Technical Report Documentation Page

1. Report No. FHWA/TX-10/0-5862-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION OF POTENTIAL BENEFITS OF WIDER AND BRIGHTER EDGE LINE PAVEMENT MARKINGS		5. Report Date February 2010 Published: July 2010 6. Performing Organization Code
7. Author(s) Jeffrey D. Miles, Paul J. Carlson, Ryan Eurek, Jon Re, and Eun Sug Park		8. Performing Organization Report No. Report 0-5862-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-5862
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: September 2007–September 2009 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Benefits of Wider Longitudinal Markings

URL: http://tti.tamu.edu/documents/0-5862-1.pdf

16. Abstract

This report documents the findings of a two-year study that investigated the potential benefits of wider edge line pavement markings. There were four general tasks discussed in the report: 1) review of literature, 2) survey of the state of the practice, 3) summary of recent safety analyses, and 4) a human factors nighttime study of the impact of wider and brighter edge line pavement markings. The results show that states are increasing their use of wider edge lines, and safety studies are beginning to show evidence supporting the use of wider edge lines for two-lane highways. The human factors study included surrogate safety measures, such as lateral placement, edge line encroachments, and driver eye glance patterns. The results from these metrics all support positive safety findings. Pavement marking brightness had less of an impact than pavement marking width on these operational metrics. In this study, there was no attempt to relate pavement marking retroreflectivity to safety. The researchers recommend the use of wider pavement markings on two-lane highways with additional experimentation to verify the benefits described in this report.

17. Key Words Wider Edge Line Pavement Marking, Human Factors, Safety, Lateral Placement, Encroachment, Eye-Tracking, Speed, Tangent, Horizontal Curve	18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 136	22. Price

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

EVALUATION OF POTENTIAL BENEFITS OF WIDER AND BRIGHTER EDGE LINE PAVEMENT MARKINGS

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Report 0-5862-1
Project 0-5862
Project Title: Benefits of Wider Longitudinal Markings

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

February 2010
Published: July 2010

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the researchers, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The engineer in charge of the project was Paul J. Carlson, P.E. #85402.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The researchers would like to thank the project director, Brian Stanford of the TxDOT Traffic Operations Division, for providing guidance and expertise on this project. The authors would also like to thank other members of the TxDOT Project Monitoring Committee for their assistance:

- Tom Beeman of the TxDOT Design Division,
- Angie Ortegon of the TxDOT San Angelo District; and
- Cynthia Flores of the TxDOT Traffic Operations Division.

Special thanks also go to several Texas Transportation Institute employees. Ivan Lorenz, Dick Zimmer, and Ryan Eurek helped design, install, and test the variable lighting systems on the instrumented vehicle. Ivan Lorenz, Ryan Eurek, and Dan Walker were instrumental in preparing the Texas A&M Riverside Campus roadway network by clearing the roadway course and installing the pavement markings. Jesse Stanley was a crucