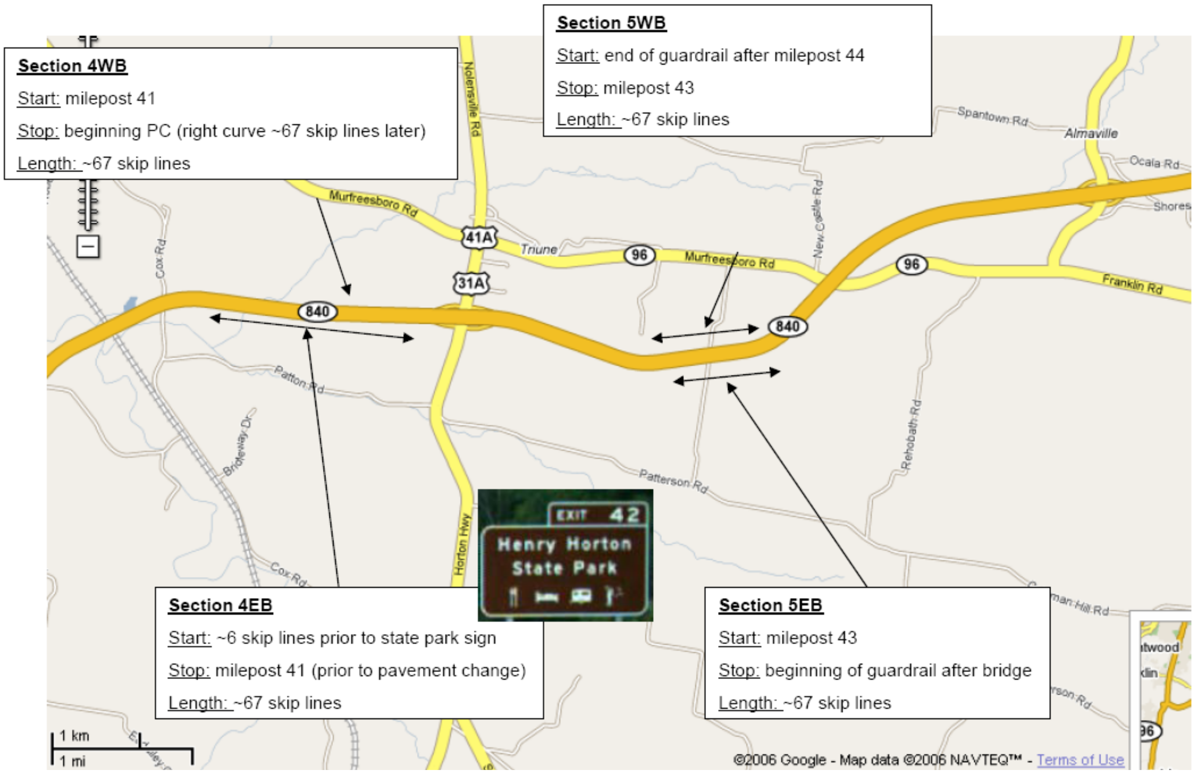


©Google and Navteq

Figure 62. Illustration. Test sections 1 and 2 (Nashville, TN).(120)

©Google and Navteq

Figure 63. Illustration. Test section 3 (Nashville, TN).(120)



©Google and Navteq

Figure 64. Illustration. Test sections 4 and 5 (Nashville, TN).(120)

NASHVILLE PAVEMENT MARKINGS

Table 72. Pavement markings in Nashville, TN.

Test Section	Marking Type	Application Type	Placement (Inlaid)	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 (inlaid)	75	40	Potters type 1 AC110 coating	8 lb/100 ft^2
			Deep (inlaid)	185	40		
3 TN-N	Thermoplastic (Ennis)	Spray	Shallow (inlaid)	85	90	Potters type 1 AC110 coating	8 lb/100 ft^2
			Deep (inlaid)	270	90		
4 TN-N	Thermoplastic (Ennis)	Extruded	Shallow (inlaid)	95	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
			Deep (inlaid)	180	120		
5 TN-N	Thermoplastic (Gulfline)	Inverted profile	Shallow (inlaid)	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 (inlaid)	55	12	Potters type 1 AC110 coating	8 lb/100 ft^2
			Deep (inlaid)	145	12		
7 TN-N	Polyurea (Epoplex)	Spray	Shallow (inlaid)	110	20	Prismo high index cluster and Potters type 4 Visibead plus 2	8 lb cluster and 10 lb type 4 per gallon
			Deep (inlaid)	165	20		
8 TN-N	3M all-weather paint	Spray	Shallow (inlaid)	135	26	Swarco type 2 and 3M elements	18 g type 2 and 7.5 g elements per linear ft
			Deep (inlaid)	175	26		
9 TN-N	High-build acrylic waterborne paint (Ennis)	Spray	Shallow (inlaid)	100	25	Swarco type 3 virgin glass	10–12 lb/100 ft^2
			Deep (inlaid)	175	25		

N/A = Not applicable.

Note: Edge and lane lines were initially installed on October 16, 2006, with long-line striping equipment.

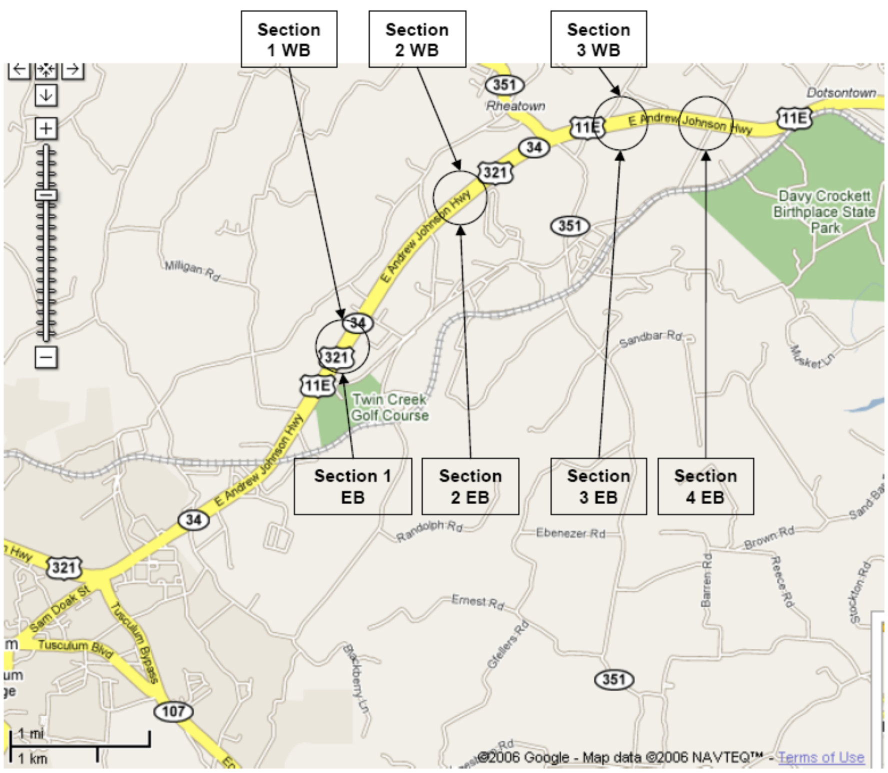
Table 73. Lead-free thermoplastic pavement markings in Nashville, TN.

Test Section	Marking Type	Application Type	Placement (Inlaid)	Groove Depth (mil)	Material Thickness (mil)	Bead Type	Bead Rate
10 TN-N	Ennis lead-free thermoplastic	Extruded	Surface	0	80	AASHTO M247 with AC110 coating[33]	8–10 lb/100 ft^2
11 TN-N	Swarco lead-free thermoplastic	Extruded	Surface	0	80	AASHOT M247 with AC110 coating[33]	8–10 lb/100 ft^2
12 TN-N	Dobco lead-free thermoplastic	Extruded	Surface	0	85	AASHOT M247 with AC110 coating[33]	8–10 lb/100 ft^2

Note: All pavement markings were installed on June 5, 2008, with long-line striping equipment.

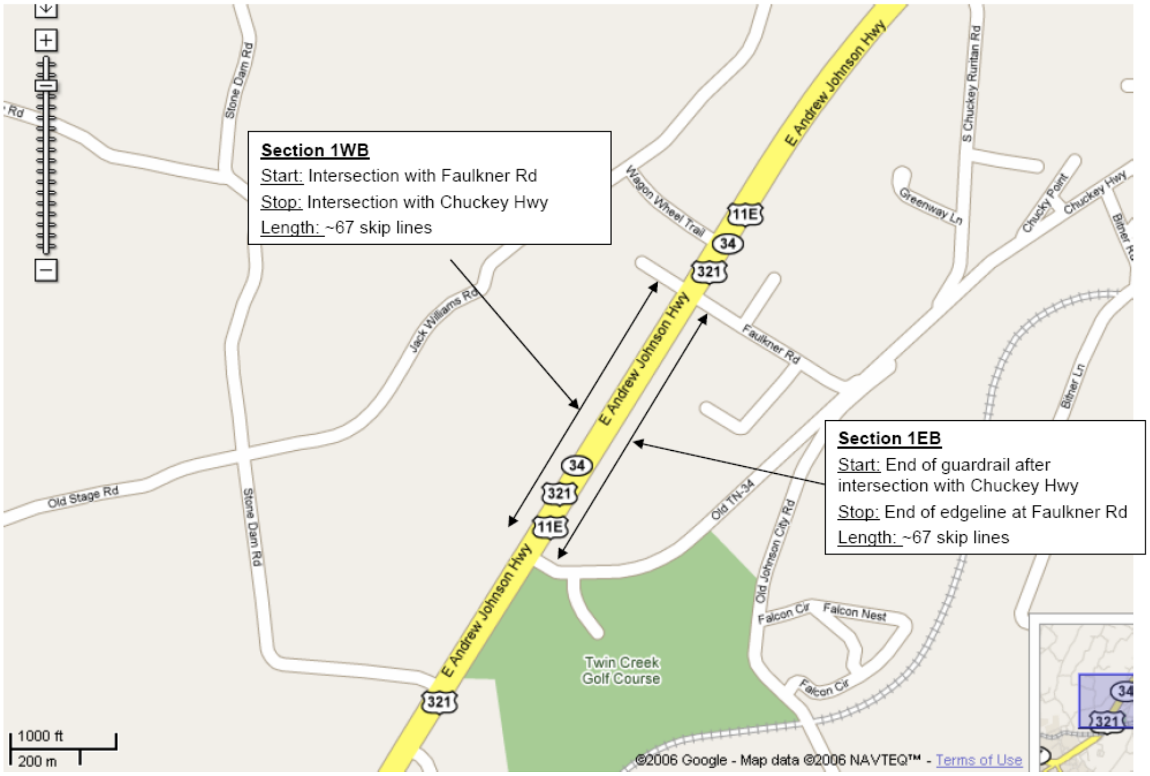
TUSCULUM PAVEMENT MARKING TEST DECK AREA

Figure 65. Photo. SR 34 (Tusculum, TN).



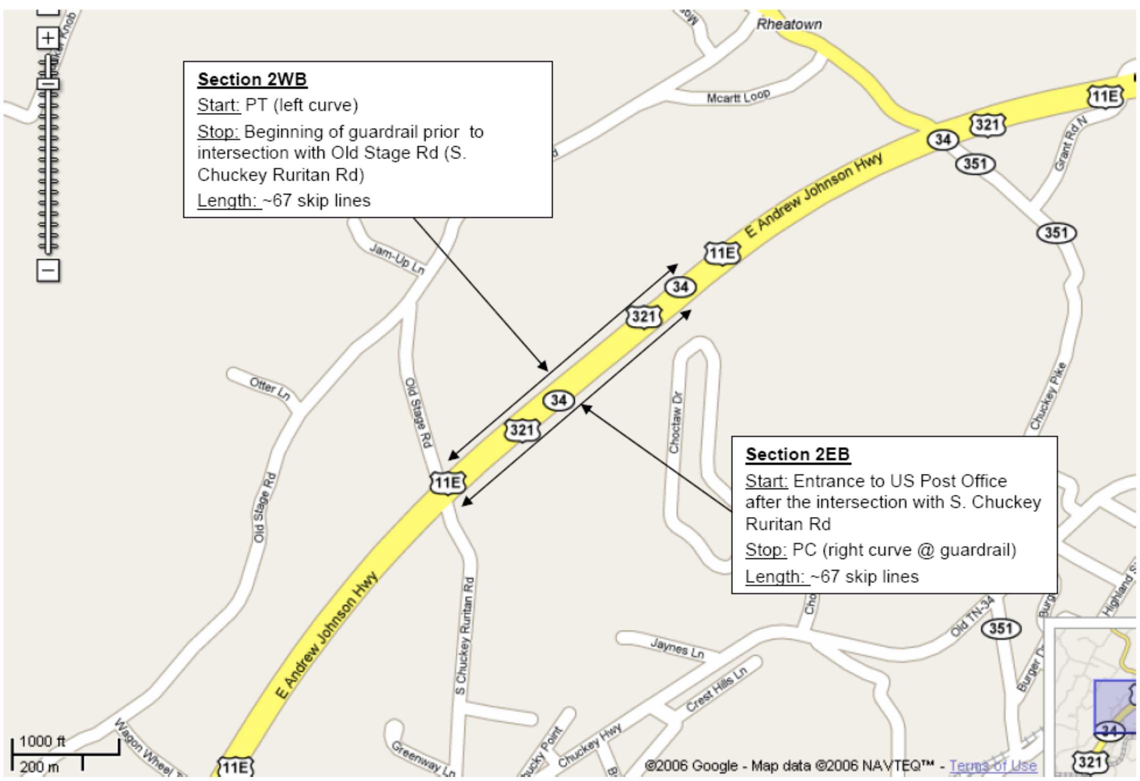
©Google and Navteq

Figure 66. Illustration. Proposed pavement marking installation sites (Tusculum, TN).[121]



©Google and Navteq

Figure 67. Illustration. Test section 1 (Tusculum, TN).(121)



©Google and Navteq

Figure 68. Illustration. Test section 2 (Tusculum, TN).(121)

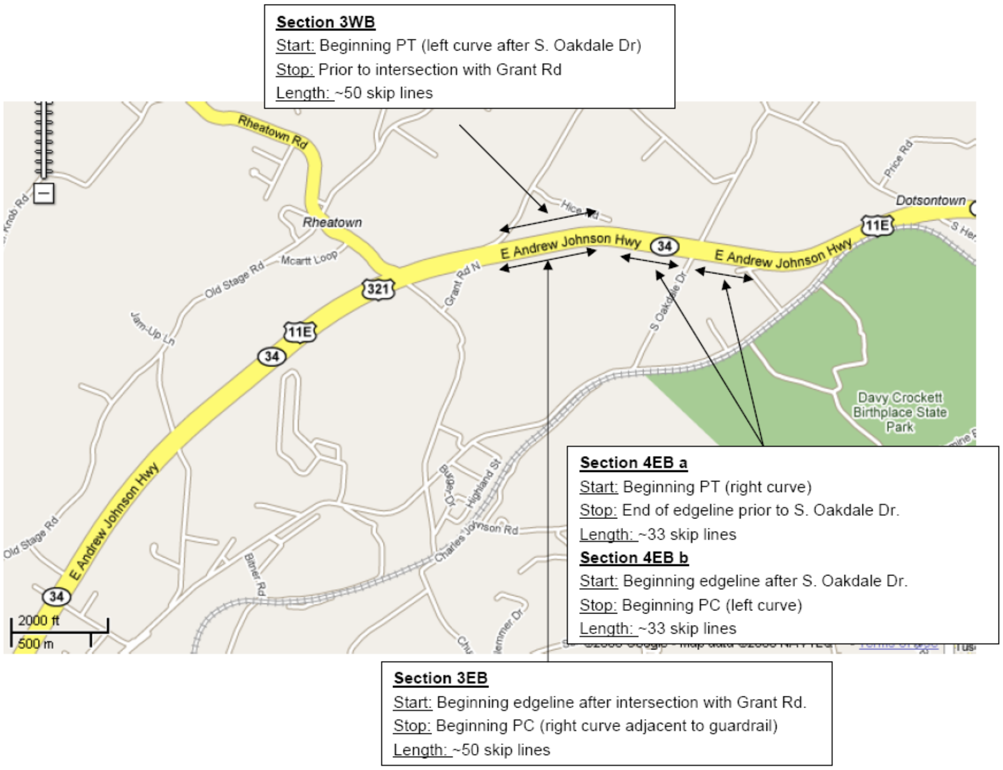


Figure 69. Illustration. Test sections 3 and 4 (Tusculum, TN).(121)

TUSCULUM PAVEMENT MARKINGS

Table 74. Pavement markings in Tusculum, TN.

Test Section	Marking Type	Application Type	Placement	Groove Depth (mil)	Material Thickness (mil)	Bead Type	Bead Rate
1 TN-T	Modified epoxy (Epoplex)	Spray	Shallow (inlaid)	100	22	Type 4 Visibead plus 2 = E16, type 1 MnDOT spec	10 lb type 4 and 6 lb type 1 per 100 ft^2
			Deep (inlaid)	125			
2 TN-T a	MMA (Degussa)	Extruded	Shallow (inlaid)	100	90	Swarco AASHTO M247(33)	8–10 lb/100 ft^2
			Deep (inlaid)	170			
2 TN-T b	MMA (Degussa—Pathfinder™)	Agglomerate	Shallow(inlaid)	100	200	Swarco AASHTO M247(33)	8–10 lb/100 ft^2
			Deep (inlaid)	170			
3 TN-T	Low-temperature acrylic waterborne paint (Ennis)	Spray	Shallow(inlaid)	50	15	AASHTO M247(33)	8 lb/100 ft^2
			Deep (inlaid)	110			
4 TN-T	High-build acrylic waterborne paint (Ennis)	Spray	Shallow(inlaid)	105	24	Potters type 4 Visibead plus 2	12 lb/100 ft^2
			Deep (inlaid)	150			
5 TN-T a	ATM pavement marking tape 300	Rolled	Shallow (inlaid)	60	100	N/A	N/A
			Deep (inlaid)	130			
5 TN-T b	ATM pavement marking tape 400	Rolled	Shallow(inlaid)	25	100	N/A	N/A
			Deep (inlaid)	195			
6 TN-T	TN standard thermoplastic (superior)	Extruded	Shallow(inlaid)	70	90	Swarco AASHTO M247(33)	8–10 lb/100 ft^2
			Deep (inlaid)	320			
7 TN-T	Modified urethane (IPS)	Spray	Shallow(inlaid)	110	15	Type 4 Visibead plus 2 = E16, type 1 MnDOT spec	10 lb type 4 and 8 lb type 1 per 100 ft^2
			Deep (inlaid)	170			

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. Edge line and lane lines were initially installed May 14, 2007.

APPENDIX B. PAVEMENT MARKING RETROREFLECTIVITY DEGRADATION GRAPHS

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

ALASKA TEST DECK

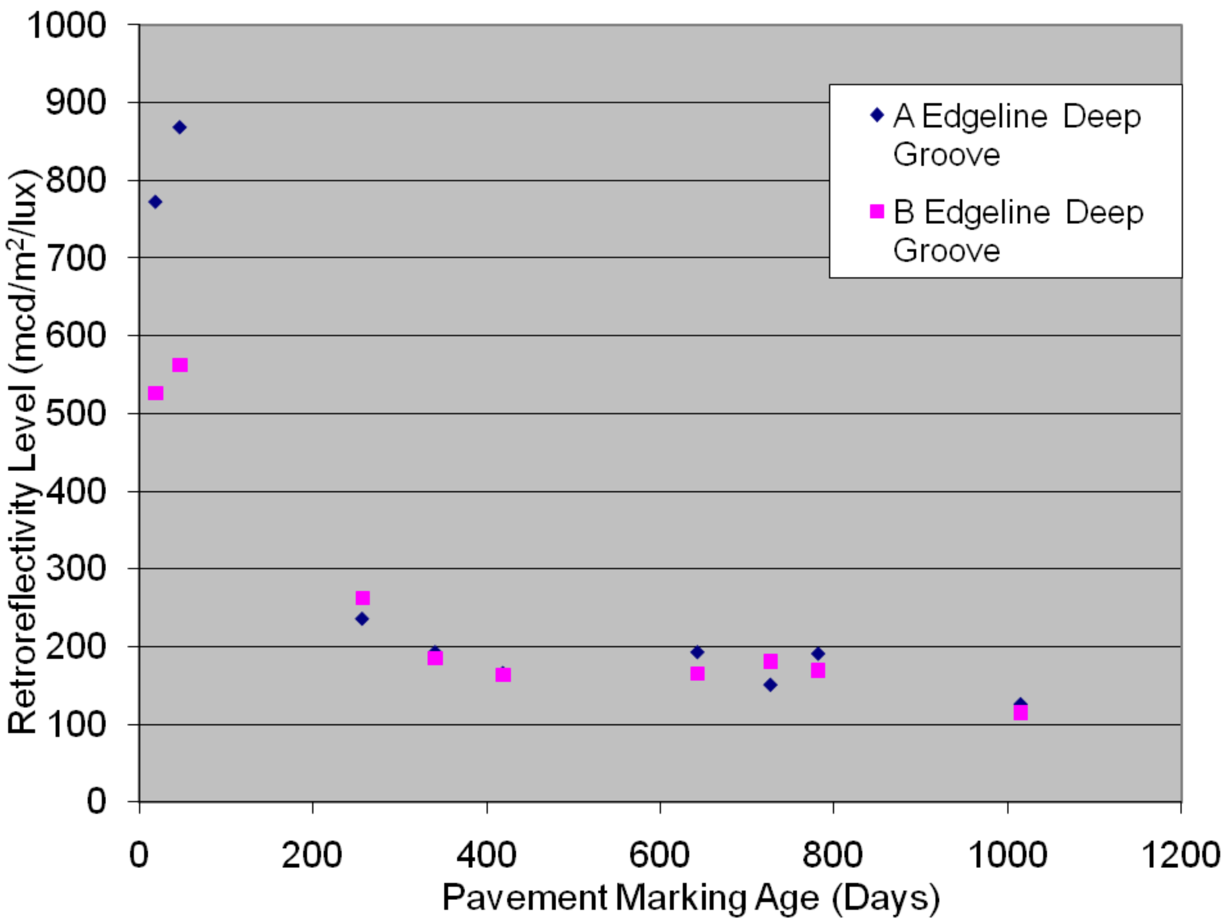


Figure 70. Graph. Retroreflectivity degradation sections 5 AK a and 5 AK b.

NASHVILLE, TN, TEST DECK

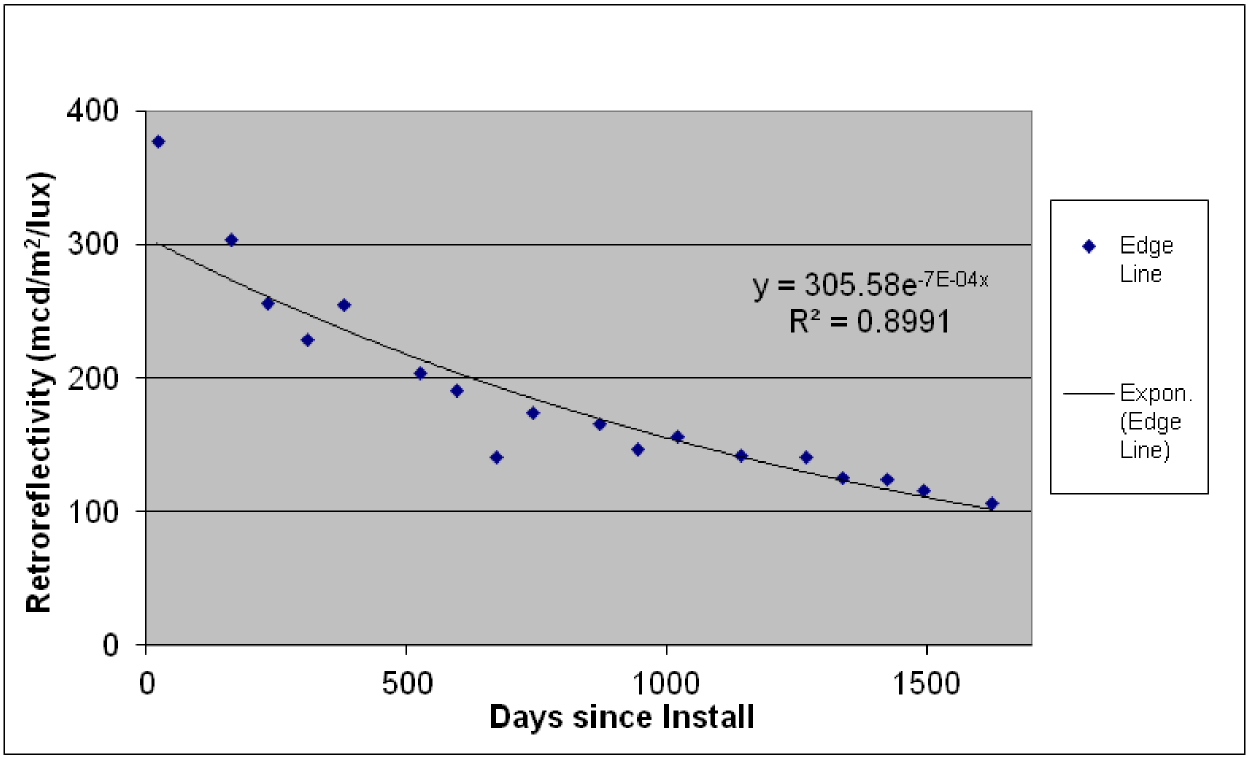


Figure 71. Graph. Retroreflectivity degradation section 1 TN-N.

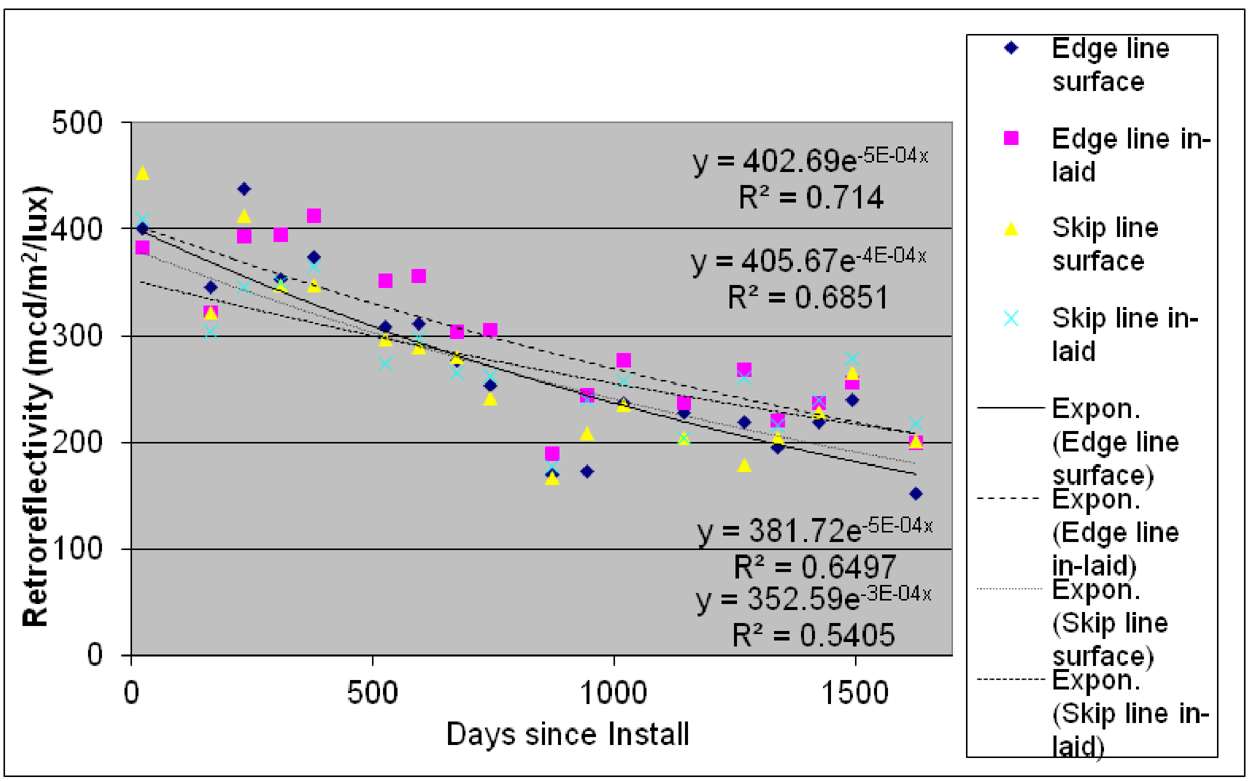


Figure 72. Graph. Retroreflectivity degradation section 2 TN-N.

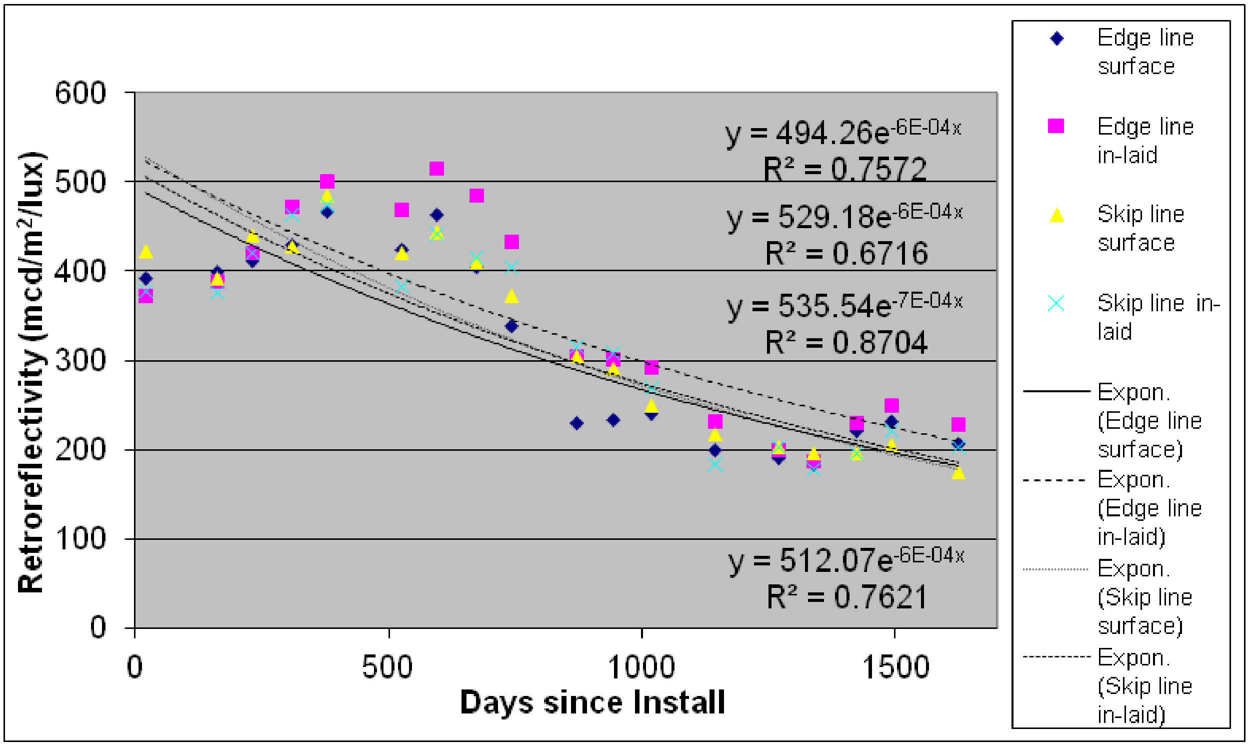


Figure 73. Graph. Retroreflectivity degradation section 3 TN-N.

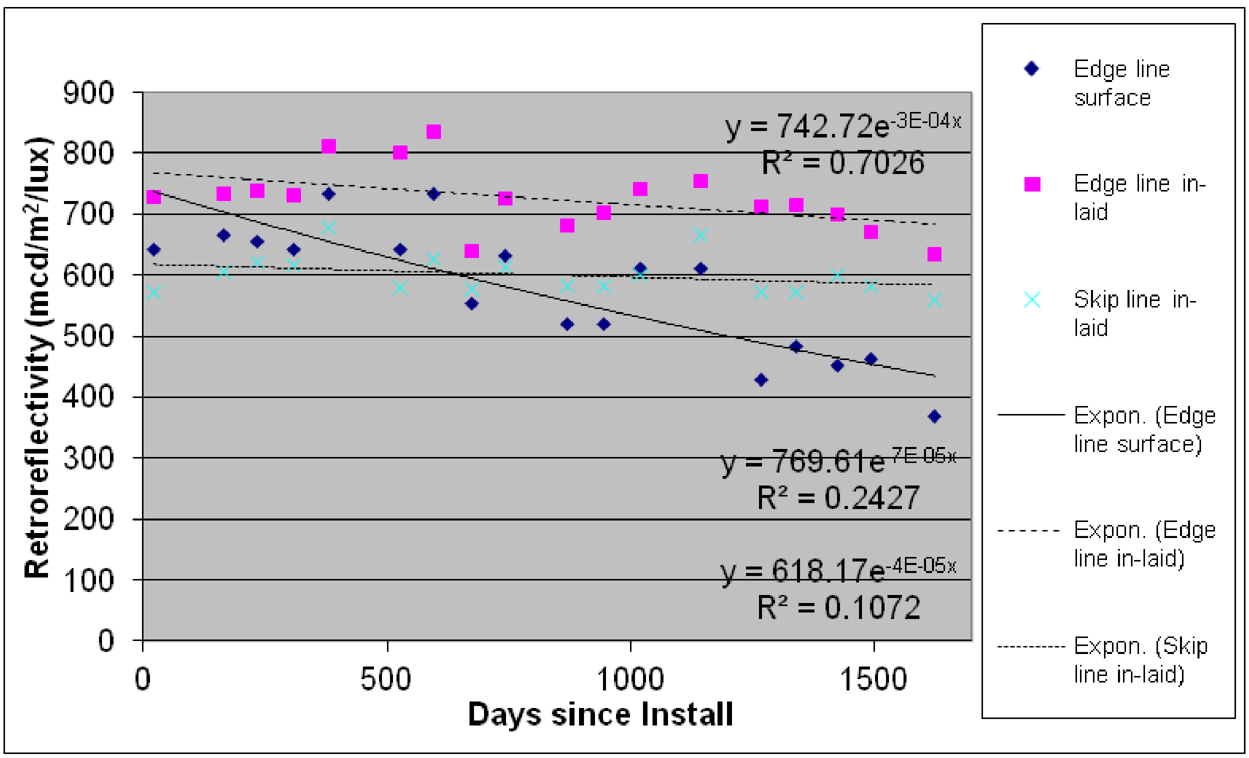


Figure 74. Graph. Retroreflectivity degradation section 4 TN-N.

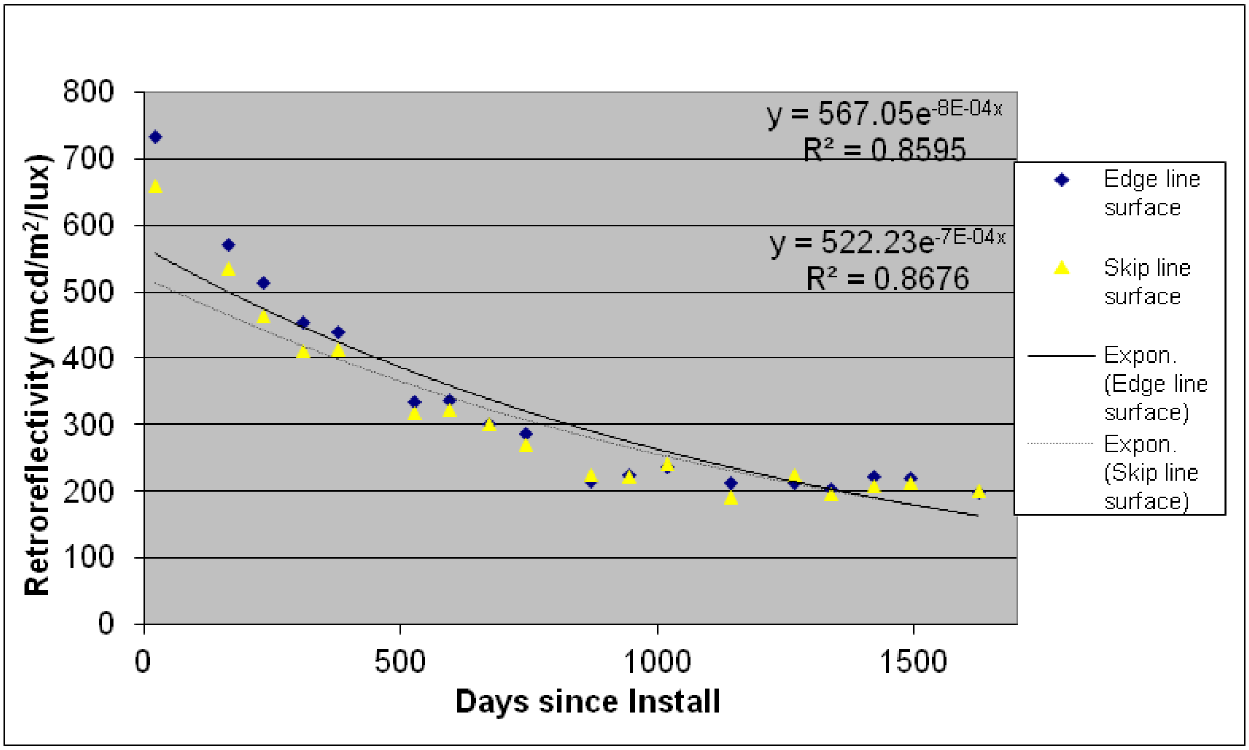


Figure 75. Graph. Retroreflectivity degradation section 5 TN-N.

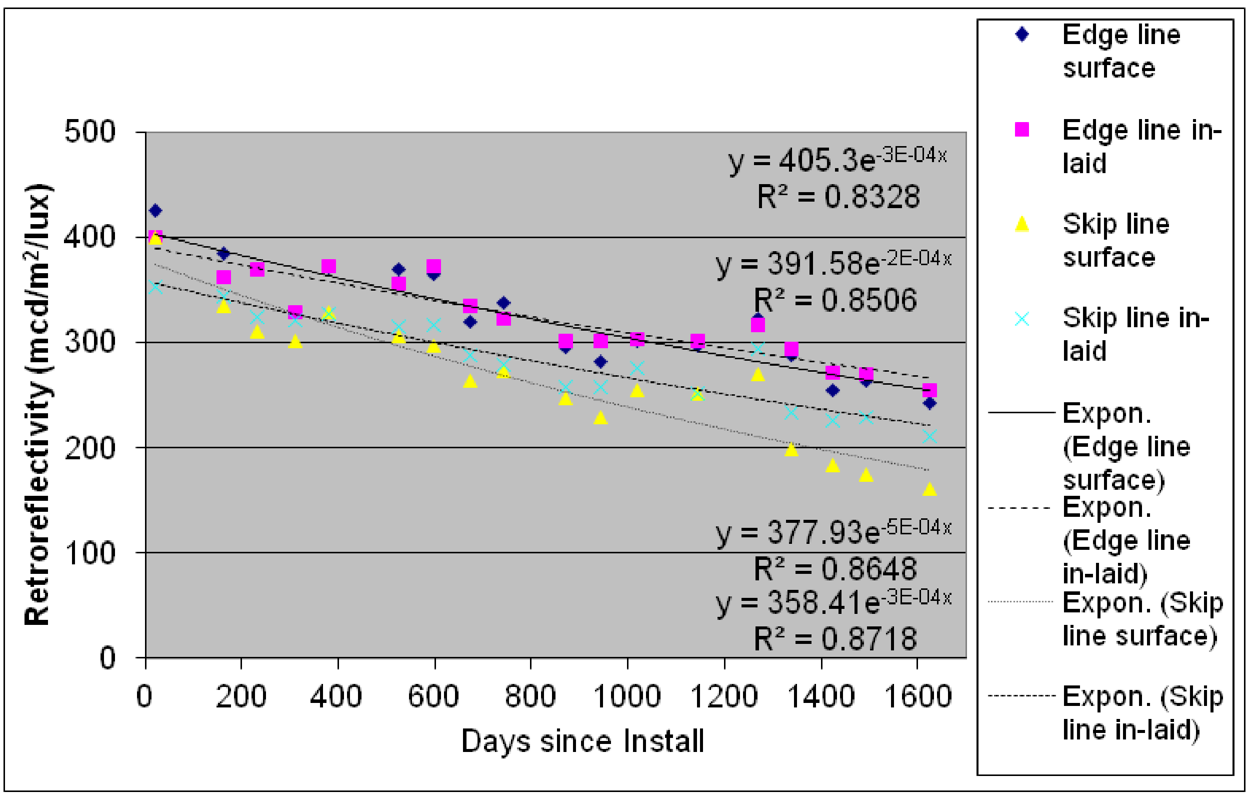


Figure 76. Graph. Retroreflectivity degradation section 6 TN-N.

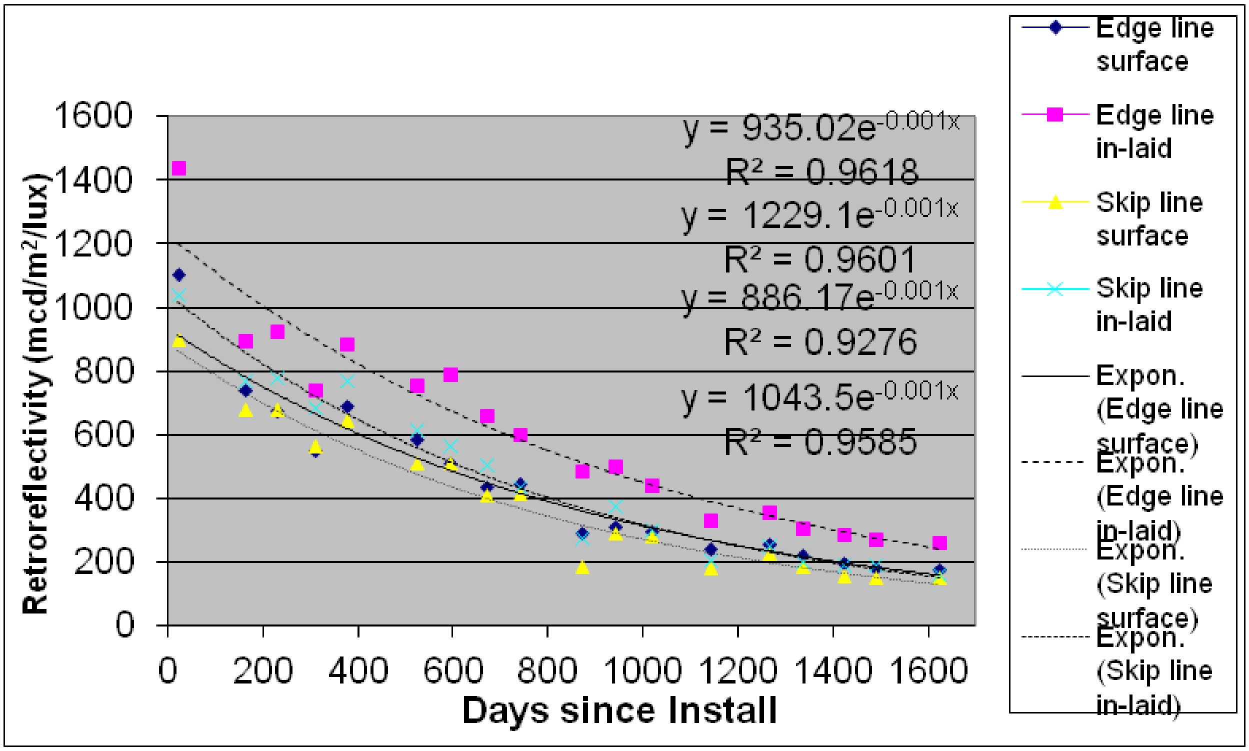


Figure 77. Graph. Retroreflectivity degradation section 7 TN-N.

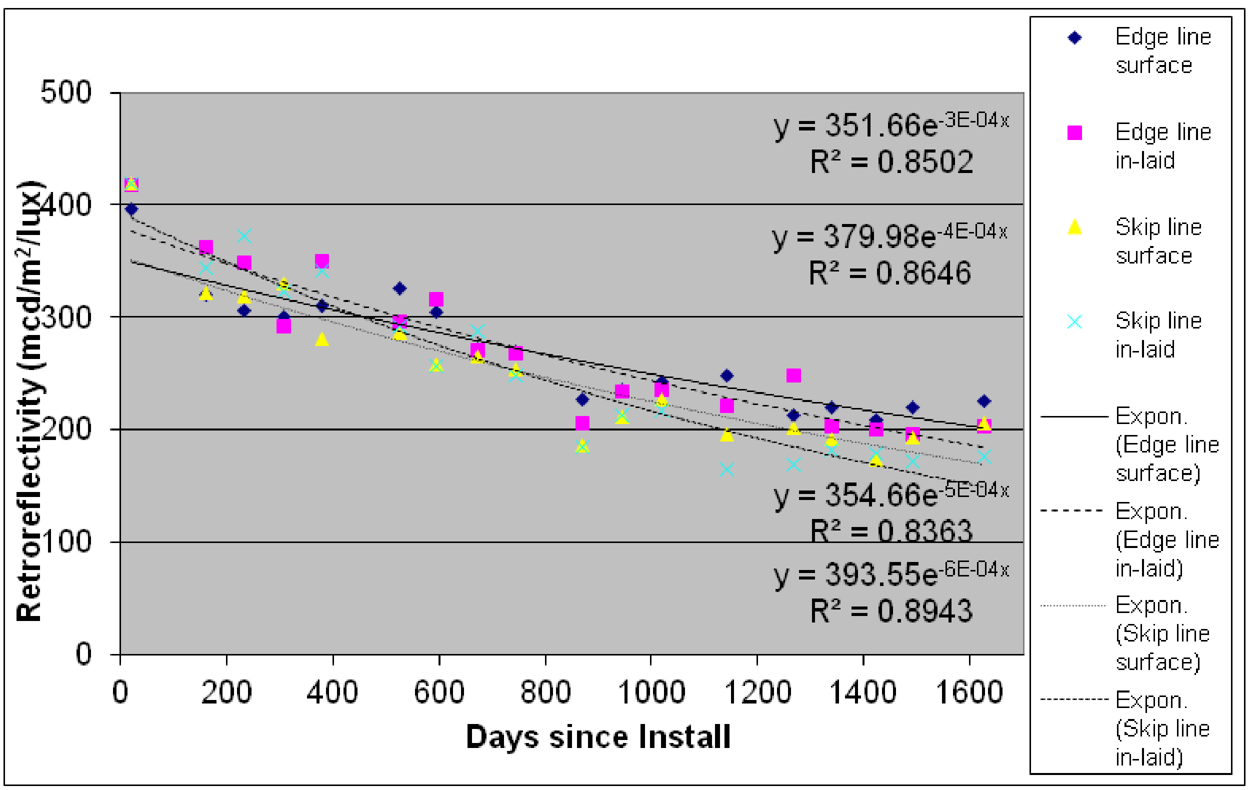


Figure 78. Graph. Retroreflectivity degradation section 8 TN-N.

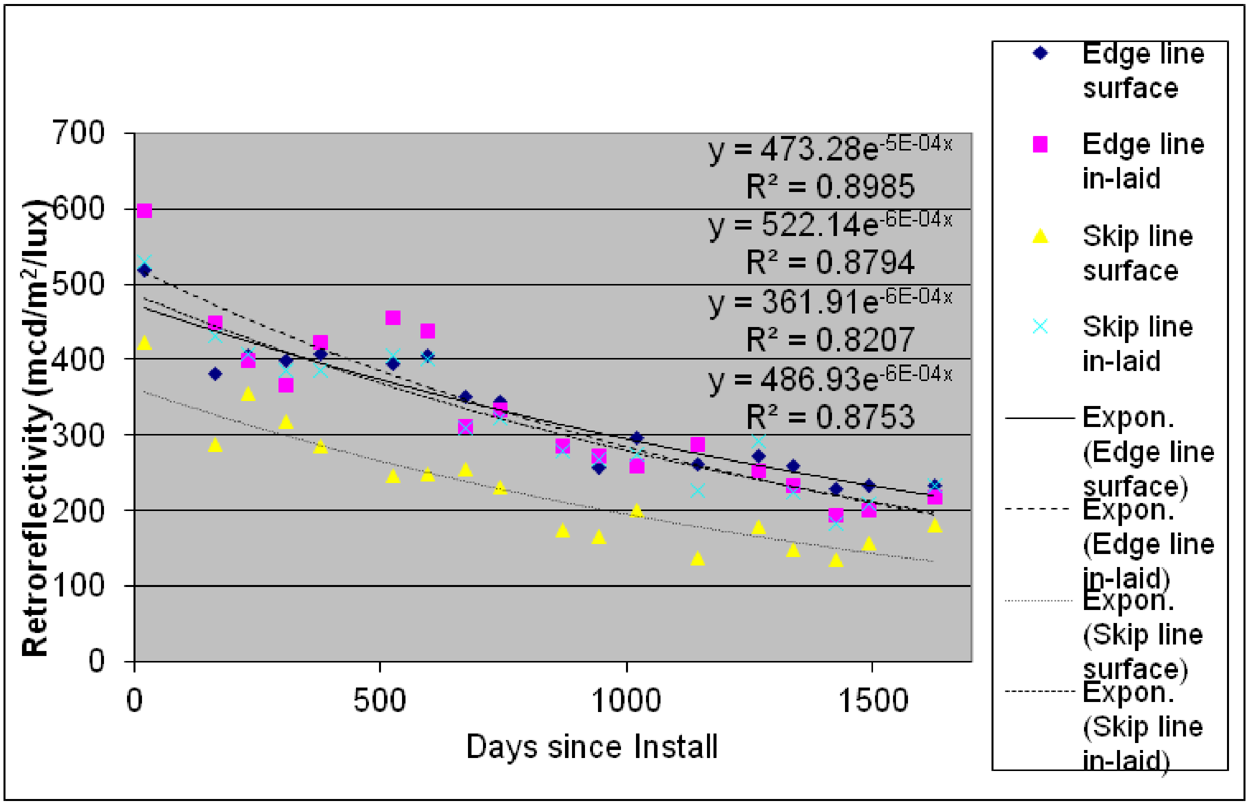


Figure 79. Graph. Retroreflectivity degradation section 9 TN-N.

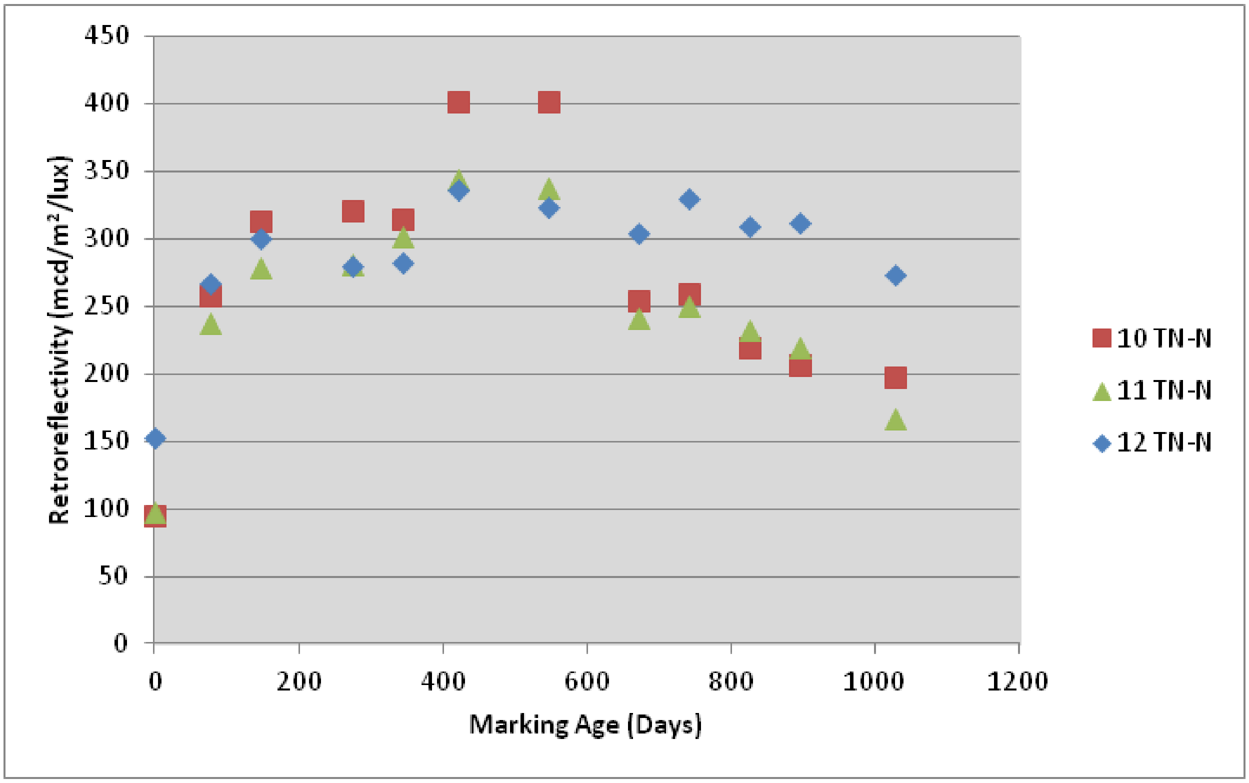


Figure 80. Graph. Retroreflectivity degradation sections 10 TN-N, 11 TN-N, and 12 TN-N.

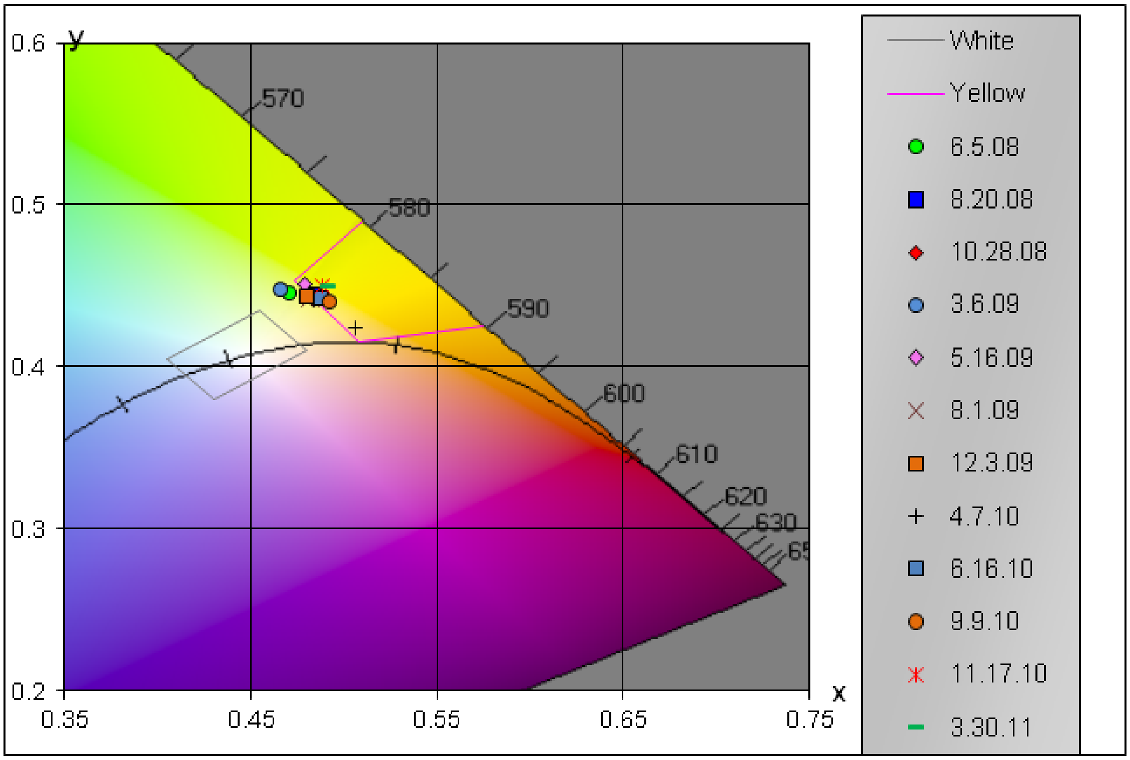


Figure 81. Graph. Nighttime 98-ft (30-m) color degradation section 10 TN-N.

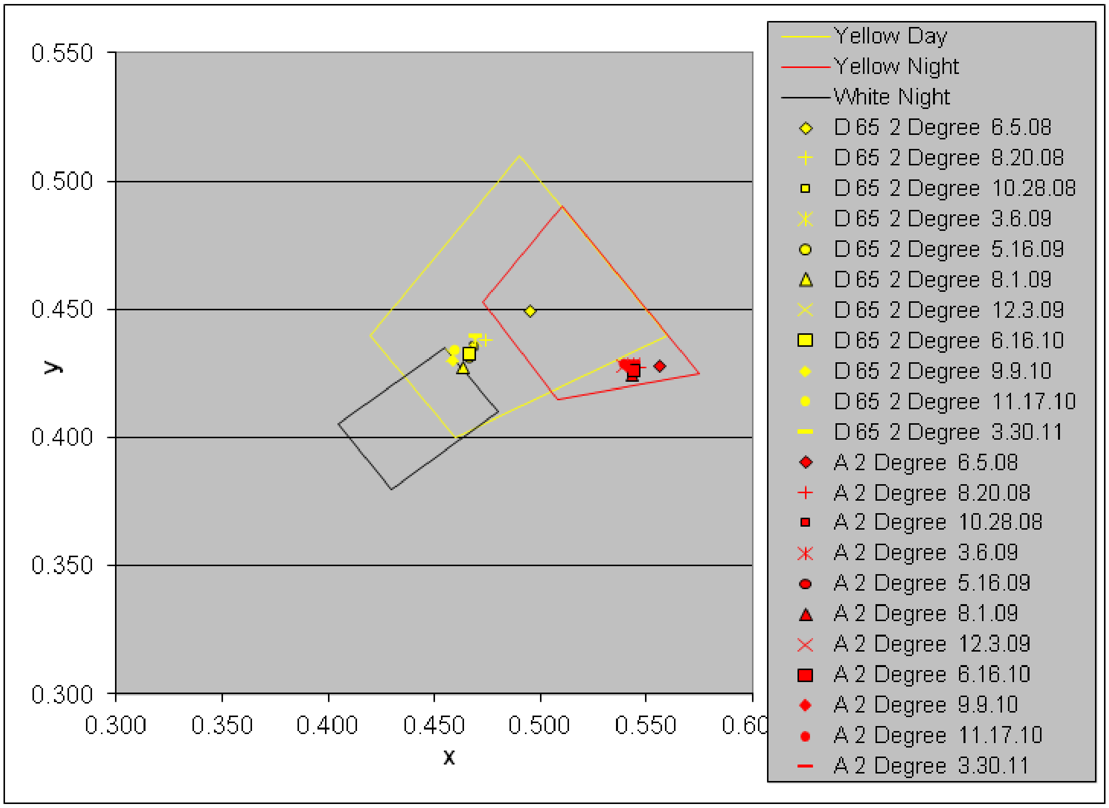


Figure 82. Graph. 45-degree/0-degree color degradation section 10 TN-N.

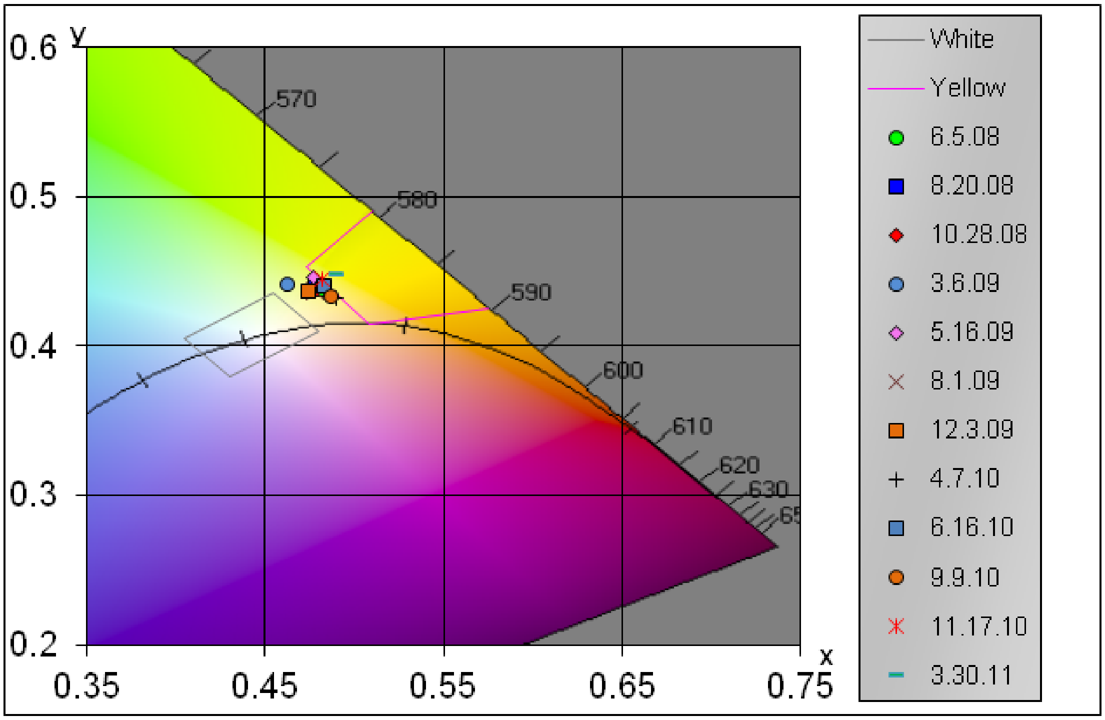


Figure 83. Graph. Nighttime 98-ft (30-m) color degradation section 11 TN-N.

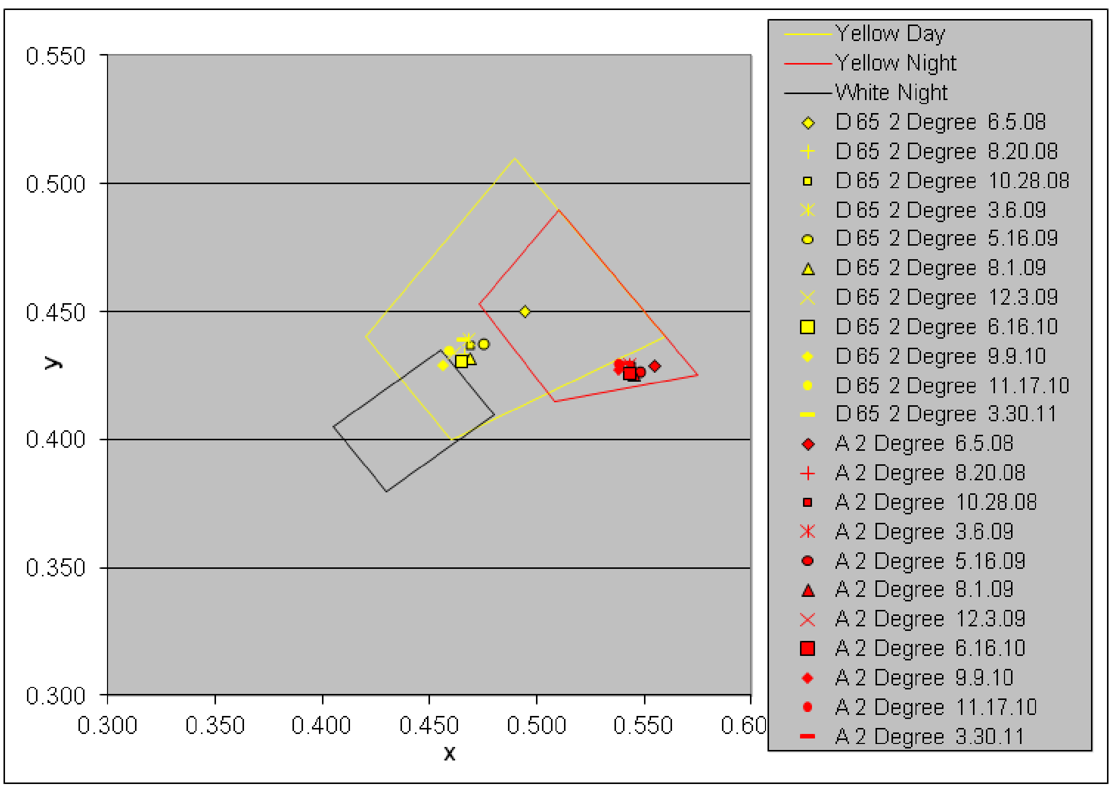


Figure 84. Graph. 45-degree/0-degree color degradation section 11 TN-N.

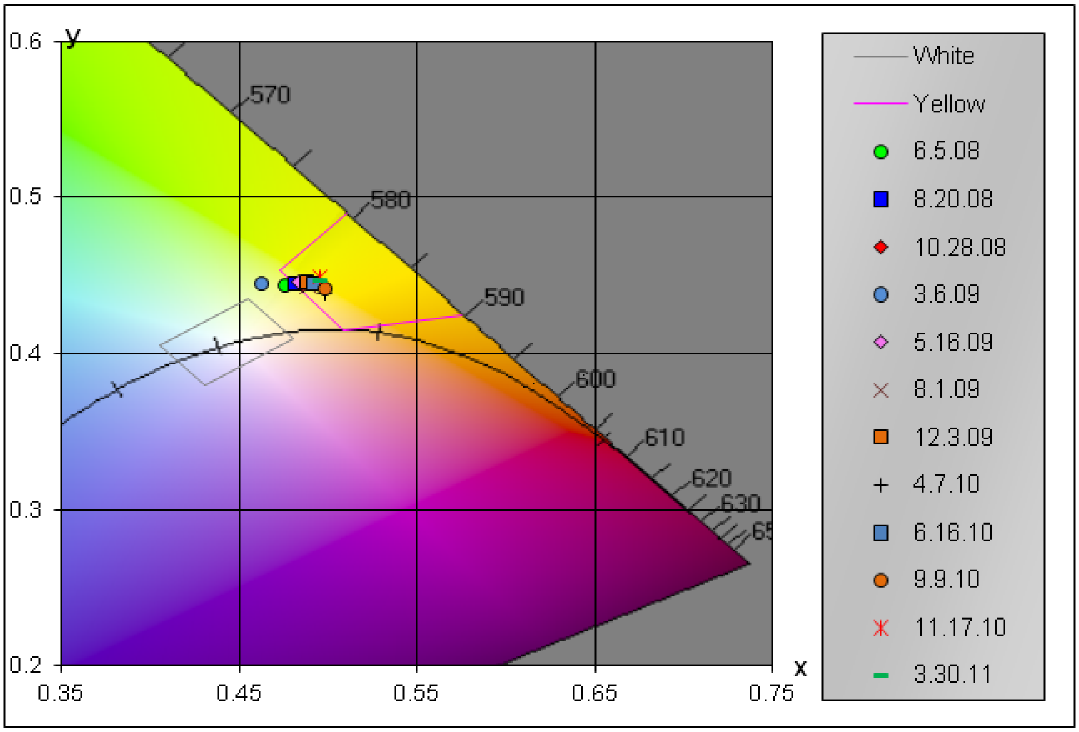


Figure 85. Graph. Nighttime 98-ft (30-m) color degradation section 12 TN-N.

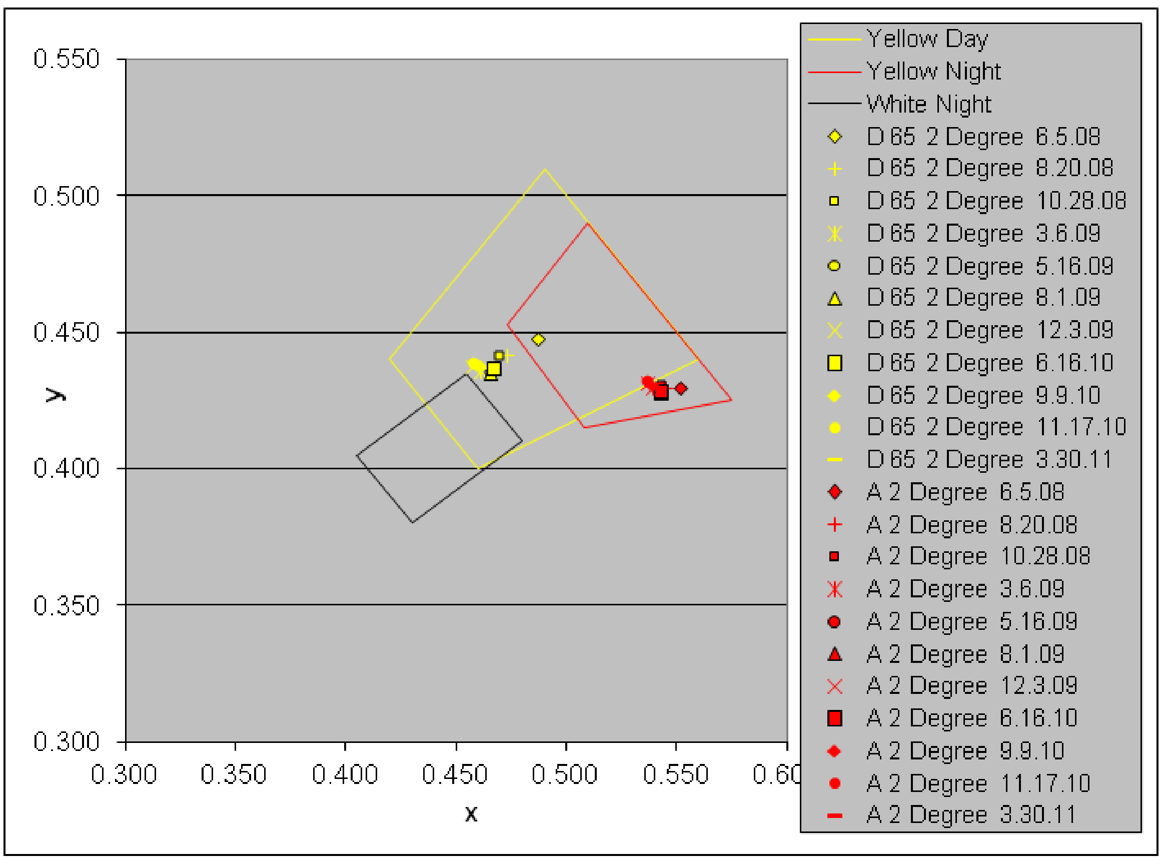


Figure 86. Graph. 45-degree/0-degree color degradation section 12 TN-N.

TUSCULUM, TN, TEST DECK

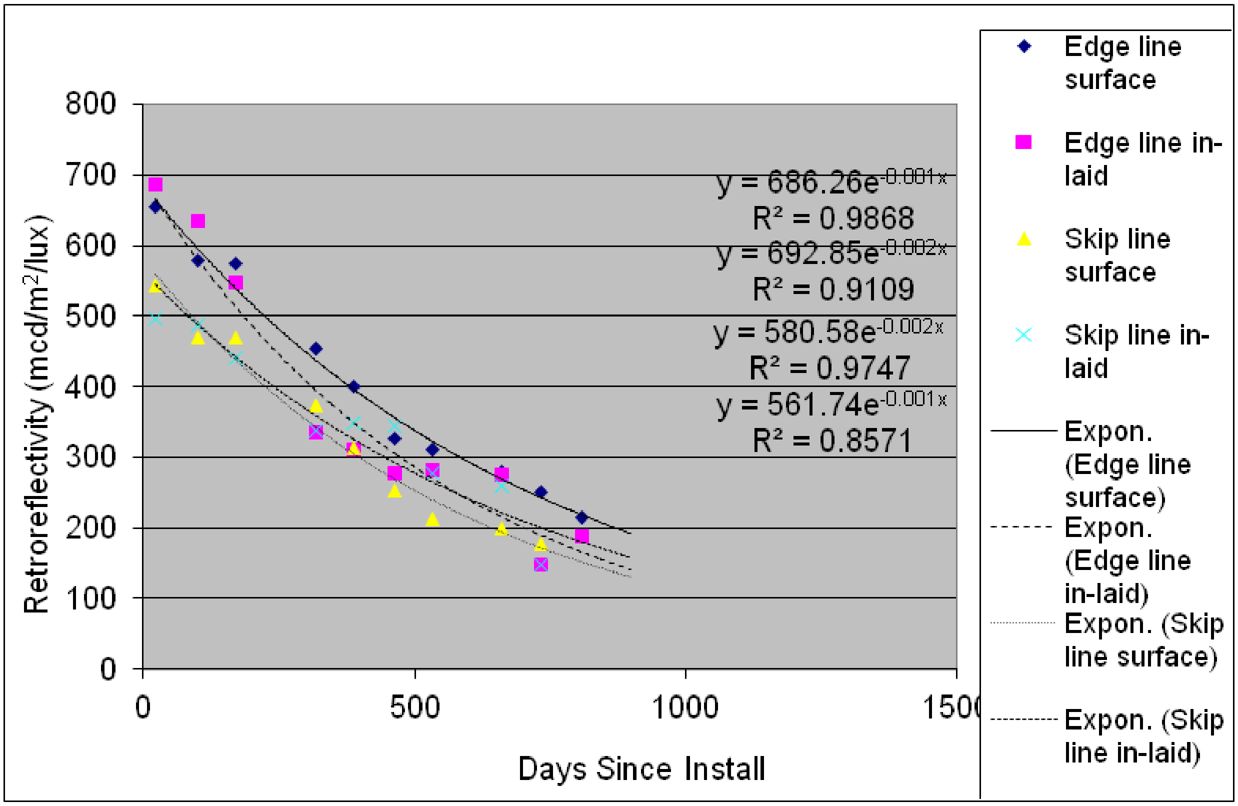


Figure 87. Graph. Retroreflectivity degradation section 1 TN-T.

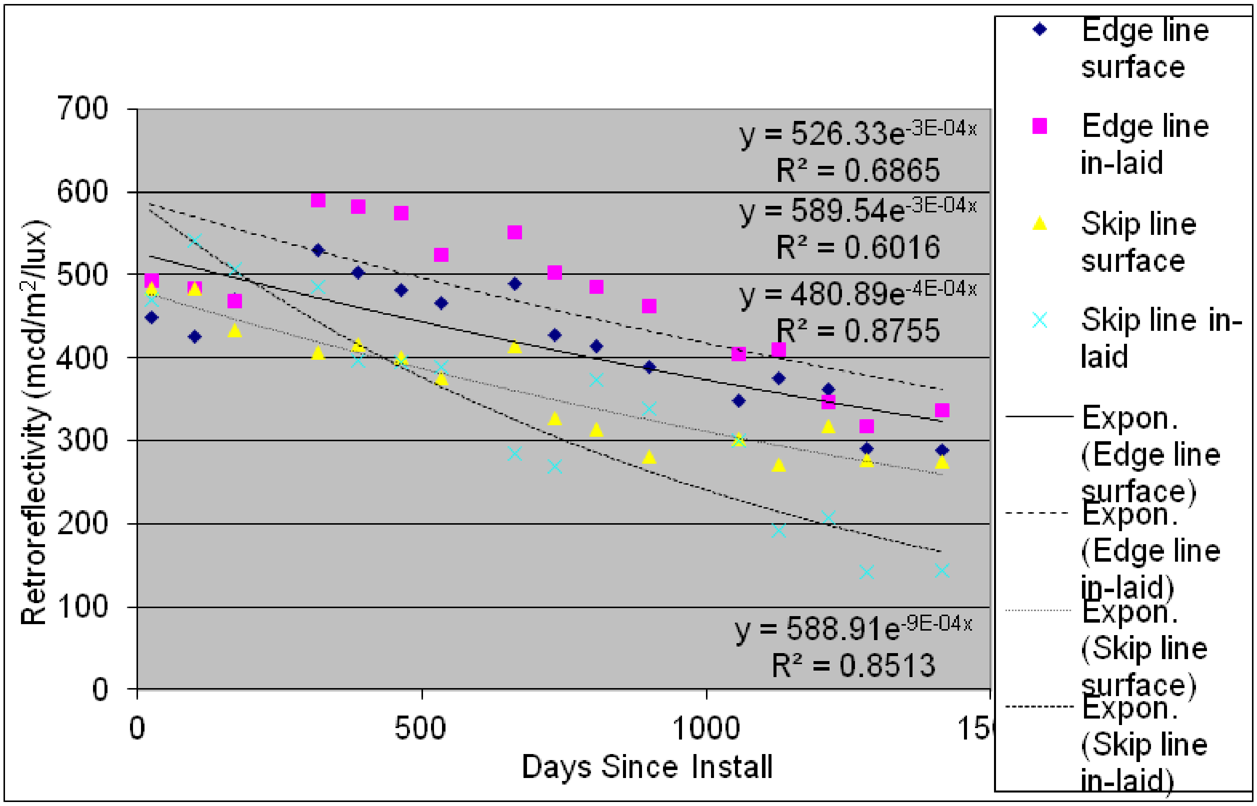


Figure 88. Graph. Retroreflectivity degradation section 2 TN-T a.

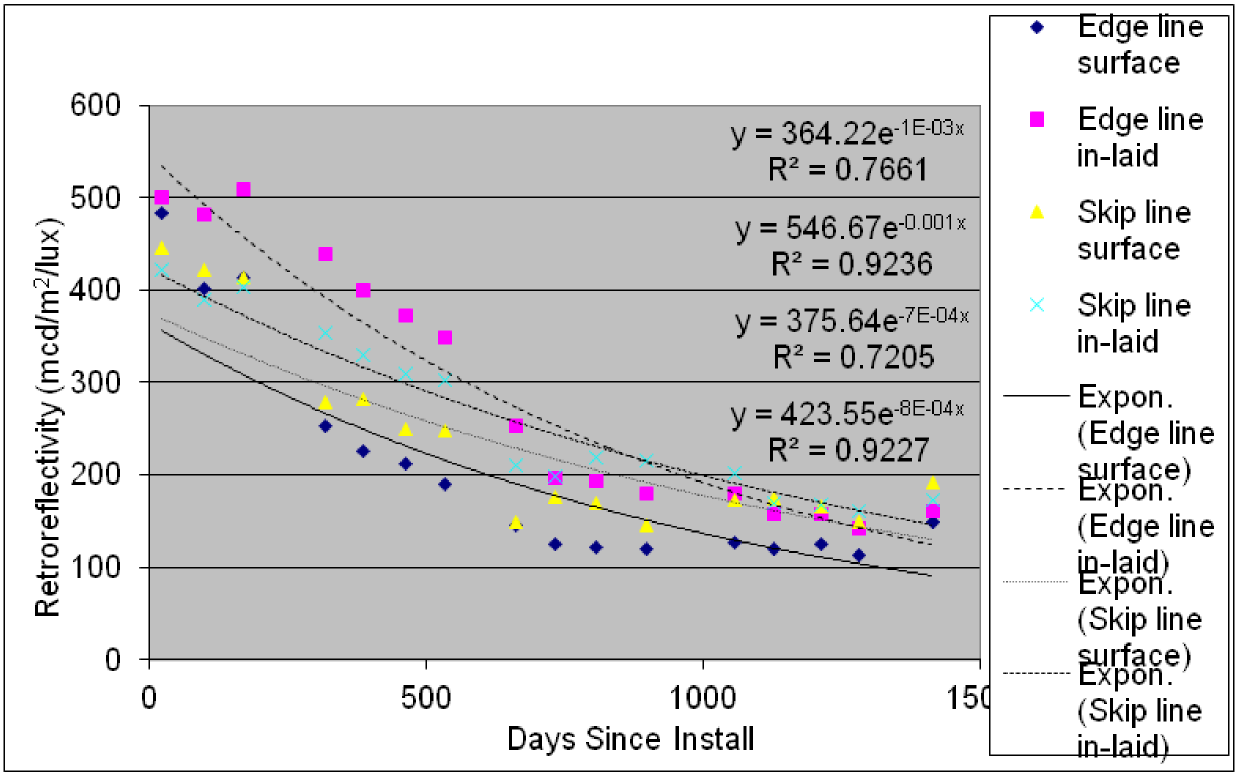


Figure 89. Graph. Retroreflectivity degradation section 2 TN-T b.

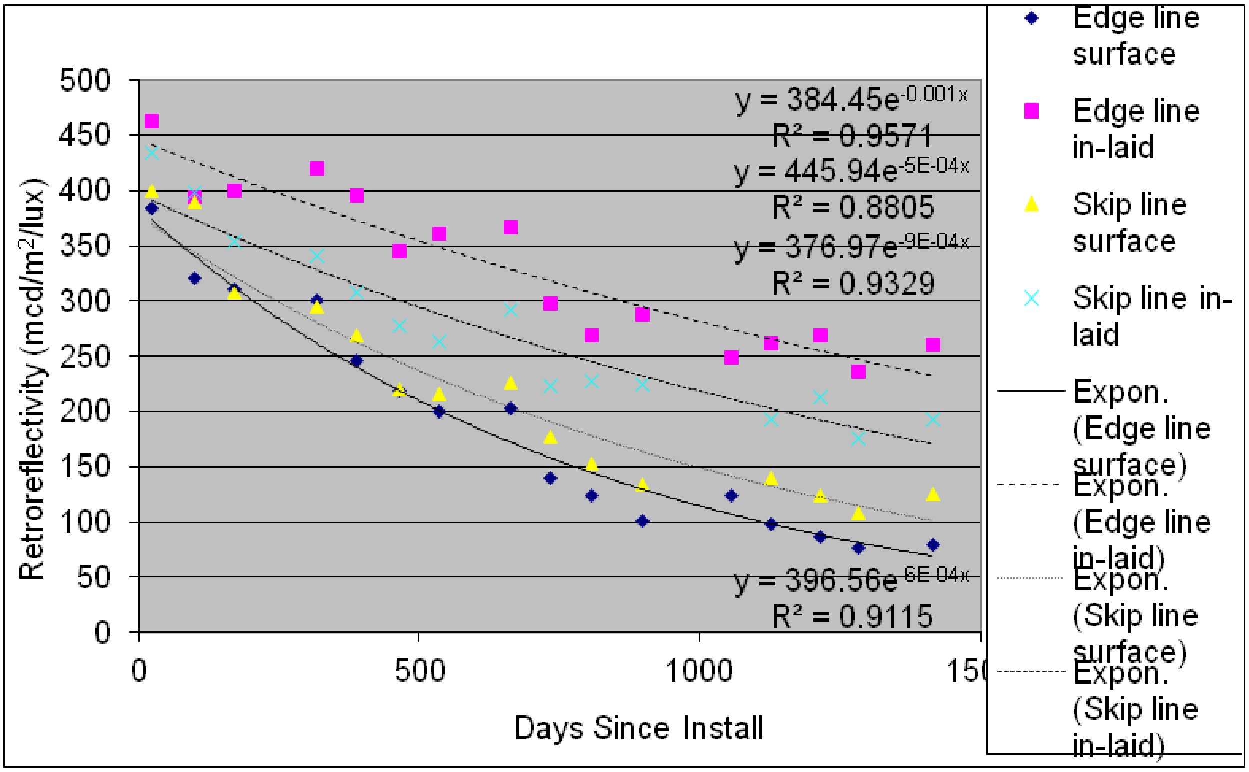


Figure 90. Graph. Retroreflectivity degradation section 3 TN-T.

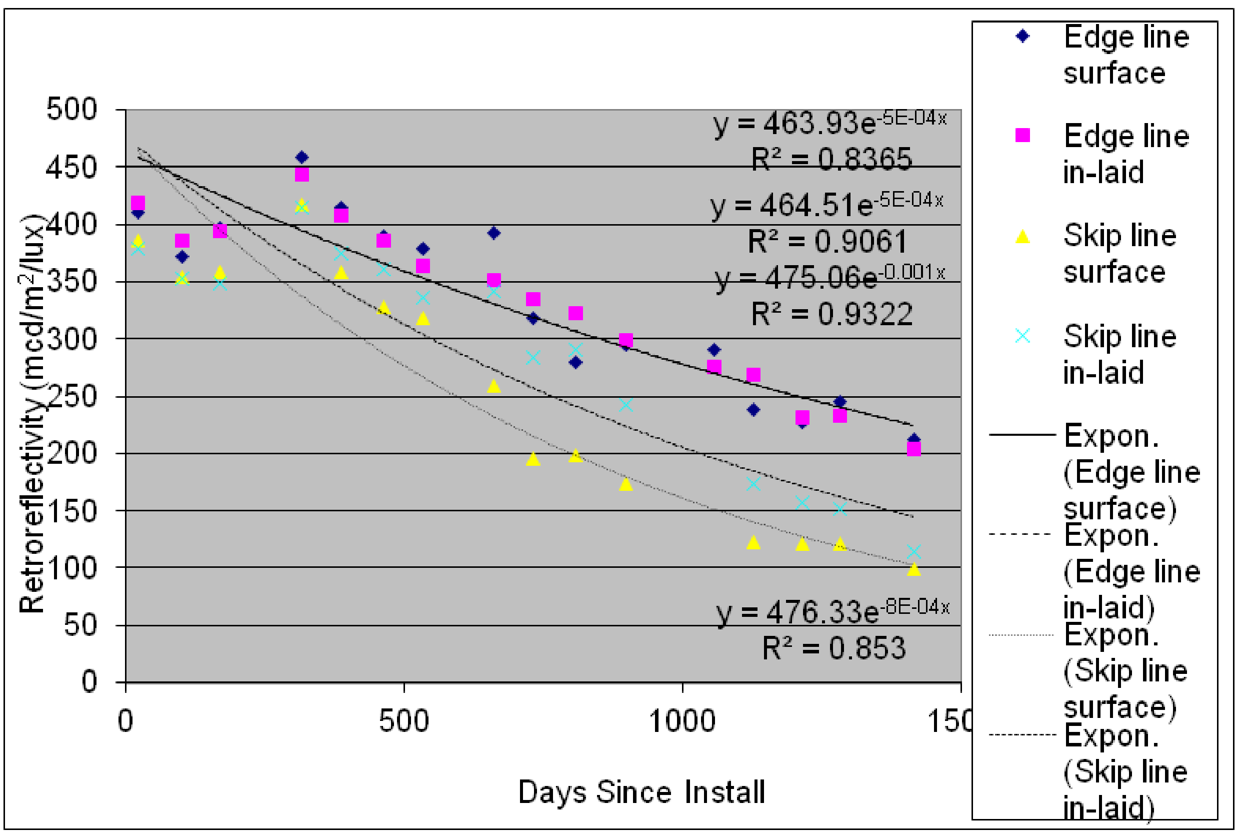


Figure 91. Graph. Retroreflectivity degradation section 4 TN-T.

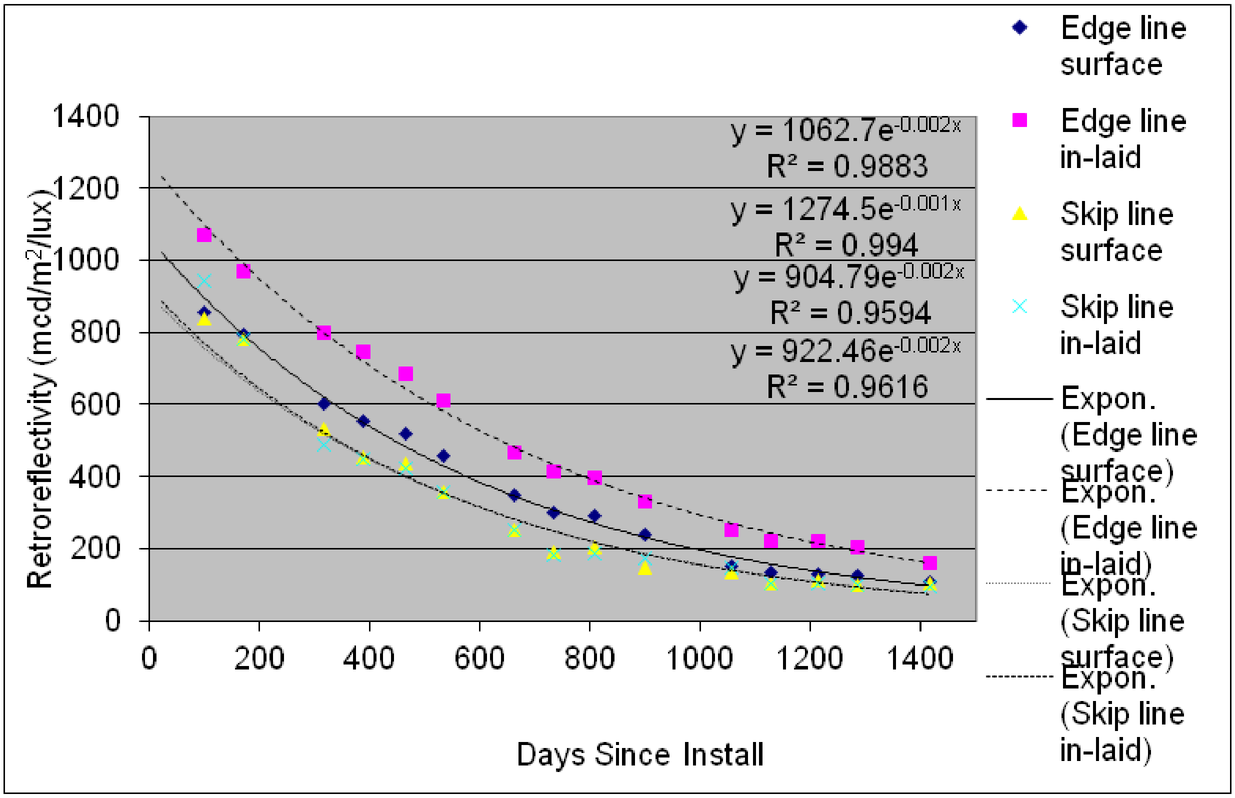


Figure 92. Graph. Retroreflectivity degradation section 5 TN-T a.

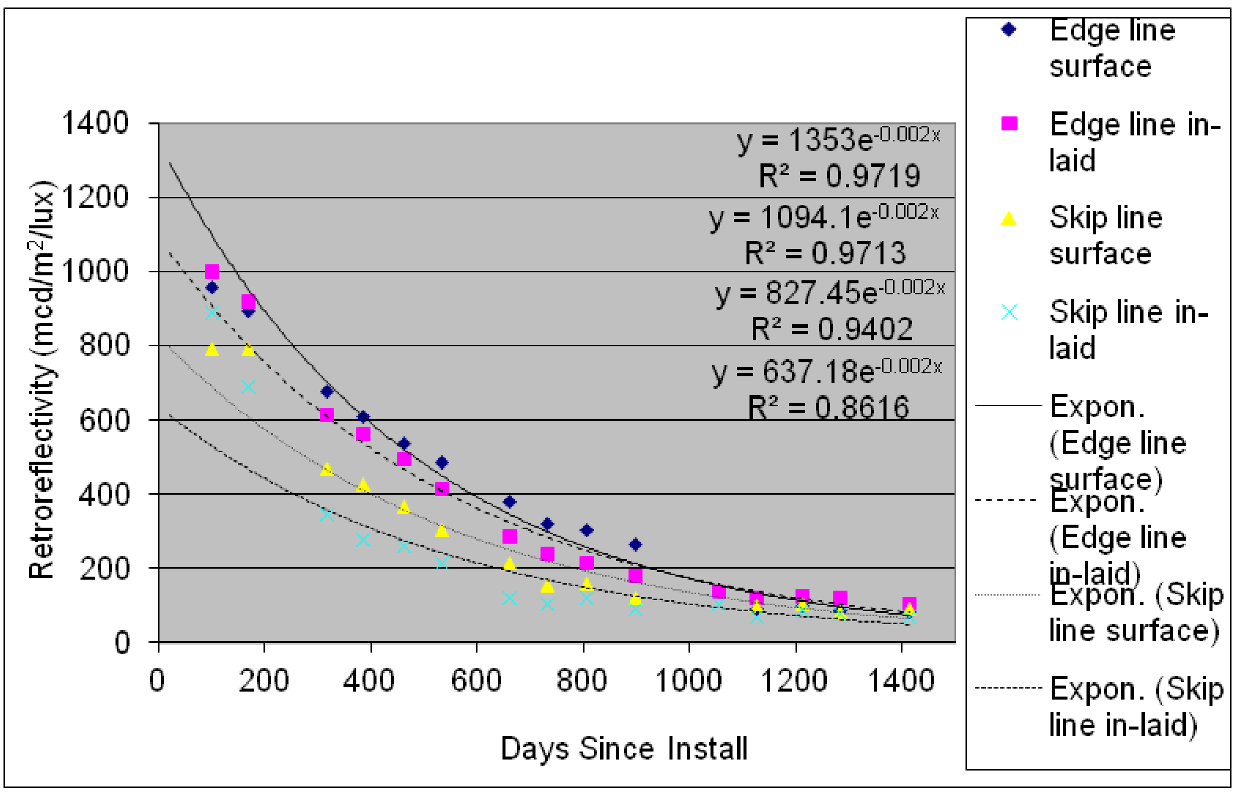


Figure 93. Graph. Retroreflectivity degradation section 5 TN-T b.

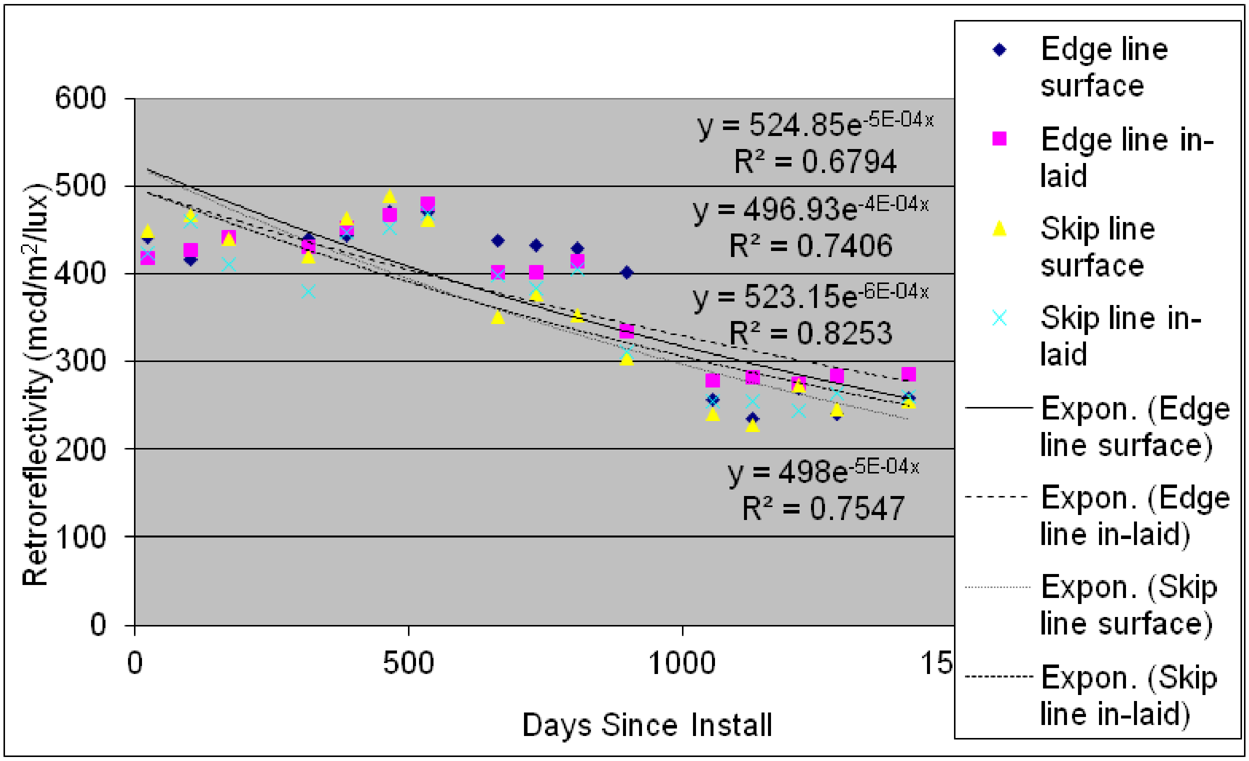


Figure 94. Graph. Retroreflectivity degradation section 6 TN-T.

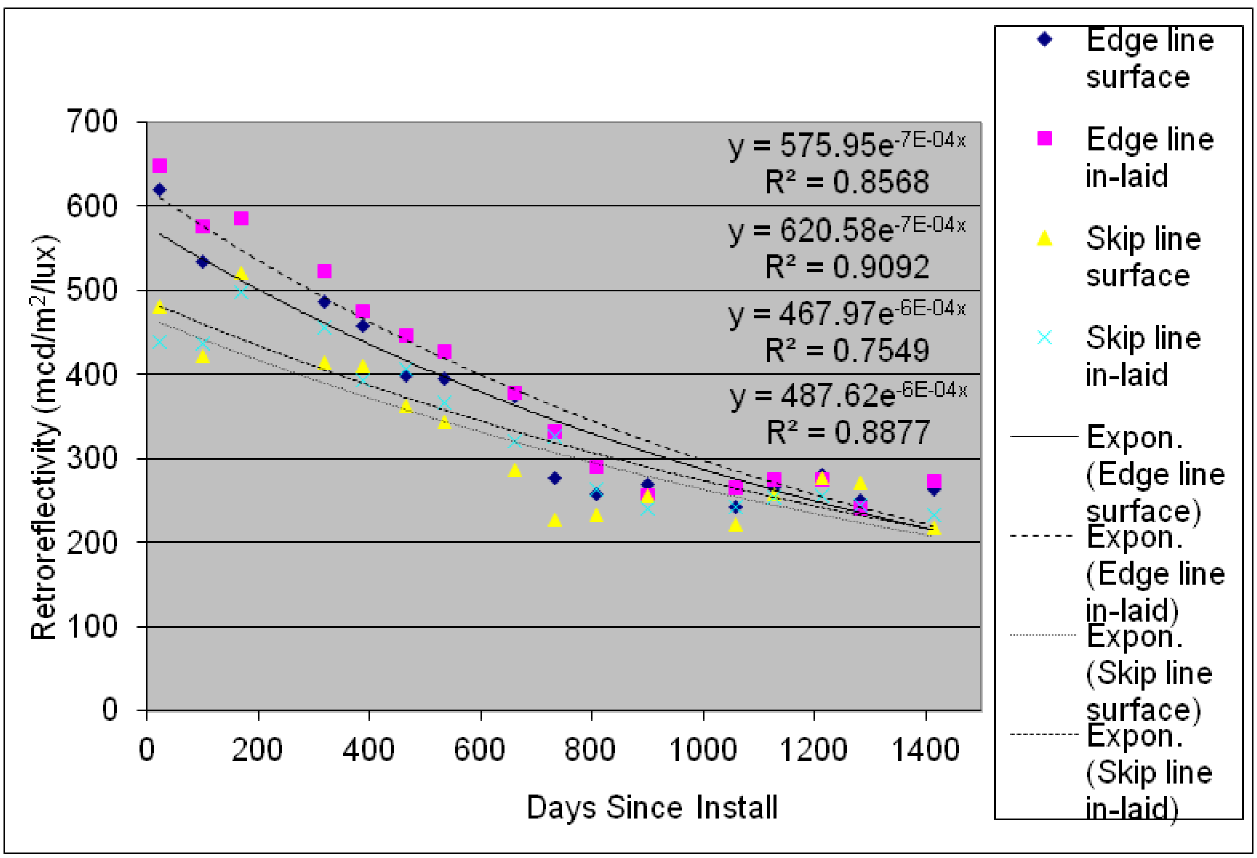


Figure 95. Graph. Retroreflectivity degradation section 7 TN-T.

APPENDIX C. PAVEMENT MARKING COST EFFECTIVENESS TABLES

This appendix contains tables showing the age of pavement markings as they reach various levels of retroreflectivity. The retroreflectivity degradation curves from appendix B were used to determine the age of the markings when they reached 250, 200, 150, and 100 mcd/m^2/lux. These levels of retroreflectivity were selected because they incrementally represent a marking that is approaching a lower level of maintained retroreflectivity. As the marking reaches a minimum retroreflectivity level, the marking will need to be replaced. In addition to the age of the marking at these retroreflectivity levels, the tables include the cost of the marking per mile per year of service. The costs of each marking were described in the pavement marking costs section of this report. For more specific marking information, refer to appendix A.

NASHVILLE, TN, TEST DECK

Table 75. Cost effectiveness for section 1 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level	$/Mile/Year at Retroreflectivity Level
	Edge Line Surface	Edge Line Surface
250	0.8	2,611
200	1.7	1,237
150	2.9	737
100	4.5	469

Table 76. Cost effectiveness for section 2 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	2.4	3.3	2.5	2.9	437	1,513	428	1,704
200	3.6	4.8	3.8	4.9	297	1,036	280	1,033
150	5.0	6.8	5.4	7.3	211	736	194	685
100	7.1	9.6	7.8	10.8	149	523	135	465

Table 77. Cost effectiveness for section 3 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	3.1	3.5	3.1	3.1	517	1,565	516	1,778
200	4.1	4.6	4.0	4.1	390	1,206	399	1,356
150	5.4	6.0	5.1	5.3	296	931	309	1,038
100	7.2	7.9	6.8	7.1	221	704	234	781

Table 78. Cost effectiveness for section 4 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level			$/Mile/Year at Retroreflectivity Level		
	Edge Line Surface	Edge Line Inlaid	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Inlaid
250	9.9	44.0	62.0	265	150	106
200	12.0	52.7	77.3	220	125	85
150	14.6	64.0	97.0	181	103	68
100	18.3	79.9	124.8	144	83	53

Table 79. Cost effectiveness for section 5 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level		$/Mile/Year at Retroreflectivity Level	
	Edge Line Surface	Skip Line Surface	Edge Line Surface	Skip Line Surface
250	2.9	2.8	1,268	1,300
200	3.7	3.7	997	998
150	4.7	4.8	781	768
100	6.2	6.4	599	579

Table 80. Cost effectiveness for section 6 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	4.6	5.1	2.5	3.4	93	856	172	1,288
200	6.7	7.7	3.8	5.5	63	571	111	795
150	9.4	11.0	5.5	8.2	45	400	77	533
100	13.2	15.6	7.9	12.1	32	281	53	363

Table 81. Cost effectiveness for section 7 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	3.3	4.4	2.9	3.3	1,286	1,876	1,462	2,467
200	3.8	5.0	3.4	3.8	1,100	1,645	1,243	2,134
150	4.6	5.8	4.1	4.5	927	1,420	1,042	1,817
100	5.6	6.9	5.0	5.4	759	1,191	848	1,503

Table 82. Cost effectiveness for section 8 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	2.7	2.6	2.1	2.0	461	2,005	608	2,565
200	4.5	4.0	3.4	3.0	279	1,308	371	1,719
150	6.9	5.8	5.1	4.3	185	903	247	1,207
100	10.1	8.3	7.5	6.2	125	629	168	849

Table 83. Cost effectiveness for section 9 TN-N.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	3.6	3.4	1.6	3.3	217	1,413	484	1,457
200	4.9	4.4	2.6	4.4	161	1,084	302	1,092
150	6.6	5.7	3.9	5.8	121	834	203	825
100	8.9	7.5	5.7	7.7	89	630	139	614

TUSCULUM, TN, TEST DECK

Table 84. Cost effectiveness for section 1 TN-T.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	2.0	1.6	1.4	1.6	935	3,639	1,361	3,666
200	2.4	1.9	1.7	2.0	766	2,986	1,076	2,874
150	3.0	2.4	2.2	2.6	621	2,424	847	2,248
100	3.8	3.0	2.8	3.4	490	1,917	652	1,720

Table 85. Cost effectiveness for section 2 TN-T a.

Retroreflectivity Level (mcd/m^2/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	6.8	7.8	4.5	2.6	1,243	1,584	1,885	4,757
200	8.8	9.9	6.0	3.3	956	1,257	1,406	3,774
150	11.5	12.5	8.0	4.2	737	993	1,059	2,980
100	15.2	16.2	10.8	5.4	557	766	785	2,299

Table 86. Cost effectiveness for section 2 TN-T b.

Retroreflectivity Level (mcd/m²/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	1.0	2.0	1.5	1.9	10,243	7,248	7,005	7,690
200	1.6	2.6	2.3	2.7	6,430	5,640	4,525	5,403
150	2.4	3.3	3.4	3.7	4,345	4,385	3,107	3,906
100	3.5	4.3	4.9	5.2	2,982	3,338	2,155	2,809

Table 87. Cost effectiveness for section 3 TN-T.

Retroreflectivity Level (mcd/m²/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	1.0	3.4	1.2	2.1	412	1,271	349	2,080
200	1.6	4.8	1.9	3.1	271	918	226	1,402
150	2.2	6.5	2.7	4.4	188	675	156	987
100	3.2	8.9	3.9	6.3	132	492	108	697

Table 88. Cost effectiveness for section 4 TN-T.

Retroreflectivity Level (mcd/m²/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	3.3	3.3	1.6	2.1	238	1,428	482	2,233
200	4.5	4.5	2.2	2.9	175	1,050	358	1,659
150	6.1	6.1	3.0	3.8	131	783	268	1,246
100	8.2	8.3	4.0	5.2	96	576	198	922

Table 89. Cost effectiveness for section 5 TN-T a.

Retroreflectivity Level (mcd/m²/lux)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	2.4	3.0	2.0	2.1	3,356	3,913	3,911	5,779
200	2.7	3.5	2.4	2.4	2,908	3,442	3,332	4,935
150	3.2	4.0	2.8	2.9	2,480	2,979	2,799	4,154
100	3.9	4.7	3.5	3.5	2,055	2,504	2,284	3,396

Table 90. Cost effectiveness for section 5 TN-T b.

Retroreflectivity Level ($mcd/m^2/lux$)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	2.2	2.2	1.8	1.4	4,489	6,400	5,476	10,044
200	2.5	2.5	2.2	1.7	3,965	5,560	4,616	8,110
150	2.9	2.9	2.6	2.2	3,446	4,755	3,838	6,497
100	3.4	3.5	3.2	2.8	2,910	3,949	3,102	5,074

Table 91. Cost effectiveness for section 6 TN-T.

Retroreflectivity Level ($mcd/m^2/lux$)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	4.1	4.7	3.4	3.8	624	1,380	752	1,720
200	5.3	6.2	4.4	5.0	479	1,042	577	1,299
150	6.9	8.2	5.7	6.6	369	792	444	988
100	9.1	11.0	7.6	8.8	279	591	335	738

Table 92. Cost effectiveness for section 7 TN-T.

Retroreflectivity Level ($mcd/m^2/lux$)	Years to Reach Retroreflectivity Level				$/Mile/Year at Retroreflectivity Level			
	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid	Edge Line Surface	Edge Line Inlaid	Skip Line Surface	Skip Line Inlaid
250	3.3	3.4	2.9	3.2	453	1,594	508	1,723
200	4.1	4.2	3.9	4.1	357	1,280	375	1,336
150	5.3	5.3	5.3	5.4	281	1,020	280	1,010
100	6.9	6.9	7.2	7.2	216	794	206	752

APPENDIX D. SAFETY ANALYSES ON MULTILANE HIGHWAYS

The Illinois freeway crash data were compiled from 2001–2006 from 571 segments (708.1 mi). Table 93 provides a summary of crash rates for those 571 freeway segments. Crashes coded as “intersection” were removed from all crash counts.

Table 93. Summary of Illinois 2001–2006 freeway crash data.

Variable	4-Inch Edge Lines 4-Inch Skip Lines	4-Inch Edge Lines 6-Inch Skip Lines	5-Inch Edge Lines 5-Inch Skip Lines
Total segment length	593.1	21.4	93.6
Number of years	6	6	6
Total number of accidents	31,189	432	1,751
Crash Type	**Crash Rates (per million vehicle miles)**		
Total	0.84	0.50	0.53
F+I	0.17	0.12	0.10
PDO	0.67	0.39	0.43
Daytime	0.47	0.21	0.23
Nighttime	0.33	0.26	0.26
Daytime F+I	0.10	0.07	0.06
Nighttime F+I	0.06	0.04	0.04
Wet	0.10	0.04	0.05
Wet nighttime	0.04	0.02	0.03
Single-vehicle	0.38	0.39	0.42
Single-vehicle wet	0.06	0.04	0.04
Single-vehicle nighttime	0.20	0.22	0.24
Older driver (≥ 55 years old)	0.16	0.09	0.11
Opposite direction	0.01	0.00	0.00
Sideswipe same direction	0.14	0.04	0.05
Fixed object	0.20	0.13	0.10

The Michigan freeway crash data were compiled from 2001–2007 from 508 segments (1,067.4 mi). The annual aggregated crash counts from those 508 freeway segments are provided in table 94. Crashes coded as “intersection” or “interchange” have been removed from all crash counts.

Table 94. Annual aggregated crash counts over 508 freeway segments (1,067.4 mi) in Michigan for 2001–2007.

Crash Type	Year						
	2001	2002	2003	2004	2005	2006	2007
Total	1,364	1,347	1,466	1,692	1,556	1,529	1,489
F+I	294	288	288	313	301	291	272
PDO	1,070	1,059	1,178	1,379	1,255	1,238	1,217
Daytime	856	854	879	1,058	963	900	881
Nighttime	400	387	448	519	480	498	484
Daytime F+I	207	188	187	219	217	200	198
Nighttime F+I	68	82	82	77	65	72	60
Wet	202	200	176	217	137	245	163
Wet nighttime	56	44	53	73	37	64	48
Wet F+I	50	38	29	49	30	62	34
Single-vehicle	774	696	815	993	897	948	977
Single-vehicle wet	112	98	113	141	83	158	113
Single-vehicle nighttime	327	280	357	423	399	416	424
Single-vehicle F+I	163	133	149	162	164	146	151
Single-vehicle nighttime F+I	53	51	53	51	41	48	40
Single-vehicle wet F+I	31	17	17	31	17	38	22

Note: Crashes in 2004 are not included in the safety analysis because 2004 is the year of wider line installation.

The research team performed a safety evaluation of Michigan freeway crash data using an interrupted time series approach that introduces time as a variable to control for baseline trend and intervention (installation of wider lines) as a variable to estimate the effect of the wider lines. Because the time series plots of freeway crashes (aggregated crashes over all segments) by year indicated a possible change in the trend (not just in the level) in crashes after the intervention, a new variable, ”time after intervention,” coded as “0” before the intervention and (time – t_0), where t_0 is the year of the intervention, was also included to estimate the change in the trend in the expected number of crashes. In addition to time, intervention, and time after intervention, lane width, terrain, log(AADT), log(segment length), and log(number of rainy days) were included as predictors in the negative binomial regression model. GEEs were used as an estimation method to account for correlations in crash counts from multiple years over segments. Table 95 contains the results of applying interrupted time series approaches to the Michigan non-intersection/interchange non-winter month crash data from 508 segments (1,067.4 mi) of freeways with 3 years (2001–2003) of before and 3 years (2005–2007) of after data. It can be observed from the table that there was no statistically significant change in the level of or trend in the expected number of freeway crashes after the installation of wider lines (p-values for intervention or time after intervention were all greater than 0.05), regardless of the crash types considered in the table. That is, no consistent or statistically significant safety effects of wider lines were observed for the Michigan freeway crash data.

Table 95. Results of interrupted time series approaches applied to the Michigan non-intersection/interchange non-winter month crash data.

Variable	Intercept	Time	Intervention	Time After Intervention	Lane Width	Terrain	Log (AADT)	Log (Segment Length)	Log (Number of Rainy Days)
Total crashes	-6.7012	-0.0089	0.0831	0.0208	0.0064	-0.0806	**0.5997**	**1.3521**	0.1682
F+I	**-15.9347**	-0.0715	0.1936	0.0524	0.3270	0.2609	**0.9636**	**1.4891**	0.0831
PDO	-6.0226	0.0117	0.0640	-0.0002	-0.0593	-0.0728	**0.5784**	**1.3357**	0.1973
Daytime	-14.4469	-0.0252	0.1077	0.0339	0.3934	-0.0555	**0.8498**	**1.3990**	0.1700
Nighttime	-0.0588	0.0121	0.1723	-0.0182	-0.3580	-0.0798	**0.3279**	**1.3128**	0.0140
Daytime F+I	**-15.8048**	**-0.1267**	0.3517	0.1211	0.1888	0.4336	**1.0686**	**1.5658**	0.0220
Nighttime F+I	-19.2711	0.0725	-0.2293	-0.1077	0.5150	0.3201	**0.9362**	**1.4485**	0.1507
Wet	**-15.8378**	-0.0059	-0.1984	0.1047	0.0310	-0.3612	**0.7493**	**1.2577**	**1.3567**
Wet nighttime	**-14.7010**	0.0840	-0.3696	0.0035	0.0785	-0.5859	**0.4336**	**1.0224**	**1.5177**
Wet F+I	**-26.6570**	-0.2133	0.4955	0.2534	0.4938	0.5057	**0.9269**	**1.2374**	1.4791
Single-vehicle	-0.8200	-0.0041	0.0971	0.0567	-0.1900	-0.1669	**0.2324**	**1.3268**	0.0815
Single-vehicle wet	**-8.3744**	0.0735	-0.3716	0.0903	-0.2281	-0.4371	**0.4063**	**1.1960**	**1.1056**
Single-vehicle nighttime	0.7417	0.0205	0.1645	-0.0008	-0.3031	-0.1165	**0.1442**	**1.2660**	0.0452
Single-vehicle V+I	-10.7619	-0.0801	0.2421	0.0511	0.2354	0.2252	**0.5641**	**1.4455**	-0.0618
Single-vehicle nighttime F+I	-16.4857	0.0040	-0.1630	-0.0186	0.5384	0.0848	**0.5376**	**1.3888**	0.2870
Single-vehicle wet F+I	-19.3663	-0.2613	0.5892	0.3502	0.2290	0.6558	**0.6542**	**1.1711**	1.0341

Note: GEE approach was used as an estimation method. Bold represents statistically significant results at $\alpha = 0.05$.

APPENDIX E. LIST OF MSDS COPIES REVIEWED

MSDS COPIES REVIEWED LISTED BY MANUFACTURER

3M
3M Center, St. Paul, MN 55144-1000

- 3M™ Stamark™ High Performance Tape Series 380I ES (380I ES White, 381I ES Yellow, 380I ES-5 White/Black, 381I ES-5 Yellow/Black).
- 3M™ Stamark™ High Performance Tape Series 380 Wet Reflective ES (380WR ES White, 381WR ES Yellow, 380WR-5ES White/Black, 381WR-5ES Yellow/Black).
- 3M™ All-Weather Paint White.

ADVANCE TRAFFIC MARKINGS
P.O. Box H, Roanoke Rapids, NC 27870

- ATM White Traffic Tape.
- ATM Yellow Traffic Tape.

ENNIS PAINT, INC.
P.O. Box 404, Ennis, TX75120

- Ennis Paint Thermoplastic — Leaded Yellow Thermoplastic Roadmarking Compound.
- Ennis Paint Thermoplastic — Lead-Free Yellow Thermoplastic Roadmarking Compound.
- Ennis Paint Thermoplastic — White Thermoplastic Roadmarking Compound.
- Ennis Paint — High Solids Waterborne Lead Free Fast Dry Traffic Paint (all colors).
- Duraset — Solution of an acrylic polymer in methacrylic acid esters/acrylic acid esters binder for road markings. (Duraset Component A).
- Duraset Part B 4:1 — Solution of pigmented alkylsulfonic acid esters containing organic peroxides for polymer initiator in road markings. (Component B for the 4:1 ratio materials Duraset 2, 3, 4, and 5).

EPOPLEX, A DIVISION OF STONCOR GROUP, INC.
1000 East Park Avenue, Maple Shade, NJ 08052

- Epoplex LS50 Black.
- Epoplex LS50 Hardener.
- Epoplex LS50 White.
- Epoplex LS50 LF Yellow A.
- Epoplex LS90 LF Yellow Amine.
- Epoplex LS90 White Amine.
- Epoplex LS90SP White Amine.
- Epoplex LS90SP LF Yellow Amine.

FLINT TRADING INC.
115 Todd Court, Thomasville, NC 27360

- PreMark®.

INNOVATIVE PERFORMANCE SYSTEMS
P.O. Box 13582, Research Triangle Park, NC 27709

- HPS-2 Yellow.
- HPS-3 Catalyst.
- HPS-3 White (all grades).
- HPS-4 Catalyst.
- HPS-4 White.
- HPS-4 Yellow.
- HPS-5 Catalyst.
- HPS-5 White.
- HPS-5 Yellow.

PERVO PAINT COMPANY
6624 Stanford Avenue, Los Angeles, CA 90001

- White Rd Acetone-Based Traffic, 150VOC (# 7100-TTP-115F).
- White Rd Acetone-Based Traffic, 150VOC (# 7100R/03).
- Black Traffic Paint (# 7102/TTP115F).
- Yellow Acetone T.P. 150GPL VOC (# 7103-TTP-115F).
- Yellow Acetone T.P. 150GPLVOV (# 7103R/05).
- White Rd Acetone-Based Traffic, 150VOC (# 8100).
- Black Sovent Base Max PT150 (# 8102).
- Yellow Acetone T.P. 150GPLVOV (# 8103).

POTTERS INDUSTRIES, INC.
P.O. Box 840, Valley Forge, PA 19482

- Standard Highway Safety Marking Spheres.
- Premium Highway Safety Marking Spheres.
- Visibead® Highway Safety Marking Spheres.
- Visibead® Plus II Highway Safety Marking Spheres.
- Premix Highway Safety Marking Spheres.
- Intermix Highway Safety Marking Spheres.

STIRLING LLOYD POLYCHEM LTD.
Union Bank, King Street, Knutsford, Cheshire, Wa16 6ef, England

- Safetrack LM.

SWARCO INDUSTRIES
P.O. BOX 89, 901 North James Campbell Boulevard, Columbia, TN 38402

- Swarco Reflex Glass Bead.
- Swarcotherm ™ Alkyd Formulation/Yellow/Lead Free.

APPENDIX F. SUMMARY OF MSDS DATA

Table 96. MSDS information for paint and tape.

MSDS Section No.	MSDS Section Description	Type of Information	3M 380-381WR Tape (ANSI)	3M 380IES Tape (ANSI)	3M AWP Paint (ANSI)	ATM White Tape (OSHA)	ATM Yellow Tape (OSHA)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Summarized	Summarized	Summarized	Not listed	Not listed
		Potential health effects	Skin, eye, and respiratory system irritation; cancer	None	Skin, eye, respiratory, and gastrointestinal system irritation; target organ effects; cancer	None known or expected	None known or expected
		If listed as a carcinogen	Yes—International Agency for Research on Cancer (IARC), National Toxicology Program (NTP)	Yes	Yes—IARC, NTP	No—NTP, IARC, OSHA	No—NTP, IARC, OSHA
		Environmental effects	Not a hazardous waste per RCRA listed TCLP	Not a hazardous waste per RCRA listed TCLP	Not listed	Not listed	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	3M 380-381WR Tape (ANSI)	3M 380IES Tape (ANSI)	3M AWP Paint (ANSI)	ATM White Tape (OSHA)	ATM Yellow Tape (OSHA)
3	Composition, Information on Ingredients	Chemical name	All ingredients	All ingredients	All ingredients	None listed	None listed
		CAS registry number and percentages	All ingredients	All ingredients	All ingredients	None listed	None listed
		Established exposure guidelines	Listed for fibers	Listed for glass beads	Listed for many ingredients	N/A	N/A
		Authority (OSHA, American Conference of Governmental Industrial Hygienists (ACGIH), Chemical Manufacturer Recommended Guideline (CMRG))	ACGIH	3M	ACGIH, OSHA, CMRG	N/A	N/A
4	First Aid Procedures	Eye	Flush	None	Flush	Not listed	Not listed
		Skin	Wash	None	Wash	Not expected	Not expected
		Inhalation	Move to fresh air	None	Move to fresh air	Not expected	Not expected
		Ingestion	None	None	Water, get medical attention	Not expected	Not expected
5	Fire-Fighting Measures	Specific hazards	None	None	None	None	None
		Flash point	N/A	N/A	> 200 °F	N/A	N/A
		Explosive limits	N/A	N/A	No data available	Not established	Not established
		Suitable/unsuitable extinguishing media	Class B, Class A	Class B, Class A	Class B	Water fog, flood, dry chemical, carbon dioxide	Water fog, flood, dry chemical, carbon dioxide

MSDS Section No.	MSDS Section Description	Type of Information	3M 380-381WR Tape (ANSI)	3M 380IES Tape (ANSI)	3M AWP Paint (ANSI)	ATM White Tape (OSHA)	ATM Yellow Tape (OSHA)
5 (cont'd)	Fire-Fighting Measures (cont'd)	Instructions for firefighters	Not listed	Not listed	Not listed	None listed	None listed
		Protective equipment	Bunker gear, self-contained breathing apparatus (SCBA)	Bunker gear, SCBA	Bunker gear, SCBA	Protective clothing, SCBA	Protective clothing, SCBA
6	Accidental Release Measures	Clean-up/containment technique	N/A	N/A	Detailed clean-up instructions	Pick up and use, or dispose as solid waste	Pick up and use, or dispose as solid waste
		PPE and precautions	N/A	N/A	Not listed	Not listed	Not listed
		Environmental precautions	N/A	N/A	Prevent entry into sewer systems and bodies of water	Not listed	Not listed
		Regulatory/reporting requirements	Check applicable regulations	Check applicable regulations	Check applicable regulations	Not listed	Not listed
7	Handling and Storage	Handing—proper handling to prevent spills, fire, and explosion	Avoid breathing dust	Avoid breathing dust	Do not eat, drink, smoke. Wash after using. Do not breathe vapors, mists, or spray. Use ventilation and/or respiratory protection equipment.	Not listed	Not listed
		Storage—incompatible materials, proper storage containers, and proper storage conditions	Normal warehouse conditions	Normal warehouse conditions	Well-ventilated area	Cool, dry location	Cool, dry location

MSDS Section No.	MSDS Section Description	Type of Information	3M 380-381WR Tape (ANSI)	3M 380IES Tape (ANSI)	3M AWP Paint (ANSI)	ATM White Tape (OSHA)	ATM Yellow Tape (OSHA)
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	General ventilation	General ventilation
		Eye/face	N/A	N/A	Goggles	None	None
		Skin	N/A	N/A	Gloves and protective clothing	Gloves	Gloves
		Respiratory	Avoid breathing dust	Avoid breathing dust	Respirator	Not needed	Not needed
9	Physical and Chemical Properties	Appearance	Roll of tape	Roll of tape	Milky white liquid	White reflective tape	Yellow reflective tape
		Odor/odor threshold	Minimal	Minimal	Ammonia	None	None
		Physical state	Solid	Solid	Liquid	Solid	Solid
		pH	N/A	N/A	Listed	Not listed	Not listed
		Melting/freezing point	No data Available	No data available	N/A	Not listed	Not listed
		Boiling point/range	N/A	N/A	≥ 200 °F	N/A	N/A
		Evaporation rate	N/A	N/A	Not listed	N/A	N/A
		Vapor pressure	N/A	N/A	≤ 12.93 kPa (97 mm Hg)	N/A	N/A
		Vapor density	N/A	N/A	No data available	N/A	N/A
		Specific gravity/relative density	N/A	N/A	1.68	N/A	N/A
		VOC	N/A	N/A	Not listed	N/A	N/A
		Viscosity	N/A	N/A	Not listed	Not listed	Not listed
		Solubility	N/A	N/A	Complete	Insoluble	Insoluble
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	None known	None known	None known	None known	None known
		Incompatible materials	None known	None known	None known	Strong oxidizers	Strong oxidizers

MSDS Section No.	MSDS Section Description	Type of Information	3M 380-381WR Tape (ANSI)	3M 380IES Tape (ANSI)	3M AWP Paint (ANSI)	ATM White Tape (OSHA)	ATM Yellow Tape (OSHA)
10 (cont'd)	Stability and Reactivity (cont'd)	Hazardous decomposition products	Listed—during combustion	Listed—during combustion	None known	Listed	Listed
		Hazardous polymerization	Will not occur	Will not occur	Will not occur	Will not occur	Will not occur
11	Toxicological Information	Toxicological information	Contact 3M	Contact 3M	Contact 3M	Not listed	Not listed
		Acute dose effects (median lethal dose (LD50), median lethal concentration (LC50))	Not listed	Not listed	Not listed	None known or expected	None known or expected
		Repeated dose effects (no observed adverse effect level (NOAEL))	Not listed	Not listed	Not listed	None known or expected	None known or expected
		Carcinogenicity	Not listed	Not listed	Yes, IARC, NTP	No—NTP, IARC, OSHA	No—NTP, IARC, OSHA
		Neurological effects	Not listed	Not listed	Central nervous system depression	None listed	None listed
		Genetic effects (mutagenicity)	Not listed	Not listed	Not listed	None listed	None listed
		Reproductive effects	Not listed	Not listed	Not listed	None listed	None listed
		Developmental effects	Not listed	Not listed	Not listed	None listed	None listed
		Target organ effects	Not listed	Not listed	Central nervous system depression	None listed	None listed
12	Ecological Information	Ecotoxicity	N/A	N/A	Not determined	Not listed	Not listed
		Persistence/degradability	N/A	N/A	Not determined	Not listed	Not listed
		Bioaccumulation/ bioconcentration	N/A	N/A	Not determined	Not listed	Not listed
		Mobility: air, soil, and water	N/A	N/A	Not determined	Not listed	Not listed
		Other adverse effects	N/A	N/A	Not determined	Not listed	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	3M 380-381WR Tape (ANSI)	3M 380IES Tape (ANSI)	3M AWP Paint (ANSI)	ATM White Tape (OSHA)	ATM Yellow Tape (OSHA)
13	Disposal Considerations	Safe and environmentally preferred disposal of material and container	Sanitary landfill	Sanitary landfill	Incinerate, sanitary landfill	Check local regulations	Check local regulations
		Classification under applicable laws	Check applicable regulations	Check applicable regulations	Check applicable regulations	Check local regulations	Check local regulations
14	Transport Information	DOT proper shipping name	Not listed	Not listed	Not listed	N/A	N/A
		DOT hazard class(es)	Not listed	Not listed	Not listed	N/A	N/A
		DOT identification number	Listed	Listed	Listed	None	None
		Packing group	Not listed	Not listed	Not listed	Not listed	Not listed
15	Regulatory Information	United States, Federal	311/312, TSCA	311/312, TSCA	311/312, 313, TSCA	None listed	None listed
		United States, State	Contact 3M	Contact 3M	Contact 3M	None listed	None listed
		International	Contact 3M	Contact 3M	Contact 3M	None listed	None listed
16	Other Information	Hazard ratings	National Fire Protection Association (NFPA)	NFPA	NFPA	Not listed	Not listed
		Health	1	0	1	Not listed	Not listed
		Flammability	1	1	1	Not listed	Not listed
		Reactivity	0	0	0	Not listed	Not listed
		Other	Special hazards none	Special hazards none	Special hazards none	Not listed	Not listed
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Listed	Listed	Listed	Listed	Listed

Table 97. MSDS information for Duraset and thermoplastic.

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Duraset A (OSHA)	Ennis Duraset B (OSHA)	Ennis Lead Free Yellow Thermo (OSHA)	Ennis White Thermo (OSHA)	Ennis Leaded Yellow Thermo (OSHA)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Not listed	Not listed	Not listed	Not listed	Not listed
		Potential health effects	Eye and skin irritation, headaches, dizziness, nausea, slightly toxic by ingestion, asthma, and respiratory diseases	Eye and skin irritation, headaches, dizziness, nausea, slightly toxic by ingestion, asthma, and respiratory diseases	Eye and respiratory system irritation; skin burns	Eye and respiratory system irritation; skin burns	Eye and respiratory system irritation; skin burns
		If listed as a carcinogen	Not a carcinogen	Not a carcinogen	Not a carcinogen	Not a carcinogen	Yes—CA Proposition 65
		Environmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
3	Composition, Information on Ingredients	Chemical name	Hazardous ingredients only	Hazardous ingredients only	None listed	None listed	Hazardous ingredients only
		CAS registry number and percentages	Hazardous ingredients only	Hazardous ingredients only	None listed—no hazardous ingredients	None listed—no hazardous ingredients	Hazardous ingredients only
		Established exposure guidelines	Hazardous ingredients only	Hazardous ingredients only	None listed	None listed	Hazardous ingredients only
		Authority (OSHA, ACGIH, and CMRG)	ACGIH and OSHA	ACGIH and OSHA	None listed	None listed	Not established

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Duraset A (OSHA)	Ennis Duraset B (OSHA)	Ennis Lead Free Yellow Thermo (OSHA)	Ennis White Thermo (OSHA)	Ennis Leaded Yellow Thermo (OSHA)
4	First Aid Procedures	Eye	Flush	Flush	Flush	Flush	Flush
		Skin	Wash	Wash	Wash, apply ice to burns	Wash, apply ice to burns	Wash, apply ice to burns
		Inhalation	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air
		Ingestion	Call poison control center	Call poison control center	Induce vomiting, seek medical attention	Induce vomiting, seek medical attention	Induce vomiting, seek medical attention
5	Fire-Fighting Measures	Specific hazards	Heat, sparks, flame, mixing with air	Heat, sparks, flame, mixing with air	Emits acrid fumes, dust may form explosive mixture with air	Emits acrid fumes, dust may form explosive mixture with air	Emits acrid fumes, dust may form explosive mixture with air
		Flash point	9 °C	9 °C	> 500 °F	> 500 °F	> 500 °F
		Explosive limits	2.1–12.5 percent	2.1–12.5 percent	N/A	N/A	N/A
		Suitable/unsuitable extinguishing media	Foam, dry chemical, carbon dioxide	Foam, dry chemical, carbon dioxide	Water, dry chemical, carbon dioxide, foam	Water, dry chemical, carbon dioxide, foam	Water, dry chemical, carbon dioxide, foam
		Instructions for firefighters	Listed	Listed	Yes	Yes	Yes
		Protective equipment	Protective clothing, SCBA	Protective clothing, SCBA	SCBA	SCBA	SCBA
6	Accidental Release Measures	Clean-up/containment technique	Remove sources or heat, sparks, fire, or flame. Collect in closed chemical waste container. Absorb with inert material	Remove sources or heat, sparks, fire, or flame. Collect in closed chemical waste container. Absorb with inert material	Sweep, shovel, or vacuum into container	Sweep, shovel, or vacuum into container	Sweep, shovel, or vacuum into container
		PPE and precautions	Not listed	Not listed	Not listed	Not listed	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Duraset A (OSHA)	Ennis Duraset B (OSHA)	Ennis Lead Free Yellow Thermo (OSHA)	Ennis White Thermo (OSHA)	Ennis Leaded Yellow Thermo (OSHA)
6 (cont'd)	Accidental Release Measures (cont'd)	Environmental precautions	Not listed	Not listed	Not listed	Not listed	Not listed
		Regulatory/reporting requirements	Not listed	Not listed	Not listed	Not listed	Not listed
7	Handling and Storage	Handing—proper handling to prevent spills, fire, explosion	Protect from physical damage, ground equipment, avoid sources of heat and flame, closed containers	Protect from physical damage, ground equipment, avoid sources of heat and flame, closed containers	Protect from moisture, remove ignition sources	Protect from moisture, remove ignition sources	Protect from moisture, remove ignition sources
		Storage—incompatible materials, proper storage containers, proper storage conditions	Well-ventilated area	Well-ventilated area	Provide ventilation	Provide ventilation	Provide ventilation
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Goggles	Goggles	Face shield	Face shield	Face shield
		Skin	Gloves, protective clothing, hats, face shields	Gloves, protective clothing, hats, face shields	Gloves, long sleeves, hats	Gloves, long sleeves, hats	Gloves, long sleeves, hats
		Respiratory	Respirator	Respirator	Respirator	Respirator	Respirator
9	Physical and Chemical Properties	Appearance	Colored heavy liquid	Colored heavy liquid	Solid powder or block	Solid powder or block	Solid powder or block
		Odor/odor threshold	< 1 ppm	< 1 ppm	Odorless	Odorless	Odorless
		Physical state	Liquid	Liquid	Solid	Solid	Solid
		pH	Not listed	Not listed	Not listed	Not listed	Not listed
		Melting/freezing point	-48 °C	-48 °C	R&B 95–120 °C	R&B 95–120 °C	R&B 95–120 °C
		Boiling point/range	212 °F	212 °F	N/A	N/A	N/A
		Evaporation rate	> 1.0 x *n*-butyl acetate	> 1.0 x *n*-butyl acetate	N/A	N/A	N/A

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Duraset A (OSHA)	Ennis Duraset B (OSHA)	Ennis Lead Free Yellow Thermo (OSHA)	Ennis White Thermo (OSHA)	Ennis Leaded Yellow Thermo (OSHA)
9 (cont'd)	Physical and Chemical Properties (cont'd)	Vapor pressure	20 hPa at 20 °C	20 hPa at 20 °C	N/A	N/A	N/A
		Vapor density	Heavier than air	Heavier than air	N/A	N/A	N/A
		Specific gravity/relative density	Not listed	Not listed	1.70–2.20	1.70–2.20	1.70–2.20
		VOC	< 150 g/L	< 150 g/L	Not listed	Not listed	Not listed
		Viscosity	Not listed	Not listed	Not listed	Not listed	Not listed
		Solubility	Not listed	Not listed	N/A	N/A	N/A
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	Heat, ignition sources, aging, contamination, oxygen free atmosphere	Heat, ignition sources, aging, contamination, oxygen free atmosphere	Temperatures above 500 °F, open flame	Temperatures above 500 °F, open flame	Temperatures above 500 °F, open flame
		Incompatible materials	Listed	Listed	Strong oxidation agents	Strong oxidation agents	Strong oxidation agents
		Hazardous decomposition products	Not listed	Not listed	Listed	Listed	Listed
		Hazardous polymerization	May occur when exposed to heat or contaminated with incompatible materials	May occur when exposed to heat or contaminated with incompatible materials	Will not occur	Will not occur	Will not occur
11	Toxicological Information	Toxicological information	No data available	No data available	Not listed	Not listed	Not listed
		Acute dose effects (LD50, LC50)	Not listed	Not listed	Not expected	Not expected	Not expected
		Repeated dose effects (NOAEL)	None known	None known	None known	None known	None known
		Carcinogenicity	Not a carcinogen	Not a carcinogen	Not a carcinogen	Not a carcinogen	Yes—CA Proposition 65
		Neurological effects	None listed	None listed	None listed	None listed	None listed
		Genetic effects (mutagenicity)	None listed	None listed	None listed	None listed	None listed

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Duraset A (OSHA)	Ennis Duraset B (OSHA)	Ennis Lead Free Yellow Thermo (OSHA)	Ennis White Thermo (OSHA)	Ennis Leaded Yellow Thermo (OSHA)
11 (cont'd)	Toxicological Information (cont'd)	Reproductive effects	None listed	None listed	None listed	None listed	None listed
		Developmental effects	None listed	None listed	None listed	None listed	None listed
		Target organ effects	None listed	None listed	None listed	None listed	None listed
12	Ecological Information	Ecotoxicity	Not listed	Not listed	Not listed	Not listed	Not listed
		Persistence/degradability	Not listed	Not listed	Not listed	Not listed	Not listed
		Bioaccumulation/ bioconcentration	Not listed	Not listed	Not listed	Not listed	Not listed
		Mobility: air, soil, water	Not listed	Not listed	Not listed	Not listed	Not listed
		Other adverse effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Safe and environmentally preferred disposal of material and container	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
13	Disposal Considerations	Classification under applicable laws	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
		DOT proper shipping name	Not listed	Not listed	Not regulated	Not regulated	Not regulated
14	Transport Information	DOT hazard class(es)	3	3	Not regulated	Not regulated	Not regulated
		DOT identification number	1263	1263	Not regulated	Not regulated	Not regulated
		Packing group	II	II	Not regulated	Not regulated	Not regulated
		United States, Federal	313, TSCA	313, TSCA	313, TSCA	313, TSCA	313, TSCA
15	Regulatory Information	United States, State	CA Prop 65	CA Prop 65	CA Prop 65	CA Prop 65	CA Prop 65
		International	None listed	None listed	None listed	None listed	None listed
		Hazard ratings	Hazardous Materials Identification System (HMIS)/ NFPA	HMIS/NFPA	Not listed	Not listed	Not listed
16	Other Information	Health	2	2	1	1	1
		Flammability	3	3	1	1	1
		Reactivity	Not listed	Not listed	1	1	1
		Other	Physical hazard 2	Physical hazard 2	Not listed	Not listed	Not listed
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Not listed	Not listed	Not listed	Not listed	Not listed

N/A = Not applicable.
°F = 1.8°C + 32.

Table 98. MSDS information for paint and epoxy.

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Waterborne Paint (OSHA)	Epoplex LS50 Black (ANSI)	Epoplex LS50 Hardener (ANSI)	Epoplex LS50 White (ANSI)	Epoplex LS50 Yellow (ANSI)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Not listed	Summarized	Summarized	Summarized	Summarized
		Potential health effects	Eye irritation, headaches, dizziness, nausea, rash, and eye damage	Skin irritation	Severe burns, skin, eye, and irritation, respiratory system irritation	Skin irritation and skin sensitization	Skin irritation and skin sensitization
		If listed as a carcinogen	Not a carcinogen	Possible—IARC	Not a carcinogen	Not a carcinogen	Yes—IARC
		Environmental effects	Not listed	Harmful to aquatic organisms	Adverse effects in the aquatic environment	Harmful to aquatic organisms	Harmful to aquatic organisms
3	Composition, Information on Ingredients	Chemical name	Hazardous ingredients only	All ingredients	All ingredients	All ingredients	All ingredients
		CAS registry number and percentages	Hazardous ingredients only	Listed for all ingredients	Listed for all ingredients	Listed for all ingredients	Listed for all ingredients
		Established exposure guidelines	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Not established
		Authority (OSHA, ACGIH, CMRG)	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	Not established
4	First Aid Procedures	Eye	Flush	Rinse	Rinse	Rinse	Rinse
		Skin	Wash, apply ice to burns	Wash	Wash	Wash	Wash
		Inhalation	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air
		Ingestion	Not listed	Give water	Give water	Give water	Give water

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Waterborne Paint (OSHA)	Epoplex LS50 Black (ANSI)	Epoplex LS50 Hardener (ANSI)	Epoplex LS50 White (ANSI)	Epoplex LS50 Yellow (ANSI)
5	Fire-Fighting Measures	Specific hazards	Closed containers may explode when exposed to heat	None listed	None listed	None listed	None listed
		Flash point	> 201 °F	> 200 °F	> 236 °F	> 200 °F	> 200 °F
		Explosive limits	N/A	N/A	N/A	N/A	None
		Suitable/unsuitable extinguishing media	None	Carbon dioxide, dry chemical, foam	Carbon dioxide, dry chemical, foam	Carbon dioxide, dry chemical, foam	Carbon dioxide, dry chemical, foam
		Instructions for firefighters	None	Spray containers, collect contaminated water separately, do not discharge into drains	Spray containers, collect contaminated water separately, do not discharge into drains	Spray containers, collect contaminated water separately, do not discharge into drains	Spray containers, collect contaminated water separately, do not discharge into drains
		Protective equipment	None	SCBA	SCBA	SCBA	SCBA
6	Accidental Release Measures	Clean up/containment technique	Collect in a closed container, avoid dilution with water, avoid heat, sparks, and open flame, avoid hot metal	Soak up with absorbent materials	Soak up with absorbent materials	Soak up with absorbent materials	Soak up with absorbent materials
		PPE and precautions	Not listed	Use PPE	Use PPE	Use PPE	Use PPE
		Environmental precautions	Not listed	Do not allow material to contaminate groundwater system	Do not allow material to contaminate groundwater system	Do not allow material to contaminate groundwater system	Do not allow material to contaminate groundwater system
		Regulatory/reporting requirements	Not listed	Check applicable regulations	Check applicable regulations	Check applicable regulations	Check applicable regulations

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Waterborne Paint (OSHA)	Epoplex LS50 Black (ANSI)	Epoplex LS50 Hardener (ANSI)	Epoplex LS50 White (ANSI)	Epoplex LS50 Yellow (ANSI)
7	Handling and Storage	Handing—proper handling to prevent spills, fire, explosion	Protect from freezing	Wear PPE, use ventilation	Wear PPE, use ventilation	Wear PPE, use ventilation	Wear PPE, use ventilation
		Storage—incompatible materials, proper storage containers, proper storage conditions	Protect from freezing	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Goggles	Glasses	Glasses	Glasses	Glasses
		Skin	Gloves, long sleeves, hats	Gloves, apron, long sleeves	Gloves, apron, long sleeves	Gloves, apron, long sleeves	Gloves, apron, long sleeves
		Respiratory	Respirator	None needed	None needed	None needed	None needed
9	Physical and Chemical Properties	Appearance	Heavy liquid	Liquid	Mobile liquid, amber	White liquid	Yellow resin
		Odor/odor threshold	Not listed	Faint epoxy	Faint odor	Faint epoxy	Faint epoxy
		Physical state	Liquid	Liquid	Liquid	Liquid	Liquid
		pH	Not listed	Non-aqueous	No data	Non-aqueous	Non-aqueous
		Melting/freezing point	Not listed	Not listed	Not listed	Not listed	Not listed
		Boiling point/range	147–477°F	None	None	None	None
		Evaporation rate	0.45 x *n*-Butyl Acetate	None	Not listed	Not listed	Not listed
		Vapor pressure	97.7 mm Hg	Not determined	2.17 mm Hg at 21 °C	Not determined	Not determined
		Vapor density	Heavier than air	Not determined	No data	Not determined	Not determined
		Specific gravity/relative density	1.6–1.7	None	None	None	None
		VOC	< 150 g/L	Not listed	Not listed	Not listed	Not listed
		Viscosity	Not listed	N/A	Not determined	N/A	No data
		Solubility	Not listed	Negligible	Slight	Negligible	Negligible

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Waterborne Paint (OSHA)	Epoplex LS50 Black (ANSI)	Epoplex LS50 Hardener (ANSI)	Epoplex LS50 White (ANSI)	Epoplex LS50 Yellow (ANSI)
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	N/A	Extreme temperature, direct sunlight	Direct sources of heat	Extreme temperature, direct sunlight	Extreme temperature, direct sunlight
		Incompatible materials	N/A	Strong oxidizing agents, acids, bases	Strong oxidizing agents	Strong oxidizing agents, acids, bases	Strong oxidizing agents, acids, bases
		Hazardous decomposition products	Listed	Listed	Listed	Listed	Listed
		Hazardous polymerization	Will not occur	Will not occur	Will not occur	Will not occur	Will not occur
11	Toxicological Information	Toxicological information	Not listed	Not listed	Not listed	Not listed	Not listed
		Acute dose effects (LD50, LC50)	Not expected	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients
		Repeated dose effects (NOAEL)	Not listed	Not listed	Not listed	Not listed	Not listed
		Carcinogenicity	Not a carcinogen	Not listed	Not listed	Not listed	Not listed
		Neurological effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Genetic effects (mutagenicity)	Not listed	Not listed	Not listed	Not listed	Not listed
		Reproductive effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Developmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Target organ effects	Not listed	Not listed	Not listed	Not listed	Not listed
12	Ecological Information	Ecotoxicity	Fish: Fathead Minnow: 96 h; LC50 $\geq$ 750 mg/L	No information	No information	No information	No information
		Persistence/degradability	Data not available	No information	No information	No information	No information
		Bioaccumulation/bioconcentration	Data not available	No information	No information	No information	No information
		Mobility: air, soil, water	Data not available	No information	No information	No information	No information
		Other adverse effects	Data not available	No information	No information	No information	No information

MSDS Section No.	MSDS Section Description	Type of Information	Ennis Waterborne Paint (OSHA)	Epoplex LS50 Black (ANSI)	Epoplex LS50 Hardener (ANSI)	Epoplex LS50 White (ANSI)	Epoplex LS50 Yellow (ANSI)
13	Disposal Considerations	Safe and environmentally preferred disposal of material and container	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
		Classification under applicable laws	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
14	Transport Information	DOT proper shipping name	Not regulated	None	Listed	None	None
		DOT hazard class(es)	Not regulated	None	8	None	None
		DOT identification number	Not regulated	None	Listed	None	None
		Packing group	Not regulated	None	III	None	None
15	Regulatory Information	United States, Federal	313, TSCA	311/312, 313, TSCA, CAA	311/312, 313, TSCA, CAA	311/312, 313, TSCA, CAA	311/312, 313, TSCA, CAA
		United States, State	CA Proposition 65	New Jersey, Pennsylvania, California	New Jersey, Pennsylvania, California	New Jersey, Pennsylvania, California	New Jersey, Pennsylvania, California
		International	None listed	Canada, European Economic Community (EEC)	Canada, EEC	Canada, EEC	Canada, EEC
16	Other Information	Hazard ratings	Not listed	HMIS	HMIS	HMIS	HMIS
		Health	1	2	3	2	2
		Flammability	1	1	1	1	1
		Reactivity	0	1	1	1	1
		Other	Personal protection 0	Personal protection C	Personal protection H	Personal protection C	Personal protection C
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Not listed	Not listed	Listed	Not listed	Not listed

N/A = Not applicable.
°F = 1.8(°C) + 32.

Table 99. MSDS information for epoxy and preformed tape.

MSDS Section No.	MSDS Section Description	Type of Information	Epoplex LS90 Yellow Amine (ANSI)	Epoplex LS90 White Amine (ANSI)	Epoplex LS90SP White Amine (ANSI)	Epoplex LS90SP Yellow Amine (ANSI)	Flint PreMark (ANSI)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Summarized	Summarized	Summarized	Summarized	Not listed
		Potential health effects	Harmful if swallowed, skin irritation, skin sensitization, respiratory system irritation	Harmful if swallowed, skin irritation, skin sensitization, respiratory system irritation	Harmful if swallowed, skin irritation, skin sensitization, respiratory system irritation	Harmful if swallowed, skin irritation, skin sensitization, respiratory system irritation	Repeated overexposure can cause allergic respiratory reaction
		If listed as a carcinogen	Yes—IARC	Not a carcinogen	Not a carcinogen	Not a carcinogen	Not a carcinogen
		Environmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
3	Composition, Information on Ingredients	Chemical name	Not listed	Hazardous ingredient only	Not listed	Not listed	Listed
		CAS registry number and percentages	Not listed	Hazardous ingredient only	Not listed	Not listed	Percentages only
		Established exposure guidelines	None	Hazardous ingredient only	None	None	Not a hazardous material
		Authority (OSHA, ACGIH, CMRG)	None	OSHA, ACGIH	None	None	None
4	First Aid Procedures	Eye	Rinse	Rinse	Rinse	Rinse	Rinse
		Skin	Wash	Wash	Wash	Wash	Rinse burns, get medical treatment
		Inhalation	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air
		Ingestion	Give water	Give water	Give water	Give water	Give milk or water, get medical treatment

MSDS Section No.	MSDS Section Description	Type of Information	Epoplex LS90 Yellow Amine (ANSI)	Epoplex LS90 White Amine (ANSI)	Epoplex LS90SP White Amine (ANSI)	Epoplex LS90SP Yellow Amine (ANSI)	Flint PreMark (ANSI)
5	Fire-Fighting Measures	Specific hazards	None listed	None listed	None listed	None listed	N/A
		Flash point	> 200 °F	> 200 °F	> 200 °F	> 200 °F	482 °F
		Explosive limits	0.9–9.7 percent	0.9–9.7 percent	Not determined	Not determined	N/A
		Suitable/unsuitable extinguishing media	Carbon dioxide, dry chemical, foam	Carbon dioxide, dry chemical, foam	Carbon dioxide, dry chemical, foam	Carbon dioxide, dry chemical, foam	Water, water spray, dry chemical, carbon dioxide
		Instructions for firefighters	Spray containers, collect contaminated water separately, do not discharge into drains	Spray containers, collect contaminated water separately, do not discharge into drains	Spray containers, collect contaminated water separately, do not discharge into drains	Spray containers, collect contaminated water separately, do not discharge into drains	N/A
		Protective equipment	SCBA	SCBA	SCBA	SCBA	Not listed
6	Accidental Release Measures	Clean-up/containment technique	Soak up with absorbent materials.	Soak up with absorbent materials.	Soak up with absorbent materials.	Soak up with absorbent materials.	Allow how material to solidify, collect or scrape up
		PPE and precautions	Use PPE	Use PPE	Use PPE	Use PPE	Not listed
		Environmental precautions	Do not allow material to contaminate groundwater system	Do not allow material to contaminate groundwater system	Do not allow material to contaminate groundwater system	Do not allow material to contaminate groundwater system	Not reported
		Regulatory/reporting requirements	Check applicable regulations	Check applicable regulations	Check applicable regulations	Check applicable regulations	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	Epoplex LS90 Yellow Amine (ANSI)	Epoplex LS90 White Amine (ANSI)	Epoplex LS90SP White Amine (ANSI)	Epoplex LS90SP Yellow Amine (ANSI)	Flint PreMark (ANSI)
7	Handling and Storage	Handing – proper handling to prevent spills, fire, explosion	Wear PPE, use ventilation	Wear PPE, use ventilation	Wear PPE, use ventilation	Wear PPE, use ventilation	Avoid skin contact with hot product
		Storage – incompatible materials, proper storage containers, proper storage conditions	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Keep dry, away from heat and sunlight, store between 5 and 25 °C, store in original container	Cool, dry place
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Glasses	Glasses	Glasses	Glasses	Not listed
		Skin	Gloves, apron, long sleeves	Gloves, apron, long sleeves	Gloves, apron, long sleeves	Gloves, apron, long sleeves	Leather gloves
		Respiratory	None needed	None needed	None needed	None needed	N/A
9	Physical and Chemical Properties	Appearance	Yellow	White	White	Yellow	Solid plastic sheet
		Odor/odor threshold	Amine like	Amine like	Slight	Slight	None
		Physical state	Liquid	Liquid	Liquid	Liquid	Solid plastic sheet
		pH	Non-aqueous	Non-aqueous	Mild alkaline	Mild alkaline	Not listed
		Melting/freezing point	Not listed	Not listed	Not listed	Not listed	108–120 °C
		Boiling point/range	363—None	363—None	363—None	363—None	500F
		Evaporation rate	Not listed	Not listed	Not listed	Not listed	Not listed
		Vapor pressure	Not determined	Not determined	N/A	N/A	N/A
		Vapor density	Heavier than air	Heavier than air	Heavier than air	Heavier than air	N/A
		Specific gravity/relative density	None	None	None	None	1.90–2.0
		VOC	Not listed	Not listed	Not listed	Not listed	Not listed
		Viscosity	N/A	N/A	4000 CPS	4000 CPS	Not listed
		Solubility	Negligible	Negligible	Negligible	Negligible	Not soluble

MSDS Section No.	MSDS Section Description	Type of Information	Epoplex LS90 Yellow Amine (ANSI)	Epoplex LS90 White Amine (ANSI)	Epoplex LS90SP White Amine (ANSI)	Epoplex LS90SP Yellow Amine (ANSI)	Flint PreMark (ANSI)
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	No information	No information	No information	No information	Not listed
		Incompatible materials	Strong oxidizing agents, acids, bases	Strong oxidizing agents, acids, bases	Strong oxidizing agents, acids, bases	Strong oxidizing agents, acids, bases	Not listed
		Hazardous decomposition products	Listed	Listed	Listed	Listed	Not listed
		Hazardous polymerization	Will not occur	Will not occur	Will not occur	Will not occur	Will not occur
11	Toxicological Information	Toxicological information	Not listed	Not listed	Not listed	Not listed	Not listed
		Acute dose effects (LD50, LC50)	Not available	Not available	Not available	Not available	Not listed
		Repeated dose effects (NOAEL)	Not listed	Not listed	Not listed	Not listed	Not listed
		Carcinogenicity	Not listed	Not listed	Not listed	Not listed	Not listed
		Neurological effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Genetic effects (mutagenicity)	Not listed	Not listed	Not listed	Not listed	Not listed
		Reproductive effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Developmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Target organ effects	Not listed	Not listed	Not listed	Not listed	Not listed
12	Ecological Information	Ecotoxicity	No information	No information	No information	No information	Not listed
		Persistence/degradability	No information	No information	No information	No information	Not listed
		Bioaccumulation/bioconcentration	No information	No information	No information	No information	Not listed
		Mobility: air, soil, and water	No information	No information	No information	No information	Not listed
		Other adverse effects	No information	No information	No information	No information	Not listed
13	Disposal Considerations	Safe and environmentally preferred disposal of material and container	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
		Classification under applicable laws	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations

MSDS Section No.	MSDS Section Description	Type of Information	Epoplex LS90 Yellow Amine (ANSI)	Epoplex LS90 White Amine (ANSI)	Epoplex LS90SP White Amine (ANSI)	Epoplex LS90SP Yellow Amine (ANSI)	Flint PreMark (ANSI)
14	Transport Information	DOT proper shipping name	None	None	None	None	Not listed
		DOT hazard class(es)	None	None	None	None	Not listed
		DOT identification number	None	None	None	None	Not listed
		Packing group	None	None	None	None	Not listed
15	Regulatory Information	United States, Federal	311/312, 313, TSCA, CAA	311/312, 313, TSCA, CAA	311/312, 313, TSCA, CAA	311/312, 313, TSCA, CAA	Not listed
		United States, State	New Jersey, Pennsylvania, California	New Jersey, Pennsylvania, California	New Jersey, Pennsylvania, California	New Jersey, Pennsylvania, California	Not listed
		International	Canada, EEC	Canada, EEC	Canada, EEC	Canada, EEC	Not listed
16	Other Information	Hazard ratings	HMIS	HMIS	HMIS	HMIS	Not listed
		Health	1	1	2	2	Not listed
		Flammability	0	0	1	1	Not listed
		Reactivity	0	0	0	0	Not listed
		Other	Personal protection E	Personal protection E	Personal protection C	Personal protection C	Not listed
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Not listed	Listed	Listed	Listed	Listed

N/A = Not applicable.
°F = 1.8(°C) + 32.

Table 100. MSDS information for modified epoxy.

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Summarized	Summarized	Summarized	Summarized	Summarized
		Potential health effects	Skin sensitization, allergy reaction	Skin irritation, eye irritation, respiratory system irritation, delayed lung damage, asthma, highly toxic if inhaled, may be fatal if swallowed	Skin irritation, eye irritation, respiratory system irritation	Skin irritation, severe eye irritation, respiratory system irritation, highly toxic if inhaled, may be fatal if swallowed	Skin irritation, eye irritation, respiratory system irritation, digestive system irritation
		If listed as a carcinogen	No—IARC	No—IARC	Yes—IARC	No—IARC	No—IARC
		Environmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
3	Composition, Information on Ingredients	Chemical name	All ingredients	All ingredients	All ingredients	All ingredients	All ingredients
		CAS registry number and percentages	All ingredients	All ingredients	All ingredients	All ingredients	All ingredients
		Established exposure guidelines	All ingredients	All ingredients	All ingredients	All ingredients	All ingredients
		Authority (OSHA, ACGIH, CMRG)	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
4	First Aid Procedures	Eye	Flush, get medical attention	Flush, get medical attention	Flush, get medical attention	Flush, get medical attention	Flush, get medical attention
		Skin	Wash	Wash	Wash	Wash, get medical attention	Wash
		Inhalation	Move to fresh air	Move to fresh air, get medical attention	Move to fresh air	Move to fresh air, get medical attention	Move to fresh air, get medical attention
		Ingestion	Give water or milk, get medical attention	Give water or milk, get medical attention	Give water or milk, get medical attention	Give water or milk, get medical attention	Give water or milk, get medical attention
5	Fire-Fighting Measures	Specific hazards	Exposure to heat may cause containers to explode	Exposure to heat may cause containers to explode, combustion may cause irritating or toxic vapors	Exposure to heat may cause containers to explode	Exposure to heat may cause containers to explode	Exposure to heat may cause containers to explode
		Flash point	> 200 °F	> 200 °F	> 200 °F	> 200 °F	> 200 °F
		Explosive limits	Not available	Not available	Not available	Not available	Not available
		Suitable/unsuitable extinguishing media	Alcohol foam, carbon dioxide, dry chemical, water	Carbon dioxide, foam, dry chemical, water fog	Carbon dioxide, foam, dry chemical, water fog	Carbon dioxide, foam, dry chemical, water fog	Carbon dioxide, foam, dry chemical, water fog

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
5 (cont'd)	Fire-Fighting Measures (cont'd)	Instructions for firefighters	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool
		Protective equipment	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA
6	Accidental Release Measures	Clean-up/containment technique	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials
		PPE and precautions	Use PPE	Use PPE	Use PPE	Use PPE	Use PPE
		Environmental precautions	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways
		Regulatory/reporting requirements	Not listed	Not listed	Not listed	Not listed	Not listed
7	Handling and Storage	Handing – proper handling to prevent spills, fire, explosion	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
7 (cont'd)	Handling and Storage (cont'd)	Storage—incompatible materials, proper storage containers, proper storage conditions	Close container when not in use	Close container when not in use	Close container when not in use, store in cool, well-ventilated area	Close container when not in use, store in cool, well-ventilated area	Close container when not in use, store in cool, well-ventilated area
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Safety glasses or goggles	Safety glasses or goggles	Safety glasses or goggles	Safety glasses or goggles	Safety glasses or goggles
		Skin	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots
		Respiratory	Respirator may be needed	Respirator	Respirator	Respirator	Respirator
9	Physical and Chemical Properties	Appearance	Yellow liquid	Light amber	White	Light amber	White
		Odor/odor threshold	Mild	Mild amine	Mild	Mild amine	Mild
		Physical state	Liquid	Liquid	Liquid	Liquid	Liquid
		pH	N/A	N/A	N/A	N/A	N/A
		Melting/freezing point	Not available	Not available	Not available	Not available	Not available
		Boiling point/range	> 200 °F	Not available	Not available	Not available	Not available
		Evaporation rate	Non-volatile	< 1	Non-volatile	< 1	Non-volatile
		Vapor pressure	Not available	Not available	< 0.01 mm Hg	Not available	< 1 mm Hg
		Vapor density	Non-volatile	> 1	Non-volatile	> 1	Non-volatile
		Specific gravity/relative density	1.3	1.012–1.036	1.33–1.414	0.994–1.018	1.384
		VOC	Non-volatile	Non-volatile	Non-volatile	Non-volatile	Non-volatile
		Viscosity	Not listed	60–80 stokes	Not listed	75–90 stokes	Not listed
		Solubility	Insoluble	Not available	Insoluble	Not available	Insoluble

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	Contamination	Contamination	Contamination	Contamination	Contamination
		Incompatible materials	Strong oxidizing agents, acid, bases, primary and secondary amines	Strong oxidizing agents, acids, aldehydes, ketones	Strong oxidizing agents, mineral acids, mineral and organic bases, primary and secondary amines	Strong oxidizing agents, acids, aldehydes, ketones	Strong oxidizing agents, mineral acids, mineral and organic bases, primary and secondary amines
		Hazardous decomposition products	Listed	Listed	Listed	Listed	Listed
		Hazardous polymerization	Will not occur, runaway cure reactions may generate toxic fumes and vapors	Will not occur	Will not occur, runaway cure reactions may generate toxic fumes and vapors	Will not occur	Will not occur, runaway cure reactions may generate toxic fumes and vapors
11	Toxicological Information	Toxicological information	Detailed	Detailed	Detailed	Detailed	Detailed
		Acute dose effects (LD50, LC50)	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients
		Repeated dose effects (NOAEL)	Not listed	Suppression of weight gain, reversible—detailed information	Not listed	Not listed	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
11 (cont'd)	Toxicological Information (cont'd)	Carcinogenicity	Not a carcinogen—detailed information	Not a carcinogen—detailed information	Detailed information	Detailed information	Detailed information
		Neurological effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Genetic effects (mutagenicity)	Some effects shown in rats	Studies were negative	Some effects in animal testing	Not shown in animals	Some effects in animals
		Reproductive effects	Does not interfere with reproduction	Some effects	Not shown to interfere	Some effects in animals	Not shown in animals
		Developmental effects	Does not cause birth defects	Not considered a hazard	No effects in animal testing	Not listed	Not shown in animals
		Target organ effects	Not listed	Not listed	Not listed	Not listed	Not listed
12	Ecological Information	Ecotoxicity	Moderately toxic to aquatic organisms	Slightly toxic, detailed information	Moderately toxic to aquatic organisms	Slightly toxic to aquatic organisms	Moderately toxic to aquatic organisms
		Persistence/degradability	Below detectable limits	Inherently biodegradable	Below detectable limits	Biodegradable	Below detectable limits
		Bioaccumulation/ bioconcentration	Potential is moderate	Potential is low	Potential is moderate	Low	Potential is moderate
		Mobility: air, soil, water	Low mobility in soil	No mobility in soil	Low mobility in soil	No mobility in soil	Low mobility in soil
		Other adverse effects	Not listed	Not listed	Not listed	Not listed	Not listed
13	Disposal Considerations	Safe and environmentally preferred disposal of material and container	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-2 Yellow Epoxy Resin Paint (ANSI)	IPS HPS-3 Catalyst Modified Polyamine Paint (ANSI)	IPS HPS-3 White Epoxy Resin Paint (ANSI)	IPS HPS-4 Catalyst (ANSI)	IPS HPS-4 White Epoxy (ANSI)
13 (cont'd)	Disposal Considerations (cont'd)	Classification under applicable laws	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations
14	Transport Information	DOT proper shipping name	Not regulated	Listed	Not regulated	Listed	Not regulated
		DOT hazard class(es)	Not regulated	9	Not regulated	8	Not regulated
		DOT identification number	Not regulated	Listed	Not regulated	Listed	Not regulated
		Packing group	Not regulated	III	Not regulated	III	Not regulated
15	Regulatory Information	United States, Federal	OSHA, Environment, Health, and Safety (EHS), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA
		United States, State	California	California	California	California	California
		International	Canada	Canada	Canada	Canada	Canada
16	Other Information	Hazard ratings	HMIS/NFPA	HMIS/NFPA	HMIS/NFPA	HMIS/NFPA	HMIS/NFPA
		Health	2	2	2	2	2
		Flammability	1	1	1	1	1
		Reactivity	1	1	1	1	2
		Other	Not listed	Not listed	Not listed	Not listed	Not listed
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Listed	Listed	Listed	Listed	Listed

N/A = Not applicable.

Table 101. MSDS information for modified epoxy and paint.

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Summarized	Summarized	Summarized	Summarized	Not listed
		Potential health effects	Skin irritation, eye irritation, respiratory system irritation, digestive system irritation	Eye irritation, skin irritation, respiratory system irritation, lung damage, asthma, flu like symptoms	Skin sensitization and irritation, eye irritation, respiratory system irritation, digestive system irritation	Skin sensitization and irritation, eye irritation, respiratory system irritation, digestive system irritation	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed
		If listed as a carcinogen	No—IARC	No—IARC	No—IARC	No—IARC	Yes—CA Proposition 65
		Environmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
3	Composition, Information on Ingredients	Chemical name	All ingredients	All ingredients	All ingredients	All ingredients	Hazardous ingredients only
		CAS registry number and percentages	All ingredients	All ingredients	All ingredients	All ingredients	Hazardous ingredients only
		Established exposure guidelines	All ingredients	All ingredients	All ingredients	All ingredients	Hazardous ingredients only
		Authority (OSHA, ACGIH, and CMRG)	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
4	First Aid Procedures	Eye	Flush, get medical attention	Flush, get medical attention	Flush, get medical attention	Flush, get medical attention	Flush
		Skin	Wash	Wash	Wash	Wash	Wash
		Inhalation	Move to fresh air, get medical attention	Move to fresh air, get medical attention	Move to fresh air, get medical attention	Move to fresh air, get medical attention	Move to fresh air
		Ingestion	Give water or milk, get medical attention	Give water or milk, get medical attention	Give water or milk, get medical attention	Give water or milk, get medical attention	Get medical attention
5	Fire-Fighting Measures	Specific hazards	Exposure to heat may cause containers to explode	Exposure to heat may cause containers to explode, combustion may cause irritating or toxic vapors	Exposure to heat may cause containers to explode	Exposure to heat may cause containers to explode, combustion may cause irritating or toxic vapors	Vapors are heavier than air and can travel a significant distance, vapors can be ignited
		Flash point	> 200 °F	338 °F	> 200 °F	> 200 °F	0–5 °F
		Explosive limits	Not available	Not available	Not available	Not available	1–12.8 percent
		Suitable/unsuitable extinguishing media	Alcohol foam, carbon dioxide, dry chemical, water	Dry chemical, carbon dioxide, foam	Carbon dioxide, dry chemical, water fog, foam	Carbon dioxide, dry chemical, water fog, foam	Water fog, dry chemical, foam, carbon dioxide
		Instructions for firefighters	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool	Protect from potential explosion hazard, spray containers to cool	Use water to cool containers

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
		Protective equipment	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA
6	Accidental Release Measures	Clean up/containment technique	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials
		PPE and precautions	Use PPE	Use PPE	Use PPE	Use PPE	Use PPE
		Environmental precautions	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways
		Regulatory/reporting requirements	Not listed	Not listed	Not listed	Not listed	Comply with applicable regulations
7	Handling and Storage	Handing—proper handling to prevent spills, fire, explosion	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums, reacts violently with water	Avoid contact with eyes, skin, clothing, use with adequate ventilation, properly dispose of empty drums	Avoid contact with eyes, skin, clothing, use with adequate ventilation	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas
		Storage—incompatible materials, proper storage containers, proper storage conditions	Close container when not in use, store in cool, well-ventilated area	Close container when not in use, store in cool, well-ventilated area	Close container when not in use	Close container when not in use	Keep containers closed, keep away from heat and flames

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Safety glasses or goggles	Safety glasses or goggles	Safety glasses or goggles	Safety glasses or goggles	Goggles or face shield
		Skin	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots
		Respiratory	Respirator	Respirator	Respirator	Respirator	Respirator
9	Physical and Chemical Properties	Appearance	Yellow	Pale yellow	White	Yellow	Opaque viscous liquid
		Odor/odor threshold	Mild	Odorless	Amine	Amine	Mild ketone odor
		Physical state	Liquid	Liquid	Liquid	Liquid	Liquid
		pH	N/A	N/A	N/A	N/A	N/A
		Melting/freezing point	Not available	Not listed	Not available	Not available	Not listed
		Boiling point/range	Not available	Not available	Not available	Not available	133–279 °F
		Evaporation rate	Non-volatile	Not available	Non-volatile	Non-volatile	Slower than ether
		Vapor pressure	Not available	12 mm Hg	Non-volatile	Non-volatile	70.7 mm HG
		Vapor density	Non-volatile	Not available	Non-volatile	Non-volatile	Heavier than air
		Specific gravity/relative density	1.31	1.12	0.98	1.14	1.53
		VOC	Non-volatile	Not available	Non-volatile	Non-volatile	147 g/L
		Viscosity	Not listed	Not available	Not available	Not available	Not listed
		Solubility	Insoluble	Reacts with water	Insoluble	Insoluble	Negligible

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	Contamination	Contamination	Contamination	Contamination	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging
		Incompatible materials	Strong oxidizing agents, acid, bases, primary and secondary amines	Water, amines, alcohols, strong oxidizing agents, strong bases, acids, free radical initiators	Strong oxidizing agents, reducers	Strong oxidizing agents, reducers, acids	Alkaline materials, strong acids, oxidizing materials
		Hazardous decomposition products	Listed	Listed	Listed	Listed	Listed
		Hazardous polymerization	Will not occur, runaway cure reactions may generate toxic fumes and vapors	May occur—contact with moisture, temperatures > 400°F, contact with materials that react with isocyanates	Will occur at elevated temperatures	Will occur at elevated temperatures	Will not occur

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
11	Toxicological Information	Toxicological information	Detailed	Detailed	Detailed	Detailed	Not listed
		Acute dose effects (LD50, LC50)	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients	Listed for hazardous ingredients	Some information
		Repeated dose effects (NOAEL)	Not listed	Sensitization—detailed information	None shown	Not listed	Some information
		Carcinogenicity	Detailed information	Detailed information	Detailed information	Detailed	Yes—CA Proposition 65
		Neurological effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Genetic effects (mutagenicity)	Some effects in animals	Not listed	Not listed	Not listed	Not listed
		Reproductive effects	Not shown to interfere	Not listed	Not listed	Not listed	Not listed
		Developmental effects	Not shown in animals	Not listed	Not listed	Not listed	Not listed
		Target organ effects	Not listed	Not listed	Not listed	Not listed	Not listed
12	Ecological Information	Ecotoxicity	Moderately toxic to aquatic organisms	No information is available	No information is available	No information is available	Not listed
		Persistence/degradability	Below detectable limits	No information is available	No information is available	No information is available	Not listed
		Bioaccumulation/ bioconcentration	Potential is moderate	No information is available	No information is available	No information is available	Not listed
		Mobility: air, soil, water	Low mobility in soil	No information is available	No information is available	No information is available	Not listed
		Other adverse effects	Not listed	No information is available	No information is available	No information is available	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	IPS HPS-4 Yellow Epoxy (ANSI)	IPS HPS-5 Catalyst (ANSI)	IPS HPS-5 White (ANSI)	IPS HPS-5 Yellow (ANSI)	Pervo 7100 White Paint (OSHA)
13	Disposal Considerations	Safe and environmentally preferred disposal of material and container	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Check local regulations
		Classification under applicable laws	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Not a RCRA hazardous waste, check local regulations	Check local regulations
14	Transport Information	DOT proper shipping name	Not regulated	Not regulated	Not regulated	Not regulated	Listed
		DOT hazard class(es)	Not regulated	Not regulated	Not regulated	Not regulated	3
		DOT identification number	Not regulated	Not regulated	Not regulated	Not regulated	Listed
		Packing group	Not regulated	Not regulated	Not regulated	Not regulated	Not listed
15	Regulatory Information	United States, Federal	OSHA, EHS, CERCLA, 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA	OSHA, EHS, CERCLA, 311/312, 313, TSCA	Not listed
		United States, State	California	California	California	California	California
		International	Listed	Listed	Not listed	Canada	Not listed
16	Other Information	Hazard ratings	HMIS/NFPA	HMIS/NFPA	HMIS/NFPA	HMIS/NFPA	HMIS
		Health	2	2	2	2	1
		Flammability	1	1	1	1	1
		Reactivity	1	1	1	1	0
		Other	Not listed	Not listed	Not listed	Not listed	Personal protection H
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Listed	Listed	Listed	Listed	Not listed

N/A = Not applicable.

Table 102. MSDS information for paint.

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 7100R White Paint (OSHA)	Pervo 7102 Black Paint (OSHA)	Pervo 7103 Yellow Paint (OSHA)	Pervo 7103R Yellow Paint (OSHA)	Pervo 8100 White Paint (OSHA)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24 h)	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Not listed	Not listed	Not listed	Not listed	Not listed
		Potential health effects	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed
		If listed as a carcinogen	Yes—CA Proposition 65	Yes—CA Proposition 65	Yes—CA Proposition 65	Yes—CA Proposition 65	Yes—CA Proposition 65
		Environmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
3	Composition, Information on Ingredients	Chemical name	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only
		CAS registry number and percentages	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only
		Established exposure guidelines	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only	Hazardous ingredients only
		Authority (OSHA, ACGIH, and CMRG)	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 7100R White Paint (OSHA)	Pervo 7102 Black Paint (OSHA)	Pervo 7103 Yellow Paint (OSHA)	Pervo 7103R Yellow Paint (OSHA)	Pervo 8100 White Paint (OSHA)
4	First Aid Procedures	Eye	Flush	Flush	Flush	Flush	Flush
		Skin	Wash	Wash	Wash	Wash	Wash
		Inhalation	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air
		Ingestion	Get medical attention	Get medical attention	Get medical attention	Get medical attention	Get medical attention
5	Fire-Fighting Measures	Specific hazards	Vapors are heavier than air and can travel a significant distance, vapors can be ignited	Vapors are heavier than air and can travel a significant distance, vapors can be ignited	Vapors are heavier than air and can travel a significant distance, vapors can be ignited	Vapors are heavier than air and can travel a significant distance, vapors can be ignited	Vapors are heavier than air and can travel a significant distance, vapors can be ignited
		Flash point	0–5 °F	0–5 °F	0–5 °F	0–5 °F	0–5 °F
		Explosive limits	1–12.8 percent	1–12.8 percent	1–12.8 percent	1–12.8 percent	1–12.8 percent
		Suitable/unsuitable extinguishing media	Water fog, dry chemical, foam, carbon dioxide	Water fog, dry chemical, foam, carbon dioxide	Water fog, dry chemical, foam, carbon dioxide	Water fog, dry chemical, foam, carbon dioxide	Water fog, dry chemical, foam, carbon dioxide
		Instructions for firefighters	Use water to cool containers	Use water to cool containers	Use water to cool containers	Use water to cool containers	Use water to cool containers
		Protective equipment	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA	Protective clothing, SCBA
6	Accidental Release Measures	Clean up/containment technique	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials	Absorb with inert materials
		PPE and precautions	Use PPE	Use PPE	Use PPE	Use PPE	Use PPE

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 7100R White Paint (OSHA)	Pervo 7102 Black Paint (OSHA)	Pervo 7103 Yellow Paint (OSHA)	Pervo 7103R Yellow Paint (OSHA)	Pervo 8100 White Paint (OSHA)
6 (cont'd)	Accidental Release Measures (cont'd)	Environmental precautions	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways
		Regulatory/reporting requirements	Comply with applicable regulations	Comply with applicable regulations	Comply with applicable regulations	Comply with applicable regulations	Comply with applicable regulations
7	Handling and Storage	Handing—proper handling to prevent spills, fire, explosion	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas
		Storage—incompatible materials, proper storage containers, proper storage conditions	Keep containers closed, keep away from heat and flames	Keep containers closed, keep away from heat and flames	Keep containers closed, keep away from heat and flames	Keep containers closed, keep away from heat and flames	Keep containers closed, keep away from heat and flames
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Goggles or face shield	Goggles or face shield	Goggles or face shield	Goggles or face shield	Goggles or face shield
		Skin	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Gloves, protective clothing, boots
		Respiratory	Respirator	Respirator	Respirator	Respirator	Respirator
9	Physical and Chemical Properties	Appearance	Opaque viscous liquid	Opaque viscous liquid	Opaque viscous liquid	Opaque viscous liquid	Opaque viscous liquid
		Odor/odor threshold	Mild ketone odor	Mild ketone odor	Mild ketone odor	Mild ketone odor	Mild ketone odor
		Physical state	Liquid	Liquid	Liquid	Liquid	Liquid

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 7100R White Paint (OSHA)	Pervo 7102 Black Paint (OSHA)	Pervo 7103 Yellow Paint (OSHA)	Pervo 7103R Yellow Paint (OSHA)	Pervo 8100 White Paint (OSHA)
9 (cont'd)	Physical and Chemical Properties (cont'd)	pH	N/A	N/A	N/A	N/A	N/A
		Melting/freezing point	Not listed	Not listed	Not listed	Not listed	Not listed
		Boiling point/range	133–279 °F	133–279 °F	133–279 °F	133–279 °F	133–279 °F
		Evaporation rate	Slower than ether	Slower than ether	Slower than ether	Slower than ether	Slower than ether
		Vapor pressure	70.7 mm HG	70.7 mm HG	70.7 mm HG	70.7 mm HG	70.7 mm HG
		Vapor density	Heavier than air	Heavier than air	Heavier than air	Heavier than air	Heavier than air
		Specific gravity/relative density	1.54	1.41	1.48	1.54	1.5
		VOC	118 g/L	150 g/L	149 g/L	120 g/L	142 g/L
		Viscosity	Not listed	Not listed	Not listed	Not listed	Not listed
		Solubility	Negligible	Negligible	Negligible	Negligible	Negligible
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging
		Incompatible materials	Alkaline materials, strong acids, oxidizing materials	Alkaline materials, strong acids, oxidizing materials	Alkaline materials, strong acids, oxidizing materials	Alkaline materials, strong acids, oxidizing materials	Alkaline materials, strong acids, oxidizing materials
		Hazardous decomposition products	Listed	Listed	Listed	Listed	Listed
		Hazardous polymerization	Will not occur	Will not occur	Will not occur	Will not occur	Will not occur
11	Toxicological Information	Toxicological information	Not listed	Not listed	Not listed	Not listed	Not listed
		Acute dose effects (LD50, LC50)	Some information	Some information	Some information	Some information	Some information
		Repeated dose effects (NOAEL)	Some information	Some information	Some information	Some information	Some information

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 7100R White Paint (OSHA)	Pervo 7102 Black Paint (OSHA)	Pervo 7103 Yellow Paint (OSHA)	Pervo 7103R Yellow Paint (OSHA)	Pervo 8100 White Paint (OSHA)
11 (cont'd)	Toxicological Information (cont'd)	Carcinogenicity	Yes —CA Proposition 65	Yes —CA Proposition 65	Yes —CA Proposition 65	Yes —CA Proposition 65	Yes —CA Proposition 65
		Neurological effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Genetic effects (mutagenicity)	Not listed	Not listed	Not listed	Not listed	Not listed
		Reproductive effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Developmental effects	Not listed	Not listed	Not listed	Not listed	Not listed
		Target organ effects	Not listed	Not listed	Not listed	Not listed	Not listed
12	Ecological Information	Ecotoxicity	Not listed	Not listed	Not listed	Not listed	Not listed
		Persistence/degradability	Not listed	Not listed	Not listed	Not listed	Not listed
		Bioaccumulation/bioconcentration	Not listed	Not listed	Not listed	Not listed	Not listed
		Mobility: air, soil, water	Not listed	Not listed	Not listed	Not listed	Not listed
		Other adverse effects	Not listed	Not listed	Not listed	Not listed	Not listed
13	Disposal Consider-ations	Safe and environmentally preferred disposal of material and container	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
		Classification under applicable laws	Check local regulations	Check local regulations	Check local regulations	Check local regulations	Check local regulations
14	Transport Information	DOT proper shipping name	Listed	Listed	Listed	Listed	Listed
		DOT hazard class(es)	3	3	3	3	3
		DOT identification number	Listed	Listed	Listed	Listed	Listed
		Packing group	Not listed	Not listed	Not listed	Not listed	Not listed
15	Regulatory Information	United States, Federal	Not listed	Not listed	Not listed	Not listed	Not listed
		United States, State	CA	CA	CA	CA	CA
		International	Not listed	Not listed	Not listed	Not listed	Not listed
16	Other Information	Hazard ratings	HMIS	HMIS	HMIS	HMIS	HMIS
		Health	2	2	2	2	2
		Flammability	3	3	3	3	3
		Reactivity	0	0	0	0	0
		Other	Personal protection H	Personal protection H	Personal protection H	Personal protection H	Personal protection H
		MSDS date	Listed	Listed	Listed	Listed	Listed
		MSDS revision information	Not listed	Not listed	Not listed	Not listed	Not listed

Table 103. MSDS information for paint, beads, methyl, and thermoplastic.

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
1	Product and Company Identification	Product name	Listed	Listed	Listed	Listed	Listed	Listed
		Contact information for manufacturer	Listed	Listed	Listed	Listed	Listed	Listed
		Emergency telephone number (24-h)	Listed	Listed	Listed	Listed	Listed	Listed
2	Hazards Identification	Emergency overview	Not listed	Not listed	Summarized	Summarized	Summarized	Not listed
		Potential health effects	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed	Dizziness, breathing difficulty, headaches, loss of coordination, lung injury, central nervous system damage, skin irritation, eye irritation, poisonous if swallowed	Skin irritation, respiratory irritation, material is slippery	Respiratory system irritation, stomach pain, headache, skin irritation or sensitization, eye irritation	No health hazards	Respiratory tract irritation, skin burns
		If listed as a carcinogen	Yes—CA Proposition 65	Yes—CA Proposition 65	No—NTP, IARC, OSHA	Not considered a carcinogen	Not a carcinogen	Not a carcinogen
		Environmental effects	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
3	Composition, Information on Ingredients	Chemical name	Hazardous ingredients only	Hazardous ingredients only	All ingredients	Some ingredients	Nuisance dust only	No hazardous components
		CAS registry number and percentages	Hazardous ingredients only	Hazardous ingredients only	All ingredients	Some ingredients	Nuisance dust only	No hazardous components
		Established exposure guidelines	Hazardous ingredients only	Hazardous ingredients only	All ingredients	Listed for hazardous ingredients	Nuisance dust only	No hazardous components
		Authority (OSHA, ACGIH, and CMRG)	ACGIH and OSHA	ACGIH and OSHA	ACGIH and OSHA	ACGIH and PEL	PEL	ACGIH and OSHA

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
4	First Aid Procedures	Eye	Flush	Flush	Flush	Flush	Flush	Not listed
		Skin	Wash	Wash	Wash	Wash	Not listed	Cool and dress burns
		Inhalation	Move to fresh air	Move to fresh air	Move to fresh air	Move to fresh air, get medical attention	Move to fresh air	Not listed
		Ingestion	Get medical attention	Get medical attention	None required	Give water or milk, get medical attention	Not listed	Not listed
5	Fire-Fighting Measures	Specific hazards	Vapors are heavier than air and can travel a significant distance, vapors can be ignited	Vapors are heavier than air and can travel a significant distance, vapors can be ignited	Material is non-combustible	Creates toxic vapors/fumes, closed containers may explode when exposed to heat	Does not ignite, not a fire hazard	Avoid contact with water
		Flash point	0–5 °F	0–5 °F	Not listed	20–22 °C	N/A	> 475 °F
		Explosive limits	1–12.8 percent	1–12.8 percent	Not listed	2–13 percent	N/A	Not known
		Suitable/ unsuitable extinguishing media	Water fog, dry chemical, foam, carbon dioxide	Water fog, dry chemical, foam, carbon dioxide	Compatible with all extinguishing media	Foam, dry chemicals, sand, dolomite, water spray, fog or mist	Not a fire hazard	Water spray, dry chemical, carbon dioxide, foam
		Instructions for firefighters	Use water to cool containers	Use water to cool containers	None required	Cool containers to prevent explosion	None	None
		Protective equipment	Protective clothing, SCBA	Protective clothing, SCBA	Rubber boots with slip-resistant soles	Protective clothing, SCBA	None	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
6	Accidental Release Measures	Clean-up/containment technique	Absorb with inert materials	Absorb with inert materials	Shovel or sweep, avoid generating dust	Absorb with inert materials	Vacuum or sweep up	Scoop or sweep granular material, allow molten material to cool before disposal
		PPE and precautions	Use PPE	Use PPE	Rubber boots with slip-resistant soles	Use PPE	Not listed	Not listed
		Environmental precautions	Prevent material from contaminating soil, entering sewers or waterways	Prevent material from contaminating soil, entering sewers or waterways	Sinks in water, no known hazard to aquatic life	Avoid discharge into aquatic environment	Not listed	Check local regulations
		Regulatory/reporting requirements	Comply with applicable regulations	Comply with applicable regulations	No CERCLA required quantities for this material	Not listed	Not RCRA hazardous material	Check local regulations
7	Handling and Storage	Handing—proper handling to prevent spills, fire, explosion	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas	Use non-sparking utensils, avoid hot metal surface, use in cool, ventilated areas	Avoid contact with skin, eyes, avoid breathing dust, keep container closed, use ventilation, promptly clean up spills	Keep away from sparks and flames, ventilate	None	Be prepared for emergencies

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
7 (cont'd)	Handling and Storage (cont'd)	Storage—incompatible materials, proper storage containers, proper storage conditions	Keep containers closed, keep away from heat and flames	Keep containers closed, keep away from heat and flames	Keep containers closed, store in clean metal, fiber, or plastic containers	Store in closed container, cool, dry, well-ventilated place, protect from light, prevent static discharges	None	Keep in ventilated area
8	Exposure Controls and Personal Protection	Engineering controls	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation	Ventilation
		Eye/face	Goggles or face shield	Goggles or face shield	Safety glasses	Safety goggles	Safety goggles	Safety goggles
		Skin	Gloves, protective clothing, boots	Gloves, protective clothing, boots	Body covering clothing	Gloves	Gloves	Gloves, heat protective clothing
		Respiratory	Respirator	Respirator	Respirator	Respirator may be used	Respirator	Respirator
9	Physical and Chemical Properties	Appearance	Opaque viscous liquid	Opaque viscous liquid	Glass bead	Viscous liquid	White	Granular
		Odor/odor threshold	Mild ketone odor	Mild ketone odor	Odorless	Characteristic	No odor	Alkyd oil
		Physical state	Liquid	Liquid	Solid	Liquid	Solid	Solid
		pH	N/A	N/A	N/A	Not listed	Not listed	Not listed
		Melting/freezing point	Not listed	Not listed	730 °C	Not listed	> 1,100 °F	200 °F
		Boiling point/range	133–279 °F	133–279 °F	Not listed	100 °C	Not measurable	N/A
		Evaporation rate	Slower than ether	Slower than ether	Not listed	Not listed	Not listed	N/A
		Vapor pressure	70.7 mm HG	70.7 mm HG	Not listed	Not listed	N/A	N/A
		Vapor density	Heavier than air	Heavier than air	Not listed	Not listed	N/A	N/A

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
9 (cont'd)	Physical and Chemical Properties (cont'd)	Specific gravity/ relative density	1.5	1.44	2.5 g/cm^3	Not listed	2.4–2.6	2.3 max
		VOC	147 g/L	147 g/L	Not listed	Not listed	Not listed	Negligible
		Viscosity	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
		Solubility	Negligible	Negligible	Insoluble	Slightly soluble	N/A	Negligible
10	Stability and Reactivity	Stability	Stable	Stable	Stable	Stable	Stable	Stable
		Conditions to avoid	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging	Excessive heat, poor ventilation, corrosive atmospheres, excessive aging	None required	Heat, sparks, flames, light	None	Temperatures > 500 °F
		Incompatible materials	Alkaline materials, strong acids, oxidizing materials	Alkaline materials, strong acids, oxidizing materials	Hydrofluoric acid	Oxidizers, acids, aluminum, zinc, amines, peroxides, aluminum and iron chlorides	None	None
		Hazardous decomposition products	Listed	Listed	None known	Not listed	None	Listed
		Hazardous polymerization	Will not occur	Will not occur	Not listed	Polymerizes easily with evolution of heat	Will not occur	Will not occur

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
11	Toxicological Information	Toxicological information	Not listed	Not listed	Listed	Detailed information	Not listed	Not listed
		Acute dose effects (LD50, LC50)	Some information	Some information	Detailed information	Detailed information	Not listed	Not listed
		Repeated dose effects (NOAEL)	Some information	Some information	Some information	Not listed	Not listed	Not listed
		Carcinogenicity	Yes—CA Proposition 65	Yes—CA Proposition 65	No known effects	Some information	Not listed	Not listed
		Neurological effects	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
		Genetic effects (mutagenicity)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
		Reproductive effects	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
		Developmental effects	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
		Target organ effects	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
12	Ecological Information	Ecotoxicity	Not listed	Not listed	No known reports of ecotoxicity	Not classified as environ-mentally hazardous	Not listed	Not listed
		Persistence/ degradability	Not listed	Not listed	Persistent	Not readily biodegradable	Not listed	Not listed
		Bioaccumulation/ bioconcentration	Not listed	Not listed	Will not bioconcentrate	Does not bioaccumulate	Not listed	Not listed
		Mobility: air, soil, water	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
		Other adverse effects	Not listed	Not listed	Sinks in water, insoluble in water	Not listed	Not listed	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
13	Disposal Considerations	Safe and environmentally preferred disposal of material and container	Check local regulations	Check local regulations	Not a hazardous waste	Check local regulations, cured product is industrial waste, unused product is hazardous waste	Check local regulations	Check local regulations
		Classification under applicable laws	Check local regulations	Check local regulations	Check local regulations	Check local regulations, cured product is industrial waste, unused product is hazardous waste	Check local regulations	Check local regulations
14	Transport Information	DOT proper shipping name	Listed	Listed	Not regulated	Listed for hazardous ingredients	Not listed	Not listed
		DOT hazard class(es)	3	3	Not regulated	3	Not listed	Not listed
		DOT identification number	Listed	Listed	Not regulated	Listed for hazardous ingredients	Not listed	Not listed
		Packing group	Not listed	Not listed	Not regulated	II	Not listed	Not listed
15	Regulatory Information	United States, Federal	Not listed	Not listed	CERCLA, Superfund Amendments and Reauthorization Act (SARA) Title III, TSCA, FDA	SARA 302, CERCLA, 313, CAA, TSCA	EPA, RCRA, CERCLA	OSHA, SARA Title III
		United States, State	California	California	Not listed	Several listed	Not listed	Not listed
		International	Not listed	Not listed	Not listed	Several listed	Not listed	Not listed

MSDS Section No.	MSDS Section Description	Type of Information	Pervo 8102 Black Paint (OSHA)	Pervo 8103 Yellow Paint (OSHA)	Potters Glass Beads (ANSI)	Stirling Lloyd SafeTrack LM MMA (ANSI)	Swarco Reflex Glass Beads (OSHA)	Swarco Alkyd Yellow Thermoplastic (OSHA)
16	Other Information	Hazard ratings	HMIS	HMIS	Not listed	NFPA	HMIS	Not listed
		Health	2	2	Not listed	2	0	Not listed
		Flammability	3	3	Not listed	3	0	Not listed
		Reactivity	0	0	Not listed	2	0	Not listed
		Other	Personal protection H	Personal protection H	Not listed	Not listed	Not listed	Not listed
		MSDS date	Listed	Listed	Listed	Listed	Not listed	Listed
		MSDS revision information	Not listed	Not listed	Listed	Listed	Not listed	Listed

N/A = Not applicable.
°F = 1.8(°C) + 32.

APPENDIX G. PRESENCE ANALYZER

The focus of this research was to develop an objective, consistent, repeatable, and quantifiable pavement marking presence tool that would provide the percent of material remaining on an in-service pavement marking utilizing digital images of the markings and image analysis software.

TOOL DEVELOPMENT

The research team established a number of short- and long-term goals for measuring the amount of pavement marking remaining on different highway segments. This appendix summarizes the short-term findings. Although this publication reports on markings placed on concrete roadways, the tool has been set up to accommodate a variety of pavement surface types, including asphalt and seal-coated roads.

All calculations are based on a digital image of the subject pavement marking along with the identification of the pavement surface type. From this, the program provides the calculation for the percent paint remaining.

Image segmentation is the process of assigning a set of image pixels to regions that have common characteristics. The proposed system tries to segment images of white or yellow pavement markings into foreground (marking) and background (pavement) parts. The system then objectively reports the presence by calculating the percentage of white and yellow paint to the total image area. The system assumes that the image being processed complies with the general rules specified by transportation department protocol (i.e., image resolution, image dimensions, and the number of images taken for a specific segment length) used for detecting presence.

The system consists of three major stages: an image enhancement stage, a clustering stage, and an analysis stage (see figure 96).

In the first stage, image enhancement, a number of filters are applied to maximize the probability of differentiating the white and yellow color markings from the grey color of the concrete. Hue, saturation and lightness (HSL) filters are used on images of yellow markings, while YCbCr filters (blue-red chroma filters) are used with images of white markings. The filters include histogram equalization in the red-green-blue color space as well as color separation filters in other color spaces. The different values for the filters used are chosen empirically.

The second stage is independent of the marking’s color. It takes the output image of the image enhancement stage and performs the following operations:

- **Gray level conversion**: Each colored pixel in the image is represented by a single value in the range of 0 to 255.
- **Binary image conversion**: Every pixel in the grey level image is labeled to either a foreground or a background pixel based on the value of the pixel compared to a threshold, which is determined empirically (threshold = 50).
- **Connected component analysis**: The different adjacent pixels with similar labels are grouped into one component.

The third stage, analysis, collects statistics of the different connected components, their count and size, and reports the percentage of foreground (white or yellow paint) to background (grey) pixels.

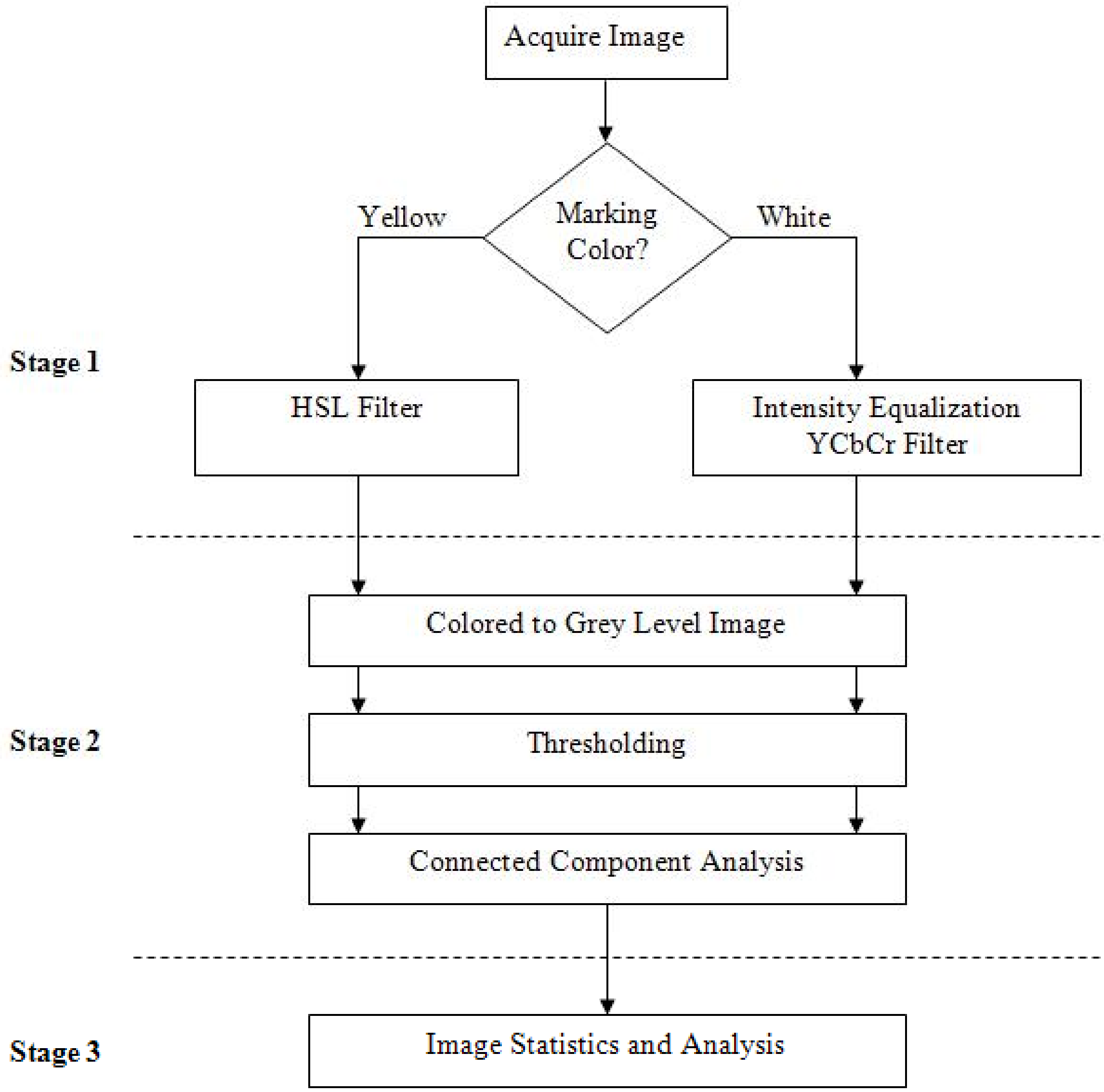


Figure 96. Illustration. Three major stages for calculating percent paint remaining.

CALIBRATION

The tool was tested against different combinations of known composition. Figure 97 shows a combination of processed black and white squares (white area shown in red for contrast), which the tool accurately showed 50 percent remaining. More calibration is needed to ensure accurate and consistent determination of pavement marking material remaining.

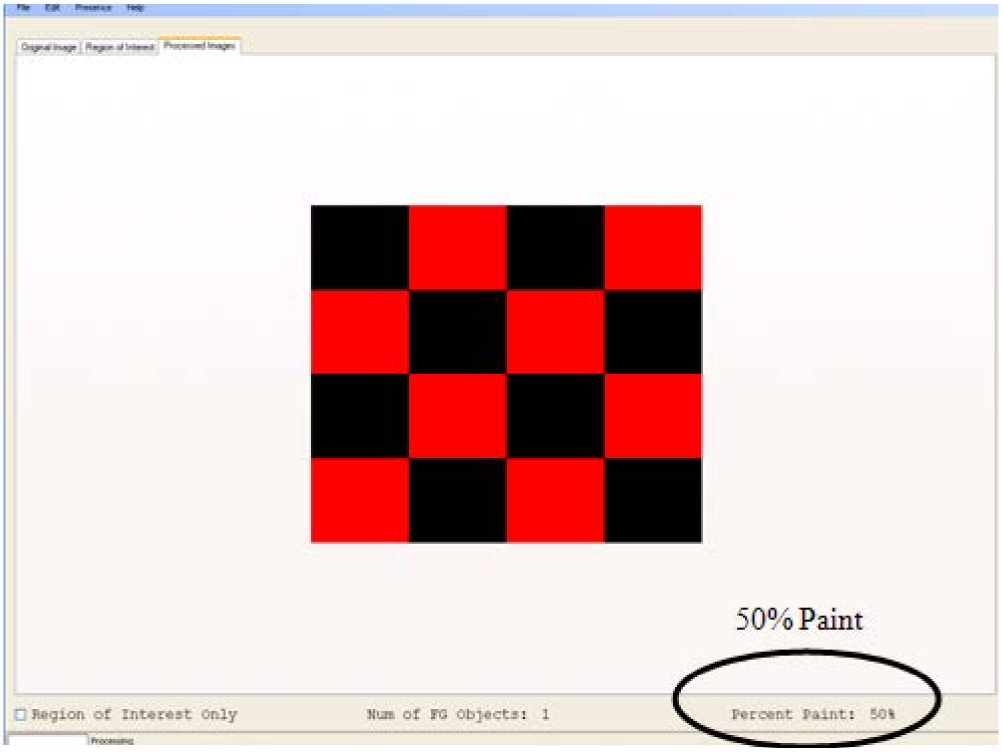


Figure 97. Screenshot. Calibrating the image processing tool.

EXPERIMENTAL RESULTS

The proposed system was applied on several color field images of white and yellow markings on concrete. Figure 98 shows an example of the tool being used to analyze white paint on an asphalt surface. The upper portion of the photo shows the original image. The colors on the lower image show processed paint by color. The color is used to provide feedback on contiguous areas of foreground material. Although there is room for improvement, comparing the two images reveals very close pattern recognition of paint material. By viewing the upper image, it may be difficult to estimate that there is 50 percent paint remaining. The tool greatly reduces subjectivity and provides much needed repeatability to the analysis of presence.

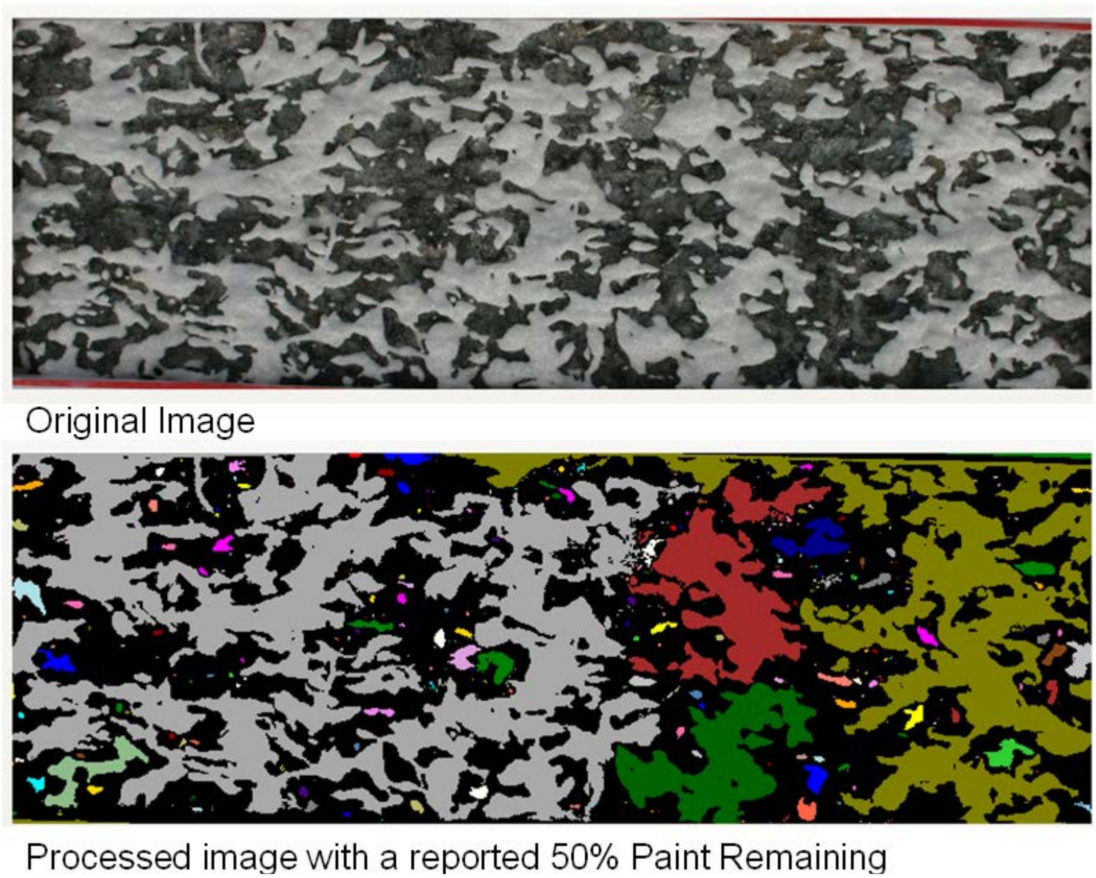


Figure 98. Photo. MMA pavement marking processed using the presence tool.

SUMMARY

This research enhances the ability to analyze the presence of in-service pavement markings. This innovation comes through applying established capabilities developed within image processing technologies. These initial findings have produced a repeatable, objective, and efficient method to evaluate pavement marking presence. Further research and development are needed to add different pavement types, determine the minimum image resolution needed for accurate and repeatable measurements, and improve the user interface to allow for further enhancements of the results by identifying and fixing false positives and false negatives.

Objective presence assessments, in combination with retroreflectivity conditions, will facilitate managing markings for both their day and night performance. This combination will enhance decisionmaking in terms of marking installation and maintenance, overall investment, safety, and the use of new products and will further innovation. Figure 99 shows how data from this study could be used to manage pavement markings and make decisions regarding the most cost effective materials and installation techniques to specify.

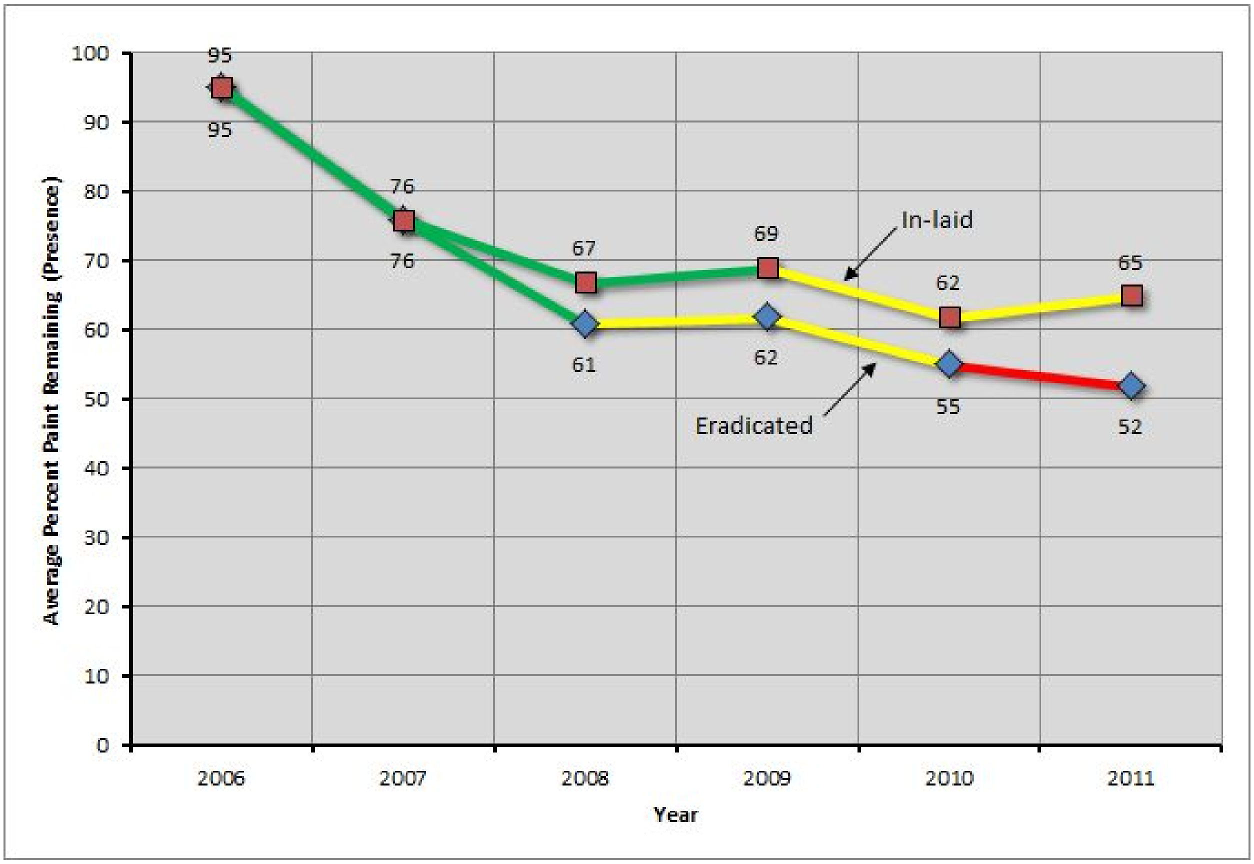


Figure 99. Graph. Section TN 3 WB eradicated versus inlaid.

APPENDIX H. MANAGEMENT TOOLS

CHALLENGES

Pavement markings enhance public safety by providing both orientation and guidance to roadway users. However, providing visible markings year-round is a considerable challenge to roadway agencies given the harsh conditions in which they must perform. These conditions include both wear and tear from traffic, winter operations, and roadway surface conditions. As an example, figure 100 and figure 101 show a pavement marking in Alaska, both when a new edge line was installed in 2006 and the resulting damage 2 years later in 2008.

Figure 100. Photo. Pavement marking installed in Alaska in 2006.

Figure 101. Photo. Pavement marking after 2 years in Alaska in 2008.

Agencies must also select the most effective pavement marking and optical bead package for each roadway condition and ensure a high-quality installation. As shown in figure 102 and figure 103, the installation process involves placing both the marking material and glass beads appropriately while driving with traffic along the roadway.

Figure 102. Photo. Pavement marking installation.

Figure 103. Photo. Close-up of pavement marking installation.

It is common to experience a wide variation in marking practices and policies even among adjacent States in similar regions. Agencies are constantly trying to balance resources between traditional and more expensive durable materials in the face of existing policies, user needs, construction seasons, and climate conditions.

This chapter summarizes a prototype PMST developed as part of this project, which is based on the results of two Tennessee test decks (Nashville and Tusculum) that were evaluated between 2006 and 2011.

PMST METHODOLOGY

The concept behind the PMST is to provide practitioners with a prototype tool that would assist in the selection of pavement markings based on the demonstrated product performances of different materials from the two Tennessee test decks. The tool is interactive and provides users with pavement marking material options based on a desired performance level.

TEST DECKS

Two pavement marking test decks were installed in Tennessee with cooperation from TDOT. In 2006, a test deck was installed near Nashville, TN, on SR 840. The test deck consisted of 9 different pavement marking materials, and the roadway has an AADT of 19,000. Winter operations for this test deck are considered minimal. The second test deck is in northeastern Tennessee on SR 340 near Tusculum, TN. The test deck again consisted of 9 different pavement marking materials, and the roadway has an AADT of 12,000. Winter operations for this test deck are considered minimal.

Retroreflectivity data were collected using a handheld pavement marking retroreflectometer and a mobile retroreflectometer. The handheld retroreflectometer only measures edge line markings, whereas the mobile retroreflectometer measures both edge line and lane line markings. All retroreflectivity measurements were collected in dry conditions. Photographic images of each section were taken using a digital camera to document the change in daytime presence over time.

PAVEMENT MARKING PERFORMANCE

Retroreflectivity data were collected roughly every 3 months for each test deck, as shown in table 104 and table 105.

Table 104. Nashville, TN, test deck evaluation data collection periods.

Day	Date
21	January 2000
162	June 2000
231	August 2000
308	November 2000
378	January 2001
525	June 2001
595	August 2001
672	November 2001
742	January 2002
870	May 2002
942	July 2002
1,018	October 2002
1,142	February 2003
1,267	June 2003
1,337	August 2003
1,422	November 2003
1,491	January 2004
1,624	June 2004

Table 105. Tusculum, TN, test deck evaluation data collection periods.

Day	Date
22	January 2000
99	April 2000
169	June 2000
316	November 2000
386	January 2001
463	April 2001
533	June 2001
661	October 2001
732	January 2002
807	March 2002
898	June 2002
1,056	November 2002
1,126	January 2003
1,213	April 2003
1,282	July 2003
1,414	November 2003

Table 106 and table 107 show the summarized retroreflectivity results for each Tennessee test deck by product type, installation style (eradicated/inlaid), and by the number of days after installation.

As shown in table 106, initial retroreflectivity values for the Nashville test deck ranged from 1,411 to 366 mcd. After 1,624 days, these values had dropped to a range of 644 to 105 mcd. Note that the test markings degraded at different rates, both by product and installation method, so the rank order of the products by retroreflectivity did not remain the same at the end of the evaluation as at the beginning. Some trends are evident in the various products' performance relative to the group over time, and some differences can be seen between application methods for the same product. For example, the extruded thermo performance was significantly better for the inlaid application (644 mcd) versus eradicated (371 mcd). The loss in retroreflectivity after 1,624 days ranged from 12 percent (extruded thermo, inlaid) up to 77 percent (polyuria, inlaid).

As shown in table 107, initial retroreflectivity values for the Tusculum test deck ranged from 1,152 to 377 mcd. After 1,414 days, these values ranged from 342 to 82 mcd. The modified epoxy material was judged to have failed after the reading on day 807 and was removed from the test. The low-temperature acrylic was significantly better in the inlaid application (246 mcd) versus eradicated (77 mcd). The loss in retroreflectivity after 1,414 days ranged from 34 percent (MMA, Degussa flatline, inlaid) to 92 percent (400 tape, eradicated).

Table 106. Nashville test deck retroreflectivity (mcd).

Materials	Installation Style	Number of Days																	
		21	**162**	**231**	**308**	**378**	**525**	**595**	**672**	**742**	**870**	**942**	**1,018**	**1,142**	**1,267**	**1,337**	**1,422**	**1,491**	**1,624**
Spray thermo	In rumble stripe	366	279	255	228	237	186	181	137	164	145	136	149	133	130	120	117	114	105
	Eradicated	413	348	411	357	390	317	314	275	264	170	171	245	231	217	199	224	244	152
	Inlaid	405	327	398	394	421	356	353	303	304	191	242	274	241	267	223	244	261	211
	Eradicated	394	408	412	440	478	434	475	418	354	241	242	246	205	192	190	221	235	211
	Inlaid	375	402	432	473	516	494	535	499	448	332	308	307	234	209	184	229	246	233
Extruded thermo	Eradicated	643	666	658	644	734	644	736	556	632	520	521	613	612	431	485	454	465	371
	Inlaid	737	732	740	741	806	774	811	622	729	681	698	737	730	714	721	698	684	644
Inverted thermo	Eradicated	740	578	524	470	455	342	340	306	291	219	228	239	214	213	208	225	227	200
Low-temp acrylic	Eradicated	419	375	375	340	371	370	374	324	338	298	282	302	281	327	291	256	263	218
	Inlaid	399	367	370	336	368	363	380	335	332	306	304	304	299	326	297	274	274	262
Polyurea	Eradicated	1,100	758	684	535	697	611	546	445	449	296	312	301	248	267	229	204	188	176
	Inlaid	1,411	889	869	708	835	700	693	581	522	410	426	369	288	308	259	240	230	225
3M AWP	Eradicated	393	313	297	280	304	313	299	255	262	220	222	230	228	211	200	192	200	205
	Inlaid	423	367	351	290	354	316	327	270	271	210	237	237	226	242	207	206	201	207
High-build paint	Eradicated	538	403	425	414	429	428	426	376	371	303	277	319	288	302	277	250	254	245
	Inlaid	559	416	373	353	388	391	384	290	309	258	248	241	251	235	217	181	189	203

Note: Eradicated installations were in shallow grooves in the road surface ranging from 55 to 135 mil in depth. Inlaid installations were in grooves ranging from 145 to 270 mil in depth.

Table 107. Tusculum test deck retroreflectivity (mcd).

Materials	Installation Style	Number of Days															
		22	**99**	**169**	**316**	**386**	**463**	**533**	**661**	**732**	**807**	**898**	**1,056**	**1,126**	**1,213**	**1,282**	**1,414**
Modified epoxy (sprayed)	Eradicated	659	581	548	419	361	291	276	246	219	198						
	Inlaid	695	625	549	313	277	253	249	276	153	161						
MMA (Degussa)—Flatline	Eradicated	449	421	470	526	500	481	463	476	425	413	390	353	372	354	290	281
	Inlaid	516	504	496	613	602	586	538	573	508	492	473	416	414	367	330	342
MMA (Degussa)—Pathfinder	Eradicated	485	413	422	263	235	222	197	152	129	123	122	127	119	124	111	150
	Inlaid	511	493	521	461	419	388	366	263	211	204	188	185	169	163	149	164
Low-temp acrylic	Eradicated	377	308	302	277	230	208	189	185	127	119	98	110	91	82	74	76
	Inlaid	458	389	396	410	372	335	341	341	276	257	270	250	245	248	218	246
High-build acrylic	Eradicated	407	376	404	450	411	388	375	385	302	277	289	288	233	225	236	204
	Inlaid	428	404	408	446	412	381	364	343	306	298	272	256	239	217	204	180
300 tape (ATM)	Eradicated	950	857	796	604	555	520	458	350	303	292	242	152	136	131	125	109
	Inlaid	1,152	1074	972	803	749	688	611	468	418	399	331	253	222	222	207	163
400 tape (ATM)	Eradicated	1,082	959	894	678	613	540	486	380	322	304	267	106	93	101	88	82
	Inlaid	1,079	1,002	922	614	563	496	415	287	239	214	180	138	123	126	120	104
Standard thermo	Eradicated	441	424	447	441	449	473	479	444	441	436	406	273	249	280	249	258
	Inlaid	433	436	450	432	450	466	476	403	365	361	286	260	272	277	276	285
Modified urethane	Eradicated	645	557	583	478	438	378	374	342	255	239	240	225	242	253	222	241
	Inlaid	649	571	576	526	466	432	430	374	317	283	253	261	273	276	245	276

Note: Eradicated installations were in shallow grooves in the road surface ranging from 25 to 110 mil in depth. Inlaid installations were in grooves ranging from 110 to 320 mil in depth. Blank cells indicate a test deck section where the pavement marking was considered to have failed and was replaced. No further measurements were made on those test sections.

The performance analysis included graphing the performance of each product over time and, as shown in figure 104, considering the impact of grooving versus eradication. A trend analysis was also conducted for each product in an effort to create the performance prediction curves that serve as the engine for the PMST tool (see figure 105).

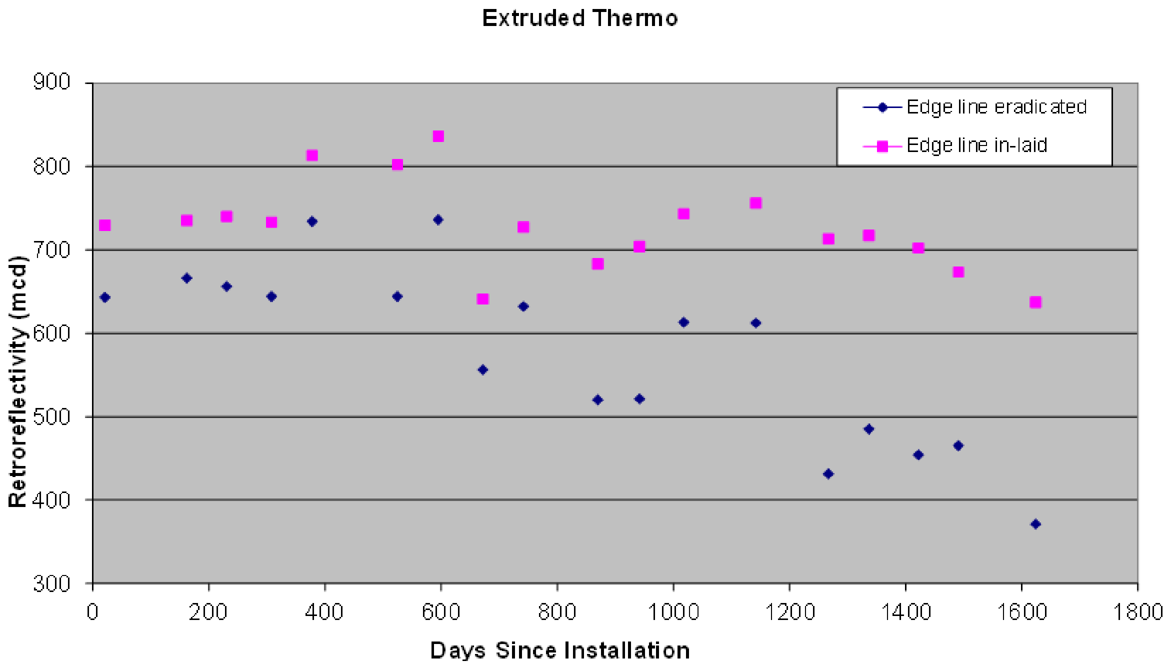


Figure 104. Graph. Eradicated versus inlaid.

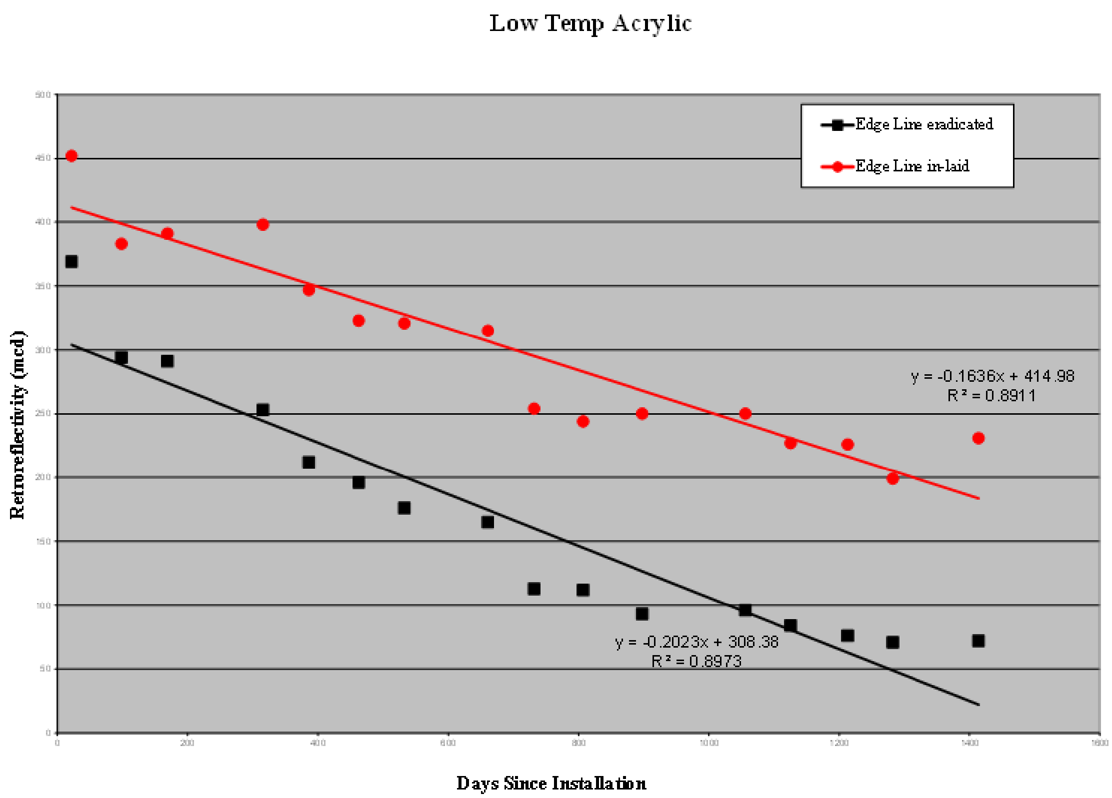


Figure 105. Graph. Trend line analysis of PMST marking materials.

To simplify the results, PMST combines the common products from the two Tennessee decks into the list of marking products and glass bead optics shown in table 108.

Table 108. Marking products and glass bead optic specifications.

Product	Optics Used
Extruded thermo (90 mil)	AASHTO M247[33]
Extruded thermo (120 mil)	Type 1 and type 4 Visibead plus 2
Sprayed thermo	Type 1
High-build acrylic paint	Type 3 virgin glass
Low-temperature acrylic	AASHTO M247[33]
MMA (splatter)	AASHTO M247[33]
MMA (extruded)	30/50 mesh, 30-30-40 Swarco mega blend
Modified epoxy	Type 4 Visibead plus 2, type 1 MnDOT spec
Modified urethane	Type 4 Visibead plus 2, type 1 MnDOT spec
Polyurea	Prismo high index cluster and Potters type 4 Visibead plus 2

PMST DEVELOPMENT

The PMST selection engine is based on regression equations that were developed for each pavement marking product. The selection functionality was created as follows:

- Sort, select, and format material and roadway section information from the two Tennessee test decks.
- Develop prediction curves based on the retroreflectivity measurements taken per test section and product.
- Define critical user input parameters along with modifying factors for operations and roadway conditions.
- Develop disclaimer information.
- Develop a Web-based application and graphical interface.
- Test, evaluate, and modify the functionality and performance of the tool.

RESULTS

The use and functionality for the resulting PMST is shown in the following series of figures (see figure 106 through figure 120):

- **Location**: The tool can be found at http://www.ctre.iastate.edu/PMST/.
- **Initial Splash Screen**: The initial screen, shown in figure 106, provides the user with important information regarding the purpose and limitations of the prototype tool. Hyperlinks are provided to additional reference materials.

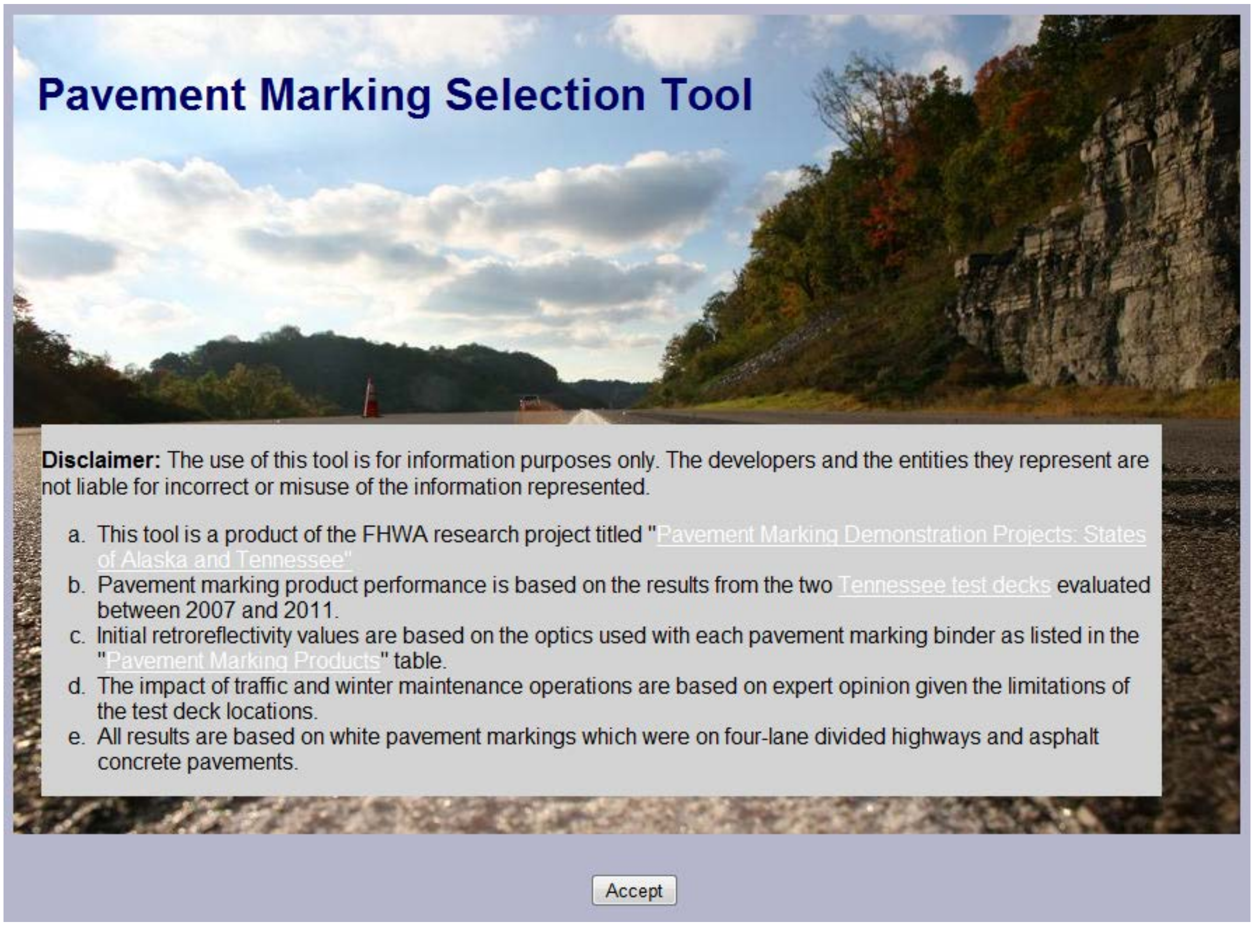


Figure 106. Screenshot. PMST splash screen.

- **User Interface**: Figure 107 shows the single-screen working area for the tool along with the key input and output spaces. This single-screen format allows the users to view both input and output information at the same time. The user is not required to leave this screen, nor are they required to click through menus or other input/output areas. The user can also modify inputs and immediately see the change in results without leaving the working screen.

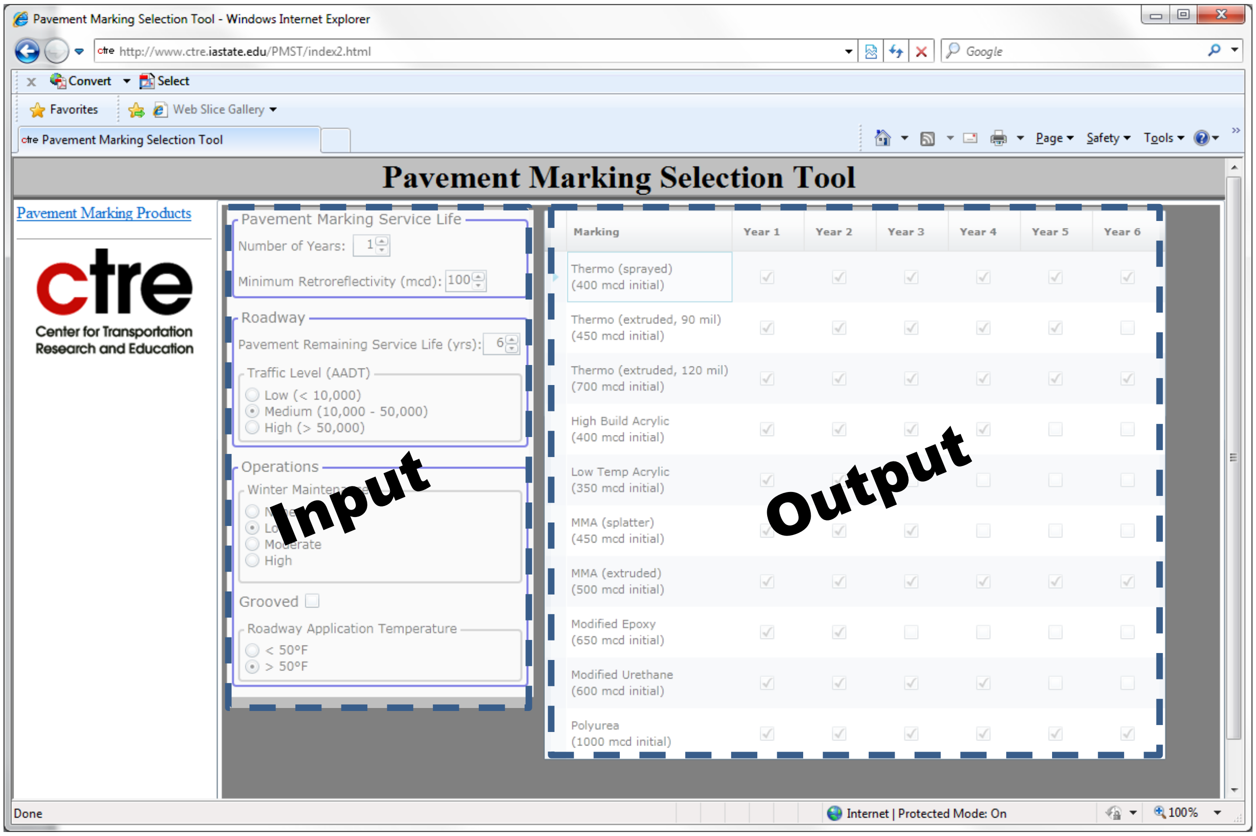


Figure 107. Screenshot. PMST single-screen working area.

- **Inputs**: In order to simply use of the tool (and minimize errors), radial buttons and drop-down choice boxes are used for all user inputs, as shown in figure 108. This information is further described in the following sections.

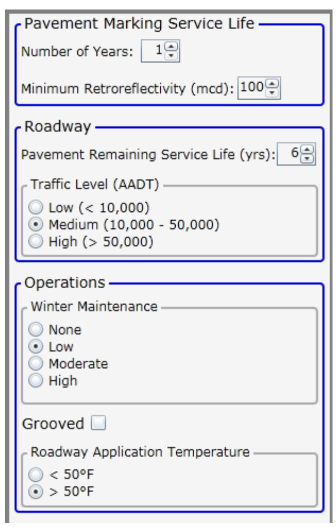
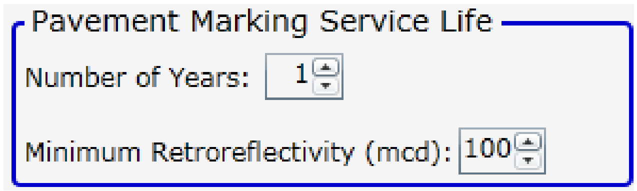


Figure 108. Screenshot. PMST user input options.

- **Pavement Marking Service Life**: The tool was specifically designed to provide information on pavement marking performance. The input could be communicated as, “What pavement marking product will give me a minimum retroreflectivity of X at the end of X years?” The input constraints are shown in figure 109.



Input Parameter	Increments	Minimum	Maximum
Number of Years	1	1	6
Minimum Retroreflectivity (mcd)	25	100	400

Figure 109. Screenshot. Pavement marking service life inputs.

- **Roadway**: Roadway input values allow the user to further refine the output information to the roadway conditions under consideration (see figure 110). These input constraints include remaining service life for the pavement and traffic levels.

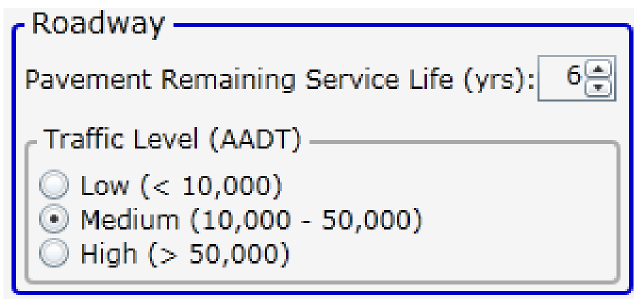


Figure 110. Screenshot. Roadway value inputs.

The pavement remaining service life must be higher than the desired years of performance or the software will give a warning message. The input constraints for pavement remaining service life are shown in figure 111.

Input Parameter	Increments	Minimum	Maximum
Pavement Remaining Service Life (yrs)	1	1	6

Figure 111. Screenshot. Input constraints for pavement service life.

- **Operations**: These inputs include the level of winter operations, whether the markings will be placed in a groove or not (inlaid), and the roadway temperature at application (see figure 112). Winter maintenance was established to provide scenarios that are different than the Tennessee test deck conditions (which were categorized as low). It is up to the user to determine the appropriate level for the target State. Evaluation of several levels is recommended when considering product performance.

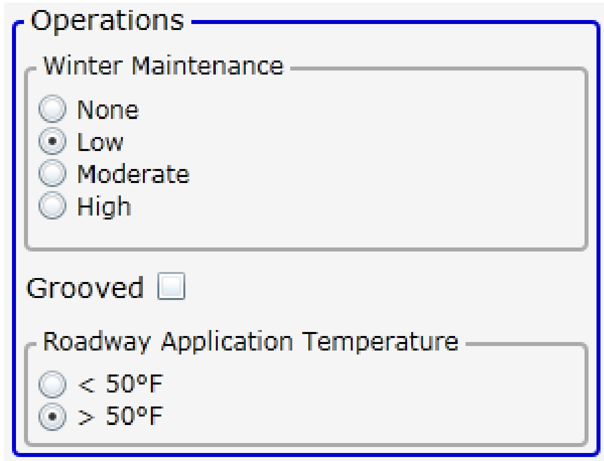


Figure 112. Screenshot. Operations options.

- **Outputs:** The output area is arranged in a tabular format by product and year of performance (see figure 113). Based on the inputs, the output area shows either a checked or empty box by product and year. Each checked box indicates a pavement marking product that met the user's input requirement for the minimum retroreflectivity level at the end of the desired years of performance. The maximum number of years that can be shown is six. The tool results are based on having a similar initial retroreflectivity as indicated by each product within the output area.

Marking	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Thermo (sprayed) (400 mcd initial)	✓	✓	✓	✓	✓	✓
Thermo (extruded, 90 mil) (450 mcd initial)	✓	✓	✓	✓	✓	
Thermo (extruded, 120 mil) (700 mcd initial)	✓	✓	✓	✓	✓	✓
High Build Acrylic (400 mcd initial)	✓	✓	✓	✓		
Low Temp Acrylic (350 mcd initial)	✓	✓				
MMA (splatter) (450 mcd initial)	✓	✓	✓			
MMA (extruded) (500 mcd initial)	✓	✓	✓	✓	✓	✓
Modified Epoxy (650 mcd initial)	✓	✓				
Modified Urethane (600 mcd initial)	✓	✓	✓	✓		
Polyurea (1000 mcd initial)	✓	✓	✓	✓	✓	✓

Figure 113. Screenshot. PMST outputs.

- **Functionality**: The prototype tool provides an indication of pavement marking performance based on user inputs. On initiation, the Web-based tool shows the default traffic and operational conditions from which the source performance data were collected. “What if” scenarios can be quickly evaluated given that outputs are instantly recalculated with each change to the inputs. Several examples follow that show the impact of traffic, winter maintenance, and grooving.

The base condition and a comparison of five scenarios are shown in figure 114.

Input Parameter	Base Condition	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Number of Years	2	2	2	2	2	2
Minimum Retroreflectivity (mcd)	200	200	200	200	200	200
Pavement Remaining Life	6	6	6	6	6	6
AADT	Medium	**High**	Medium	Medium	Medium	**High**
Winter Maintenance	Low	Low	**High**	Low	Low	**High**
Grooving	No	No	No	**Yes**	No	**Yes**
Application Temperature	>50	>50	>50	>50	**<50**	>50

Figure 114. Screenshot. “What if” scenarios produced.

A summary of changes per scenario, including the base conditions and scenarios 1–5 is as follows:

- **Base conditions**: There are eight products that meet the criteria, and two of these will perform for the entire duration (see figure 115).

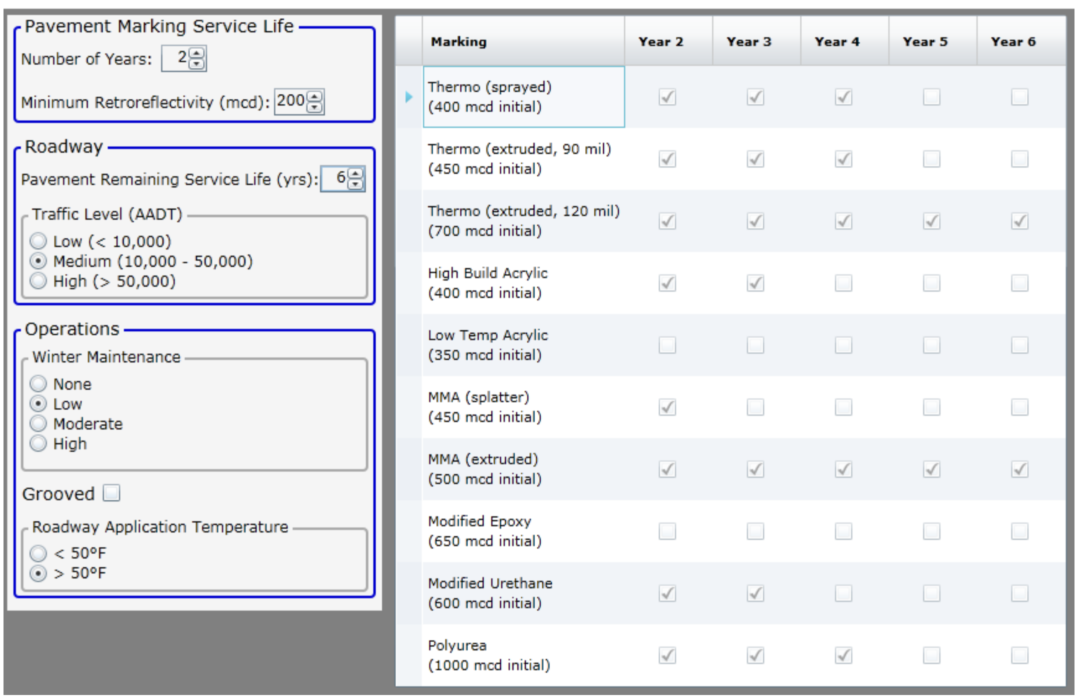


Figure 115. Screenshot. Base conditions scenario.

- **Scenario 1**: Change AADT from medium to high. There are seven products that meet the criteria, and only one of these will perform for the entire duration (see figure 116).

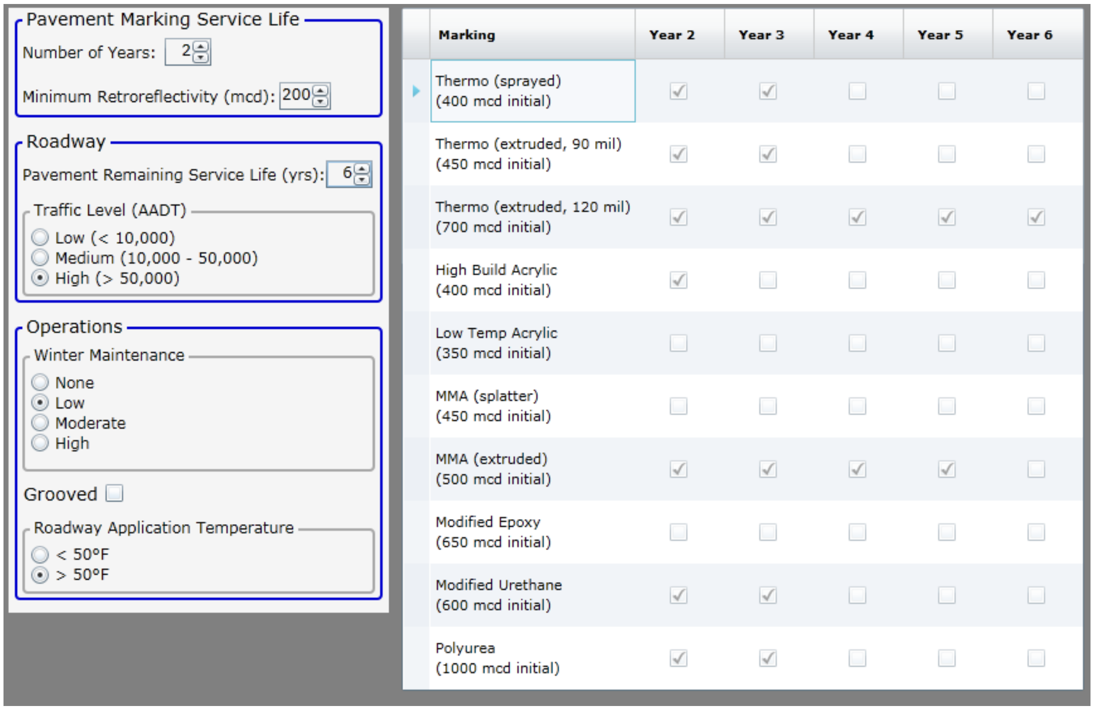


Figure 116. Screenshot. Scenario 1.

- **Scenario 2**: Change winter maintenance from low to high. There are seven products that meet the criteria, and only one of these will perform the entire duration (see figure 117).

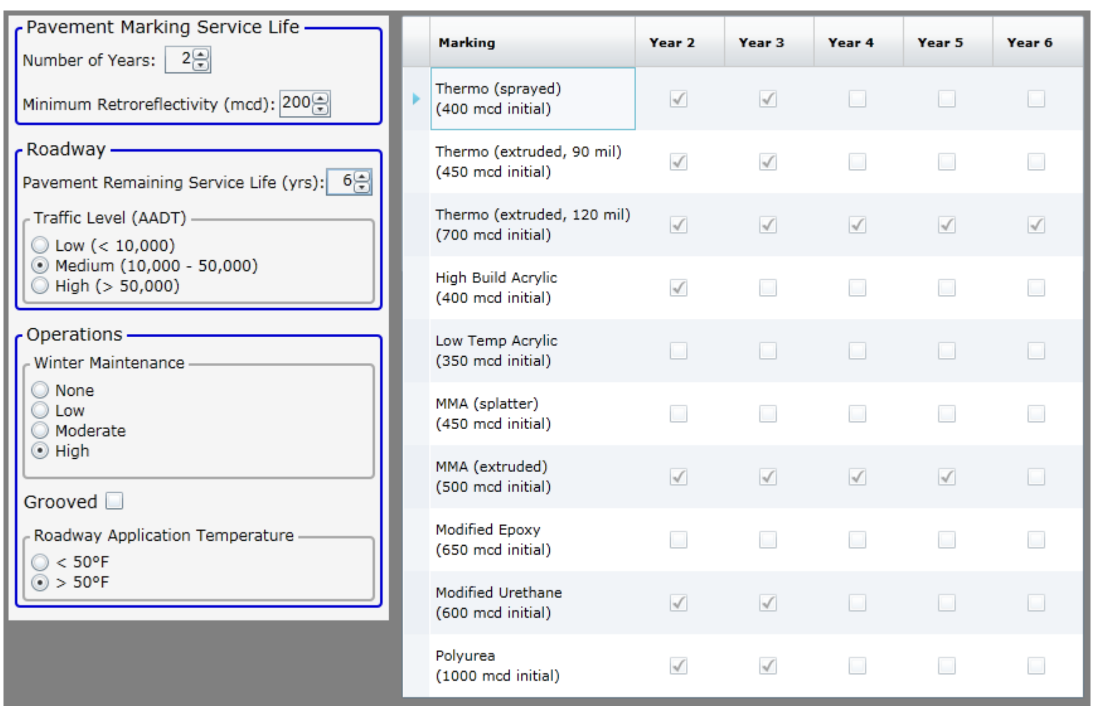


Figure 117. Screenshot. Scenario 2.

- **Scenario 3**: Change grooving to yes. There are nine products that meet the criteria, and two of these will perform the entire duration (see figure 118).

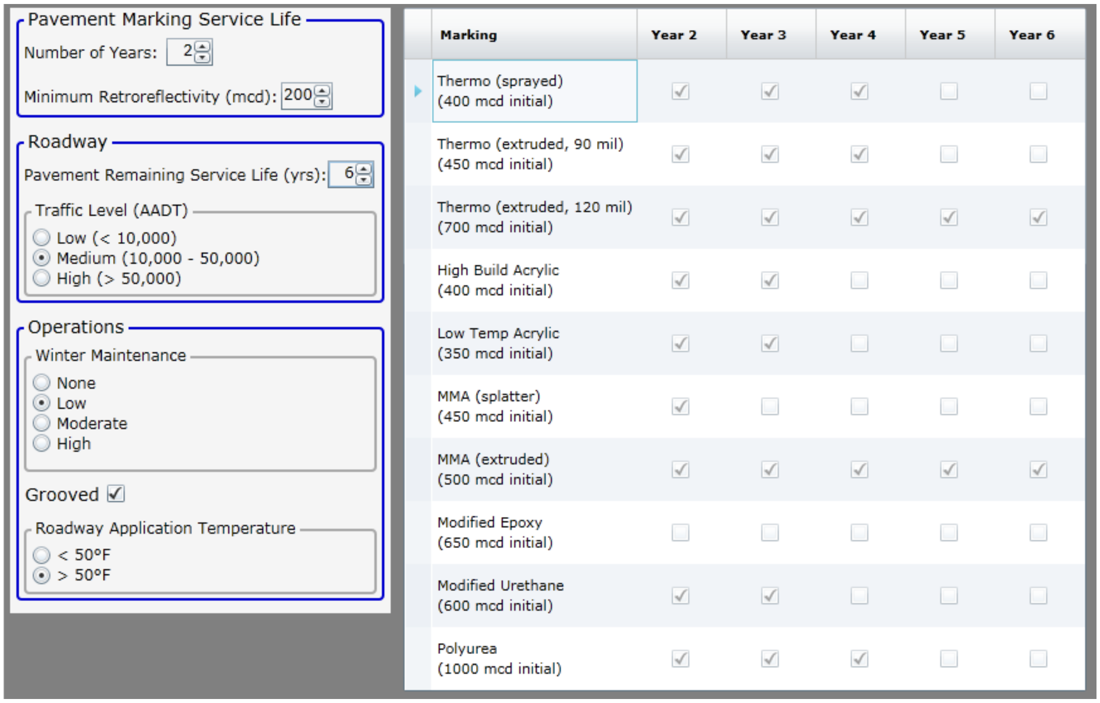


Figure 118. Screenshot. Scenario 3.

- **Scenario 4**: Change roadway application temperature to < 50 °F. There are only two products that meet the criteria, and one of these will perform for the entire duration (see figure 119).

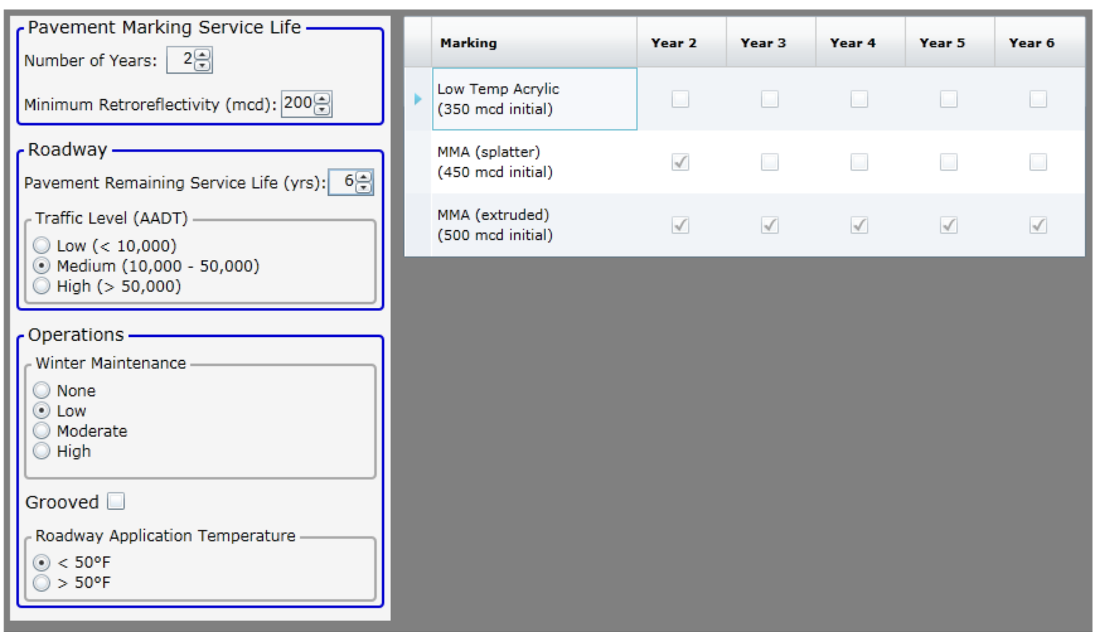


Figure 119. Screenshot. Scenario 4.

- **Scenario 5**: Combined scenarios 1–3 (AADT, winter maintenance, and grooving). There are four products that meet these criteria, and only one of these will perform for the entire duration (see figure 120).

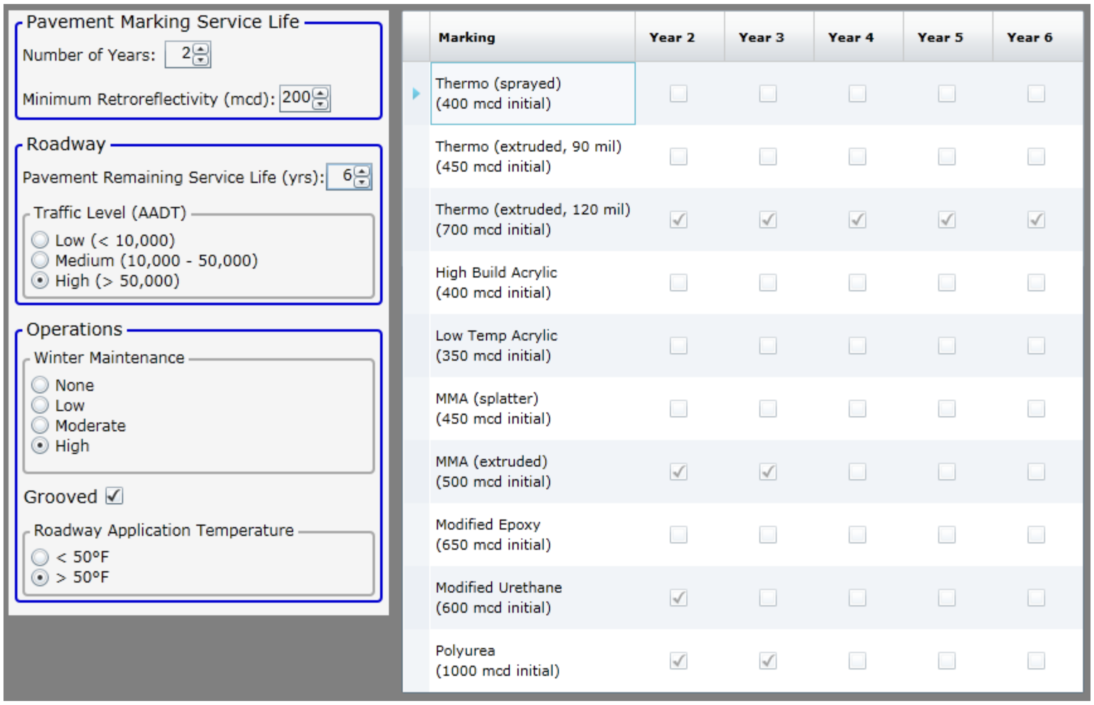


Figure 120. Screenshot. Scenario 5.

APPENDIX I. REVIEW OF LOGIT MODEL ANALYSIS

MULTINOMIAL LOGIT MODEL

The multinomial logit model is widely used to estimate accident severity. Shankar and Mannering attempted to address the potential bias that univariate analyses create by presenting a multinomial logit model of motorcycle rider accident severity in single-vehicle collisions.[122] They concluded that the multinomial model is a promising approach to evaluating the determinants of motorcycle accident severity.

Savolainen and Mannering researched a similar topic (motorcyclists' injury severities in single- and multi-vehicle crashes) using a multinomial logit model for multi-vehicle crashes.[123] They concluded that collision type, roadway characteristics, alcohol consumption, helmet use, and unsafe speeds play significant roles in crash-injury outcomes. The injury severity of male and female drivers in single- and two-vehicle accidents for different types of vehicles were explored by Ulfarsson and Mannering using a multinomial logit model.[124] The results suggest that there are important behavioral and physiological differences between male and female drivers that must be explored further and addressed in vehicle and roadway design.

Multinomial logit models were used by Khorashadi et al. to explore the differences between urban and rural driver injuries in accidents that involve large trucks.[125] The results showed that many variables were significant in either the rural or the urban model but not in both because of the different perceptual, cognitive, and response demands placed on drivers in rural versus urban areas.

NESTED LOGIT MODEL

Generalized extreme value (GEV) models constitute a large class of models that exhibit a variety of substitution patterns. The unifying attribute of these models is that the unobserved portions of utility for all alternatives are jointly distributed as GEV. This distribution allows for correlations over alternatives and, as its name implies, is a generalization of the univariate extreme value distribution that is used for standard multinomial logit models. When all correlations are zero, the GEV distribution becomes the product of independent extreme value distributions, and the GEV model becomes standard multinomial logit. The class therefore includes logit but also includes a variety of other models. Hypothesis tests on the correlations within a GEV model can be used to examine whether the correlations are zero, which is equivalent to testing whether standard logit provides an accurate representation of the substitution patterns.

The most widely used member of the GEV family is nested logit. This model has been applied by many researchers in a variety of situations, including energy, transportation, housing, and telecommunications. Its functional form is simple compared to other types of GEV models. Nested logit models allow partial relaxation of the IIA property. Sometimes, different alternatives may share the same unobserved terms. The nested logit model can overcome the restriction of the multinomial logit model that requires the error term for different alternatives, ε_{in}, to be independent from each other.

Shankar et al. presented a nested logit formulation as a means for determining accident severity on rural highways given that an accident has occurred.[126] They concluded that a nested logit model, which accounted for shared unobservables between PDO and possible injury accidents, provided the best structural fit for the observed distribution of accident severities.

Chang and Mannering studied the occupancy/injury severity relationship in truck-and non-truck-involved accidents using the nested logit model.(127) The findings of the study demonstrated that the nested logit model, which was able to take into account vehicle occupancy effects and identify a broad range of factors that influence occupant injury, is a promising methodological approach.

Holdridge et al. analyzed the in-service performance of roadside hardware on the entire urban SR system in Washington State by developing multivariate nested logit models of injury severity in fixed-object crashes.(128) The models showed the contribution of guardrail leading ends toward fatal injuries and also indicated the importance of protecting vehicles from crashes with rigid poles and tree stumps.

ORDERED LOGIT AND ORDERED PROBIT MODEL

Wang and Abdel-Aty examined left-turn crash injury severity using an ordered logit model.(129) This study found that neither the total approach volume nor the entire intersection volume affected crashed injury significantly; however, the specific vehicle movements did.

Duncan et al. examined the impact of various factors on injuries to passenger car occupants involved in truck-passenger car rear-end collisions and demonstrated the use of the ordered probit model in the complex highway safety problem.(130) They concluded that the ordered probit model is flexible because it allows the injury severity probabilities to vary differently across categories.

Klop and Khattak explored the effect of a set of roadway, environmental, and crash variables on bicycle injury severity using the ordered probit model.(131) The model results showed that variables that significantly increase injury severity include straight grades, curved grades, darkness, fog, and speed limit.

Quddus et al. used an ordered probit model to examine factors that affect the injury severity of motorcycle accidents and the severity of damage to the motorcycles and vehicles involved in those crashes.(132) They concluded that factors leading to increased probability of vehicle and motorcycle damage included some similar factors and different factors.

Kockelman and Kweon described the use of ordered probit models to examine the risk of different injury levels sustained under all crash types, two-vehicle crashes, and single-vehicle crashes.(133) This work suggested that the manner of collision, the number of vehicles involved, driver gender, vehicle type, and driver alcohol use played major roles in terms of crash severity.

Adbel-Aty analyzed driver injury severity at locations of roadway sections, signalized intersections, and toll plazas using the ordered probit model.(134) This study illustrated the similarities and differences in the factors that affect injury severities at different locations.

O'Donnell and Connor used both an ordered logit model and ordered probit model to predict the severity of motor vehicle accident injuries.(135) They concluded that occupant age, vehicle speed, seat position, blood alcohol level, and type of collision affect the probabilities of serious injury and death

MIXED LOGIT MODEL

Gkritza and Mannering demonstrated a mixed logit approach that can be used to better understand the use of safety belts in single- and multi-occupant vehicles.(136) They concluded that the mixed logit model can provide a much fuller understanding of the interaction of the numerous variables that correlate with safety-belt use.

Milton et al. analyzed the injury-severity distributions of accidents on highway segments, and the effect that traffic, highway, and weather characteristics have on these distributions using a mixed logit model.(137) Their results showed that the mixed logit model has considerable promise as a methodological tool in highway safety programming.

Pai et al. estimated mixed logit models to investigate the contributory factors to motorists' right-of-way violations in different crash types.(138) It was found that motorcycle right of way was more likely to be violated on non-built-up roads and in diminished light conditions.

Kim et al. applied a mixed logit model to analyze pedestrian injury severity in pedestrian-vehicle crashes to address possible unobserved heterogeneity.(139) It was found that several factors increased the fatal injury level significantly, including darkness, drunk driving, and speeding. They found that the effect of pedestrian age was normally distributed across observations and that as pedestrians become older, the probability of fatal injury increases substantially.

Eluru et al. developed an ordered mixed logit model to examine pedestrian and bicyclist injury severity in traffic crashes.(140) They concluded that an ordered mixed logit model does not produce inconsistent estimates of the effects of some variables as does an ordered probit model. The analysis suggested that the general pattern and relative magnitude of elasticity effects of injury severity determinants are similar for pedestrians and bicyclists.

SUMMARY

There are several commonly used discrete choice models for predicting crash severity such as the multinomial logit model, the nested logit model, the ordered probit model, and the mixed logit model. These approaches have been applied to crash severity analysis on the relationship between crash severity and its contributing factors. Table 109 shows a summary of commonly used discrete choice models. Advantages and limitations as well as important assumptions of these models are presented.

Table 109. Summary of discrete choice models of crash severity.

Model Type	Previous Research	Advantage	Limitation	Assumptions
Multinomial logit	References 122–125	Readily interpretable; allows coefficients of variables to vary between different categories	Susceptible to correlation of unobserved effects from one injury severity level to the next (IIA property); does not recognize the ordering of injury severity outcomes	The error terms should be independently and identically distributed
Nested logit	References 126–128	Relaxes IIA assumption	Does not recognize the ordering of injury severity outcomes	The error terms should be GEV distributed
Ordered logit	References 129 and 135	Recognizes the ordering of injury severity outcomes	The shifts in thresholds are restricted to move in the same direction	Parallel slope assumption
Ordered probit	References 130−135	Recognizes the ordering of injury severity outcomes	The shifts in thresholds are restricted to move in the same direction	Parallel slope assumption; the error terms should be normally distributed
Mixed logit	References 136–140	It is highly flexible that it obviates the limitations of standard logit	Does not recognize the ordering of injury severity outcomes	None

REFERENCES

1. *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU). (2005). Public Law No. 109-59 Section 1907, Government Printing Office, Washington, DC.

2. Research and Innovative Technology Administration. (2007). *Pocket Guide to Transportation 2007*, U.S. Department of Transportation, Washington, DC. Obtained from: http://www.bts.gov/publications/pocket_guide_to_transportation/2007/. Site last accessed June 8, 2009.

3. Federal Highway Administration. (2003). *Manual on Uniform Traffic Control Devices for Streets and Highways*, U.S. Department of Transportation, Washington, DC.

4. American Association of State Highway and Transportation Officials. (2008). *New AASHTO Study Designed to Save Lives*, Washington, DC. Obtained from: http://news.transportation.org/press_release.aspx?Action=ViewNews&NewsID=170. Site last accessed September 4, 2009.

5. Federal Highway Administration. *Roadway Departure Safety*, U.S. Department of Transportation, Washington, DC. Obtained from: http://safety.fhwa.dot.gov/roadway_dept/. Site last accessed August 24, 2012.

6. American Association of State Highway and Transportation Officials. *Implementing the AASHTO Strategic Highway Safety Plan*, Washington, DC. Obtained from: http://safety.transportation.org/. Site last accessed September 4, 2009.

7. American Association of State Highway and Transportation Officials. *Driving Down Lane Departure Crashes—A National Priority*, Washington, DC. Obtained from: http://news.transportation.org/press_release.aspx?Action=ViewNews&NewsID=170. Site last accessed September 4, 2009.

8. Falk, K.W. and Carlson, P.J. (2008). *Pavement Marking Retroreflectivity Workshop: Summary Report*, Report No. FHWA-SA-08-003, Federal Highway Administration, Washington, DC.

9. Carlson, P.J., Park, E.S., and Andersen, C.K. (2009). “The Benefits of Pavement Markings: A Renewed Perspective Based on Recent and Ongoing Research,” *TRB DVD Compendium of Papers*, TRB Annual Meeting, Washington, DC.

10. National Association of County Engineers Resource Training and Education. *Local Road and Bridge Facts*. Obtained from: http://www.naco.org/NACETemplate.cfm?Section=Resources,_Training_and_Education&template=/ContentManagement/ContentDisplay.cfm&ContentID=8007. Site last accessed June 8, 2009.

11. Research and Innovative Technology Administration. (2004). *Table 1-4: Public Road and Street Mileage by Type of Surface*. Obtained from: http://www.bts.gov/publications/national_transportation_statistics/2004/html/table_01_04.html. Site last accessed June 8, 2009.

12. ASTM D713-90. (2010). "Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials," *Book of Standards Volume 06.02*, ASTM International, West Conshohocken, PA.

13. National Transportation Product Evaluation Program. (2004). *Project Workplan for the Field Evaluation of Pavement Marking Materials*, American Association of State Highway and Transportation Officials, Washington, DC.

14. National Transportation Product Evaluation Program. *NTPEP Best Practices Manual*, American Association of State Highway and Transportation Officials, Washington, DC.

15. Connor, B. and Bennett, J. (2001). *Selection of Pavement Marking Materials Research & Technology Transfer*, Alaska Department of Transportation, Juneau, AK.

16. Kaseko, M., Vasudevan, V., and Merrill, J. (2004). *Evaluation of Performance of Pavement Markings for Clark County Roads: Quarterly Report*, Transportation Research Center, University of Nevada, Las Vegas, NV.

17. Kaseko, M.S., Vodrazka, W.C., and Nambisan, S.S. (2001). *Comparative Evaluation of Field Performance of Pavement Marking Products on Alternative Test Deck Designs*, Proceedings from Transportation Research Board 80th Annual Meeting, National Research Council, Washington, DC.

18. Lee, J., Maleck, T., and Taylor, W. (1999). "Pavement Marking Material Evaluation Study in Michigan," *Institute of Transportation Engineers Journal*, *69*(7), 44–51.

19. Lindly, J. and Wijesundera, R. (2003). *Evaluation of Profiled Pavement Markings*, UTCA Report 01465, University Transportation Center for Alabama, Tuscaloosa, AL.

20. Hawkins, N., Smadi, O., Hans, Z., and Maze, T. (2006). "Integrated Approach to Pavement Marking Management," *Transportation Research Record 1948*, 99–100, Transportation Research Board, Washington, DC.

21. Vosburgh, J. (2005). *Pavement Marking Durability*, Presentation for Vermont Agency of Transportation, Montpelier, VT.

22. Kopf, J. (2004). *Reflectivity of Pavement Markings: Analysis of Retroreflectivity Degradation Curves*, Research Project T1803, Task 20, Washington State Transportation Center, University of Washington, Seattle, WA.

23. Martin, P., Perrin, J., Jitprasithsiri, S., and Hansen, B. (1996). *A Comparative Analysis of the Alternative Pavement Marking Materials for the State of Utah*, Department of Civil and Environmental Engineering, University of Utah, Salt Lake City, UT.

24. Lagergren, E., Bertsch, J., and Fernald, D. (2006). *I-90 Pavement Marking Material Test*, Proceedings from Transportation Research Board 85th Annual Meeting, National Research Council, Washington, DC.

25. Lundkvist, S. and Astrom, S. (2000). *The Performance of Wet Visibility Road Markings—Final Report on Provvag 1998–2000*, Report 465A, Swedish National Road and Transport Research Institute, Linköping, Sweden.

26. Migletz, J., Graham, J.L., Harwood, D.W., Bauer, K.M., and Sterner, P.L. (2000). *Evaluation of All-Weather Pavement Markings*, Report C1038/3524-04, Federal Highway Administration, McLean, VA.

27. ASTM D6359-99. (1999). "Standard Specification for Minimum Retroreflectance of Newly Applied Pavement Marking Using Portable Hand-Operated Instruments," ASTM International, West Conshohocken, PA.

28. ASTM E1710-05. (2005). "Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer," ASTM International, West Conshohocken, PA.

29. ASTM D913-10. (2010). "Standard Practice for Evaluating Degree of Traffic Paint Line Wear," *Book of Standards Volume 06.02*, ASTM International, West Conshohocken, PA.

30. ASTM D6628-03. (2010). "Standard Specification for Color of Pavement Marking Materials," ASTM International, West Conshohocken, PA.

31. Gates, T.J. and Hawkins, H.G. (2002). *The Use of Wider Longitudinal Pavement Markings*, Report No. 0024-1, Texas Transportation Institute, College Station, TX.

32. Hawkins, N., Smadi, O., Hans, Z., and Resler, J. (2007). *To Groove or Not to Groove, That is the Question*, Proceedings from Transportation Research Board 86th Annual Meeting, National Research Council, Washington, DC.

33. AASHTO M247-09. (2009). *Standard Specifications for Glass Beads Used for Pavement Markings*, American Association of State Highway and Transportation Officials, Washington, DC.

34. Center for Transportation Research and Education. *Pavement Marking Selection Tool*, Iowa State University, Ames, IA. Obtained from: http://www.ctre.iastate.edu/PMST/. Site last accessed August 24, 2012.

35. Cirillo, J.A. (1968). "Interstate System Crash Research; Study II, Interim Report II," *Public Roads*, *35*(3), 71–76.

36. Solomon, D. (1964). *Crashes on Main Rural Highways Related to Speed, Driver and Vehicle*, Bureau of Public Roads, U.S. Department of Commerce, Washington, DC.

37. Van Driel, C.J.G., Davidse, R.J., and van Maarseveen, M.F.A.M. (2004). "The Effects of an Edge Line on Speed and Lateral Position: A Meta-Analysis," *Accident Analysis and Prevention*, *36*(4), 671–682.

38. Sun, X. and Tekell, V.O. (2005). *Impact of Edge Lines on Safety of Rural Two-Lane Highways*, LTRC Report 414, Louisiana Transportation Research Center, Baton Rouge, LA.

39. Donnell, E.T., Lee, D., Molino, J., and Opiela, K.S. (2007). *Can Pavement Marking Curve Delineation Improve the Consistency of Vehicle Speed and Lane Position? Results from a Nighttime Driving Experiment*, Paper No. 07-0943, Proceedings from Transportation Research Board 87th Annual Meeting, National Research Council, Washington, DC.

40. Tsyganov, A.R., Machemehl, R.B., Warrenchuk, N.M., and Wany, Y. (2006). *Before-After Comparison of Edge Line Effects on Rural Two-Lane Highways*, CTR Technical Report 0-5090-2, Center for Transportation Research, The University of Texas, Austin, TX.

41. Taylor, J.L., McGee, H.W., Sequin, E.L., and Hostetter, R.S. (1972). *NCHRP Report 130: Roadway Delineation Systems*, National Research Council, Washington, DC.

42. Stimpson, W.A., McGee, H.W., Kittelson, W.K., and Ruddy, R.H. (1977). *Field Evaluation of Selected Delineation Treatments on Two-Lane Rural Highways*, Publication No. FHWA-RD-77-118, Federal Highway Administration, Washington, DC.

43. Cottrell, B.H. (1986). “The Effects of Wide Edge Lines on Lateral Placement and Speed on Two-Lane Rural Roads,” *Transportation Research Record 1069*, 1–6, Transportation Research Board, Washington, DC.

44. Nedas, N.D., Balcar, G.P., and Macy, P.R. (1982). “Road Markings as an Alcohol Countermeasure for Highway Safety: Field Study of Standard and Wide Edgelines,” *Transportation Research Record 847*, Transportation Research Board, Washington, DC.

45. Thomas, I.L. and Taylor, W.T. (1960). “Effect of Edge Striping on Traffic Operations,” *Highway Research Board Bulletin 244*, 11–15, Washington, DC.

46. Wheeler, R.E. (1974). “Portable Power,” *Technometrics*, *16*, 193–201.

47. Nelson, L.S. (1985). “Sample Size Tables for Analysis of Variance,” *Journal of Quality Technology*, *17*, 167–169.

48. Bratcher, T.L., Moran, M.A., and Zimmer, W.J. (1990). “Tables of Sample Sizes in the Analysis of Variances,” *Journal of Quality Technology*, *2*, 156–164.

49. Krammes, R.A., Tyer, K.D., Middleton, D.R., and Feldman, S.A. (1990). *An Alternative to Post-Mounted Delineators at Horizontal Curves on Two-Lane Highways*, Report No. 1145-1F, Texas Transportation Institute, Texas A&M University, College Station, TX.

50. Dudek, C.L., Huchingson, R.D., Creasey, F.T., and Pendleton, O. (1988). “Field Studies of Temporary Pavement Markings at Overlay Project Work Zones on Two-Lane, Two-Way Rural Highways,” *Transportation Research Record 1160*, 22–34, Transportation Research Board, Washington, DC.

51. Hall, J.W. (1987). “Evaluation of Wide Edge Lines,” *Transportation Research Record 1114*, 21–27, Transportation Research Board, Washington, DC.

52. Cottrell, B.H. (1987). *Evaluation of Wide Edge Lines on Two-Lane Rural Roads*, Publication No. FHWA-VA-85-37, Virginia Department of Transportation, Richmond, VA.

53. Hughes, W.E., McGee, H.W., Hussain, S., and Keegel, J. (1989). *Field Evaluation of Edgeline Widths*, Report No. FHWA-RD-89-111, Federal Highway Administration, Washington, DC.

54. Turner-Fairbank Highway Research Center. *HSIS—Highway Safety Information System*, McLean, VA. Obtained from: http://www.hsisinfo.org. Site last accessed June 7, 2013.

55. American Association of State Highway and Transportation Officials. *Highway Safety Manual*, Washington, DC. Obtained from: http://www.highwaysafetymanual.org/Pages/default.aspx. Site last accessed August 24, 2012.

56. American Association of State Highway and Transportation Officials. *SafetyAnalyst*, Washington, DC. Obtained from: http://www.safetyanalyst.org/index.htm. Site last accessed August 24, 2012.

57. Google Earth®. (2006). *US 50/K25 Junction to Lakin City Limit* (Map). Generated by Paul Carlson via Google Earth® on July 15, 2006.

58. Bahar, G., Mollett, C., Persaud, B., Lyon, C., Smiley, A., Smahel, T., and McGee, H. (2004). *Safety Evaluation of Permanent Raised Pavement Markers*, NCHRP Report 518, National Cooperative Highway Research Program, Washington, DC.

59. Campbell, D.T. and Ross, H.L. (1968). “The Connecticut Crackdown on Speeding: Time-Series Da*ta in Quasi-Experimental Analysis,” Law and Society Review*, *3*, 33–54.

60. Gillings, D., Makuc, D., and Siegel, E. (1981). “Analysis of Interrupted Time Series Mortality Trends: An Example to Evaluate Regionalized Perinatal Care,” *American Journal of Public Health*, *71*, 38–46.

61. Wagner, A.K., Soumerai, S.B., Zhang, F., and Ross-Degnan, D. (2002). “Segmented Regression Analysis of Interrupted Time Series Studies in Medication Use Research,” *Journal of Clinical Pharmacy and Therapeutics*, *27*, 299–309.

62. Friedman, L.S., Hedeker, D., and Richter, E.D. (2009). “Long-Term Effects of Repealing the National Maximum Speed Limit in the United States,” *American Journal of Public Health*, *99*, 1626–1631.

63. Grundy, C., Steinbach, R., Edwards, P., Green, J., Armstrong, B., and Wilkinson, P. (2009). “Effects of 20 mph Traffic Speed Zones on Road Injuries in London, 1986–2006: Controlled Interrupted Time Series Analysis,” *BMJ*, *339*, b4469.

64. Milton, J., Shankar, V., and Mannering, F. (2008). "Highway Accident Severities and the Mixed Logit Model: An Exploratory Empirical Analysis," *Accident Analysis and Prevention*, *40*(1), 260–266.

65. Bonneson, J. and Lord, D. (2006). "Theory, Explanation, *and Prediction in Road Safety," Presented at the Tran*sportation Research Board 85th Annual Meeting, Washington, DC.

66. Savolainen, P.T., Mannering, F.L., Lord, D., and Quddus, M.A. (2011). "The Statistical Analysis of Highway Crash-Injury Severities: A Review and Assessment of Methodological Alternatives," *Accident and Analysis Prevention*, *43*, 1666–1667.

67. McFadden, D., Train, K., and Tye, W. (1977). "An Application of Diagnostic Tests for the Independence of Irrelevant Alternatives Property of the Multinomial Logit Model," *Transportation Research Record 637*, 39–46, Transportation Research Board, Washington, DC.

68. Hausman, J. and McFadden, D. (1984). "Specification Tests for the Multinomial Logit Model," *Econometrica*, *52*(5), 1219–1240.

69. Texas Department of Transportation. (2004). *Pavement Marking Handbook*, Austin, TX. Obtained from: http://onlinemanuals.txdot.gov/txdotmanuals/pmh/pmh.pdf. Site last accessed December 14, 2009.

70. Virginia Department of Transportation. *Pavement Marking Certification Study Guide*, Richmond, VA. Obtained from: http://www.virginiadot.org/business/matschools.asp. Site last accessed December 14, 2009.

71. Federal Highway Administration. *Standard Specification for Construction of Roads and Bridges on Federal Highway Projects*, Washington, DC. Obtained from: http://flh.fhwa.dot.gov/resources/pse/specs/. Site last accessed August 24, 2012.

72. Jahan, K., Axe, L.B., Sandhu, N.K., Ndiba, P.K., Ramanujachary, K.V., and Magdaleno, T.F. (2010). *Heavy Metal Contamination in Highway Marking Glass Beads*, Report No. FHWA-NJ-2010-014, New Jersey Institute of Technology and Rowan University for the New Jersey Department of Transportation, Trenton, NJ.

73. Boulanger, B., Raut Desai, A., and Carlson, P. (2011). *Heavy Metal Content and Leaching Potential of Recycled Glass Beads Used in Pavement Markings*, Texas Transportation Institute, College Station, TX.

74. U.S. Environmental Protection Agency. (2007). *Method 6020A*, Washington, DC. Obtained from: http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/6020a.pdf. Site last accessed April 4, 2011.

75. U.S. Environmental Protection Agency. (1996). *Method 3050B*, Washington, DC. Obtained from: http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/3050b.pdf. Site last accessed April 4, 2011.

76. 23 CFR 771. *Environmental Impact and Related Procedures*, Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=50d1ecb1d4ff8b70f997ec0658c9d8cc;rgn=div5;view=text;node=23%3A1.0.1.8.43;idno=23;cc=ecfr. Site last accessed August 24, 2012.

77. 40 CFR 261.20–24. *Identification and Listing of Hazardous Waste*, "Characteristics of Hazardous Wastes," Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=71c270ae90a07a46072e92d367c093c3&tpl=/ecfrbrowse/Title40/40cfr261_main_02.tpl. Site last accessed August 24, 2012.

78. 40 CFR 51. *Requirements for Preparation, Adoption, and Submittal of Implementation Plans*, Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=71c270ae90a07a46072e92d367c093c3&tpl=/ecfrbrowse/Title40/40cfr51_main_02.tpl. Site last accessed August 24, 2012.

79. NESHAP. (2008). "Paint Stripping and Miscellaneous Surface Coating Operations—Area Sources," *Federal Register*, *73*(6), 1738–1768.

80. U.S. Environmental Protection Agency. (1989). *Risk Assessment Guidance for Superfund (RAGS), Volume I, Human Health Evaluation Manual (Part A) Interim Final*, EPA/540/1-89/002, Washington, DC.

81. Alaska Department of Transportation. (2005). *Alaska Storm Water Pollution Prevention Plan Guide*, Juneau, AK. Obtained from: http://www.dot.state.ak.us/stwddes/desenviron/assets/pdf/swppp/english/eng_guide_all.pdf. Site last accessed February 8, 2010.

82. California Department of Transportation. (2003). *Statewide Storm Water Management Plan*, Report No. CTSW-RT-02-008, Sacramento, CA. Obtained from: http://www.dot.ca.gov/hq/env/stormwater/pdf/swmp_may2003final.pdf. Site last accessed February 8, 2010.

83. Tennessee Department of Transportation. *Statewide Storm Water Management Plan*, Nashville, TN. Obtained from: http://www.tdot.state.tn.us/sswmp. Site last accessed February 8, 2010.

84. Texas Department of Transportation. *Storm Water Management Guidelines for Construction Activities*, Austin, TX. Obtained from: http://www.txdot.gov/txdot_library/consultants_contractors/publications/environmental_resources.htm#storm. Site last accessed February 8, 2010.

85. Minnesota Department of Transportation. *Mn/DOT Metro District's MS4 Stormwater Program*, St. Paul, MN. Obtained from: http://www.dot.state.mn.us/metro/waterresources/. Site last accessed February 8, 2010.

86. Ohio Department of Transportation. *Storm Water Management Program*, Columbus, OH. Obtained from: http://www.dot.state.oh.us/stormwater/Pages/default.aspx. Site last accessed February 8, 2010.

87. Virginia Department of Transportation. (2004). *VDOT Manual of Practice for Stormwater Management*, Richmond, VA. Obtained from: http://www.virginiadot.org/vtrc/main/online_reports/pdf/05-cr5.pdf. Site last accessed February 8, 2010.

88. New York State Department of Transportation. *Memorandum of Understanding Between the Department of Transportation and the Department of Environmental Conservation Regarding the SPDES General Permit for Stormwater Discharges from Construction Activity, GP-02-01*, Albany, NY. Obtained from: https://www.nysdot.gov/divisions/engineering/environmental-analysis/repository/spdes_mou_2003.pdf. Site last accessed February 8, 2010.

89. Colorado Department of Transportation. *Storm Water Program*, Denver, CO. Obtained from: http://www.coloradodot.info/programs/environmental/water-quality/stormwater-programs.html. Site last accessed February 8, 2010.

90. Colorado Department of Transportation. *Water Quality Program: Illicit Discharges Program*, Denver, CO. Obtained from: http://www.coloradodot.info/programs/environmental/water-quality/documents/illicit-discharge-program/cdot-idde-factsheet_1-21-08.pdf/at_download/file. Site last accessed February 8, 2010.

91. 49 CFR 171–180. *Hazardous Materials Regulations*, Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title49/49cfrv2_02.tpl. Site last accessed August 24, 2012.

92. 29 CFR 1910. *Occupational Safety and Health Standards*, Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title29/29cfr1910_main_02.tpl. Site last accessed August 24, 2012.

93. American National Standards Institute. (2004). *Standard Z400.1: Hazardous Industrial Chemicals—Material Safety Data Sheets—Preparation*, Washington, DC.

94. 29 CFR 1926.62. *Safety and Health Regulations for Construction*, “Lead,” Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=94eea052f38cae101046e869dcbfe269&rgn=div8&view=text&node=29:8.1.1.1.1.4.13.13&idno=29. Site last accessed August 24, 2012.

95. 29 CFR 1926.55. *Safety and Health Regulations for Construction*, “Gases, Vapors, Fumes, Dusts, and Mists,” Electronic Code of Federal Regulations, Government Printing Office, Washington, DC. Obtained from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=94eea052f38cae101046e869dcbfe269;rgn=div5;view=text;node=29%3A8.1.1.1.1;idno=29;cc=ecfr#29:8.1.1.1.1.4.13.6. Site last accessed August 2, 2012.

96. International Organizataion for Standardization. (2010). *ISO 14040:2006: Environmental Management—Life Cycle Assessment—Principles and Framework*, Geneva, Switzerland.

97. International Organization for Standardization. (2010). *ISO 14044:2006: Environmental Management—Life-Cycle Assessment—Requirements and Guidelines*, Geneva, Switzerland.

98. Scientific Applications International Corporation. (2006). *Life Cycle Assessment: Principles and Practice*, McLean, VA.

99. Institute for Environment and Sustainability. (2010). *ILCD Handbook, International Reference Life Cycle Data System*, Joint Research Centre, European Commission, Ispra, Italy. Obtained from: http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf. Site last accessed June 7, 2013.

100. Debaillon, C., Carlson, P., He, Y., Schnell, T., and Aktan, F. (2007). *Updates to Research on Recommended Minimum Levels for Pavement Markings Retroreflectivity to Meet Driver Night Visibility Needs*, Report No. FHWA-HRT-07-059, Federal Highway Administration, Washington, DC.

101. Alabama Department of Transportation. (2010). *Acceptance Sampling and Testing Schedule*, Birmingham, AL. Obtained from: https://www.dot.state.al.us/mtweb/Testing/testing_manual/doc/AST/AST701Rev51110.pdf. Site last accessed May 11, 2013.

102. Florida Department of Transportation. (2010). *Standard Specifications for Road Construction*, Tallahassee, FL. Obtained from: http://www.dot.state.fl.us/construction/2010Master.pdf. Site last accessed May 11, 2013.

103. North Carolina Department of Transportation. (2012). *Standard Specifications for Roads and Structures*, Raleigh, NC. Obtained from: https://connect.ncdot.gov/resources/safety/Signing%20and%20Delineation%20Library/Roadway%20Standard%20Specifications%20Division%2012%20-%20Pavement%20Markings,%20Markers%20and%20Delineation.pdf. Site last accessed May 11, 2013.

104. Kansas Department of Transportation. (2007). *806—Durable Pavement Marking*, Topeka, KS. Obtained from: http://www.ksdot.org/burConsMain/specprov/pdf/806.pdf. Site last accessed May 11, 2013.

105. Kansas Department of Transportation. (2007). *807—Painted Pavement Marking*, Topeka, KS. Obtained from: http://www.ksdot.org/burConsMain/specprov/pdf/807.pdf. Site last accessed May 11, 2013.

106. Delaware Department of Transportation. (2009). "Section C748—Pavement Markings," *Division C700—Miscellaneous Construction*, Dover, DE. Obtained from: http://www.deldot.gov/information/pubs_forms/manuals/mat_research/pdfs/part_c/c700.pdf. Site last accessed May 11, 2013.

107. Georgia Department of Transportation. (2012). *Section 652—Painting Traffic Stripe*, Atlanta, GA. Obtained from: http://www.dot.ga.gov/informationcenter/publicinformation/gptq/documents/specs/section652.pdf. Site last accessed May 11, 2013.

108. Georgia Department of Transportation. (2012). *Section 653—Thermoplastic Traffic Stripe*, Atlanta, GA. Obtained from: http://www.dot.ga.gov/doingbusiness/TheSource/special_provisions/shelf/sp653.pdf Site last accessed May 11, 2013.

109. Colorado Department of Transportation. (2013). *Revision of Sections 627 and 708—Pavement Marking Paint*, Denver, CO. Obtained from: http://www.coloradodot.info/business/designsupport/construction-specifications/2011-Specs/standard-special-provisions/section-600-revisions/627pmwbvoc.docx/view. Site last accessed May 11, 2013.

110. Texas Department of Transportation. (1999). *Test Procedure for Determining Functional Characteristics of Pavement Markings*, Designation Tex-828-B, Austin, TX. Obtained from: ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/800-B_series/pdfs/ctm828.pdf. Site last accessed August 24, 2012.

111. Kansas Department of Transportation. (2007). *Special Provision to the Standard Specification Division 806 Durable Pavement Markings*, Topeka, KS.

112. Maryland State Highway Administration. (2012). “Special Provision to Section 572 Pavement Markings,” *Traffic Control Device Design Manual*, Annapolis, MD. Obtained from: http://roads.maryland.gov/oots/part2.pdf. Site last accessed May 11, 2013.

113. Wisconsin Department of Transportation. (2013). *Section 646—Pavement Markings*, Madison, WI. Obtained from: http://roadwaystandards.dot.wi.gov/standards/stndspec/ss-06-46.pdf. Site last accessed May 11, 2013.

114. Florida Department of Transportation. (2010). *Maintenance Rating Program Handbook*, Tallahassee, FL.

115. North Carolina Department of Transportation. (2007). *RFP Element 40682*, Raleigh, NC. Obtained from: https://connect.ncdot.gov/letting/Design%20Build%20Program/Interstate%20Maintenance/FinalRFP.pdf. Site last accessed May 11, 2013.

116. Heltzel, E.R. (2011). *Turnkey Asset Maintenance Services Contract*, Virginia Department of Transportation, Richmond, VA. Obtained from: http://www.amotia.org/2011-%20presentations/2%20VDOT%20Turnkey%20Asset%20Maint%20Svcs_Emmet%20Heltzel.pdf. Site last accessed May 11, 2013.

117. Virginia Department of Transportation. (2007). *Road and Bridge Specifications*, Richmond, VA. Obtained from: http://www.virginiadot.org/business/resources/const/2007SpecBook.pdf. Site last accessed August 24, 2012.

118. National Cooperative Highway Research Program. (2010). *Pavement Marking Warranty Specifications*, Project 39-13, Washington, DC. Obtained from: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_408.pdf. Site last accessed August 24, 2012.

119. Google Earth®. (2005). *Glenn Highway in Anchorage, AK*. (Map). Generated by Paul Carlson via Google Earth® on July 15, 2006.

120. Google Maps®. (2006). *SR 840 in Nashville, TN.* (Map). Generated by Paul Carlson via Google Maps® online on July 15, 2006. (https://maps.google.com/)

121. Google Maps®. (2006). *SR 34 in Tusculum, TN.* (Map). Generated by Paul Carlson via Google Maps® online on July 15, 2006. (https://maps.google.com/)

122. Shankar, V. and Mannering, F. (1996). "An Exploratory Multinomial Logit Analysis of Single-Vehicle Motorcycle Accident Severity," *Journal of Safety Research*, *27*(3), 183–194.

123. Savolainen, P. and Mannering, F. (2007). "Probabilistic Models of Motorcyclists' Injury Severities in Single- and Multi-Vehicle Crashes," *Accident Analysis and Prevention*, *39*(5), 955–963.

124. Ulfarsson, G. and Mannering, F. (2004). "Differences in Male and Female Injury Severities in Sport-Utility Vehicle, Minivan, Pickup and Passenger Car Accidents," *Accident Analysis and Prevention*, *36*(2), 135–147.

125. Khorashadi, A., Niemeier, D., Shankar, V., and Mannering, F. (2005). "Differences in Rural and Urban Driver-Injury Severities in Accidents Involving Large-Trucks: An Exploratory Analysis," *Accident Analysis and Prevention*, *37*(5), 910–921.

126. Shankar, V., Mannering, F., and Barfield, W. (1996). "Statistical Analysis of Accident Severity on Rural Freeways," *Accident Analysis and Prevention*, *28*(3), 391–401.

127. Chang, L. and Mannering, F. (1999). "Analysis of Injury Severity and Vehicle Occupancy in Truck- and Non-Truck-Involved Accidents," *Accident Analysis and Prevention*, *31*(5), 579–592.

128. Holdridge, J., Shankar, V., and Ulfarsson, G. (2005). "The Crash Severity Impacts of Fixed Roadside Objects," *Journal of Safety Research*, *36*(2), 139–147.

129. Wang, X. and Abdel-Aty, M. (2008). "Analysis of Left-Turn Crash Injury Severity by Conflicting Pattern Using Partial Proportional Odds Models," *Accident Analysis and Prevention*, *40*(5), 1674–1682.

130. Duncan, C., Khattak, A., and Council, F. (1998). "Applying the Ordered Probit Model to Injury Severity in Truck-Passenger Car Rear-End Collisions," *Transportation Research Record 1635*, 63–71, Transportation Research Board, Washington, DC.

131. Klop, J. and Khattak, A. (1999). "Factors Influencing Bicycle Crash Severity on Two-Lane, Undivided Roadways in North Carolina," *Transportation Research Record 1674*, 78–85, Transportation Research Board, Washington, DC.

132. Quddus, M., Noland, R., and Chin, H. (2002). "An Analysis of Motorcycle Injury and Vehicle Damage Severity Using Ordered Probit Models," *Journal of Safety Research*, *33*(4), 445–462.

133. Kockelman, K. and Kweon, Y. (2002). "Driver Injury Severity: An Application of Ordered Probit Models," *Accident Analysis and Prevention*, *34*(3), 313–321.

134. Abdel-Aty, M. (2003). "Analysis of Driver Injury Severity Levels at Multiple Locations Using Ordered Probit Models," *Journal of Safety Research*, *34*(5), 597–603.

135. O'Donnell, C.J. and Connor, D.H. (1996). "Predicting The Severity of Motor Vehicle Accident Injuries Using Models of Ordered Multiple Choice," *Accident Analysis and Prevention*, *28*(6), 739–753.

136. Gkritza, K. and Mannering, F. (2008). "Mixed Logit Analysis of Safety-Belt Use in Single- and Multi-Occupant Vehicles," *Accident Analysis and Prevention*, *40*(2), 443–451.

137. Milton, J., Shankar, V., and Mannering, F. (2008). "Highway Accident Severities and the Mixed Logit Model: An Exploratory Empirical Analysis," *Accident Analysis and Prevention*, *40*(1), 260–266.

138. Pai, C., Hwang, K., and Saleh, W. (2009). "A Mixed Logit Analysis of Motorists' Right-Of-Way Violation in Motorcycle Accidents at Priority T-Junctions," *Accident Analysis and Prevention*, *41*(3), 565–573.

139. Kim, J., Ulfarsson, G., Shankar, V., and Mannering, F. (2010). "A Note on Modeling Pedestrian-Injury Severity in Motor-Vehicle Crashes With the Mixed Logit Model," *Accident Analysis and Prevention*, *42*(6), 1751−1758.

140. Eluru, N., Bhat, C., and Hensher, D. (2008). "A Mixed Generalized Ordered Response Model for Examining Pedestrian and Bicyclist Injury Severity Level in Traffic Crashes," *Accident Analysis and Prevention*, *40*(3), 1033–1054.

HRDS-10/11-13(WEB)E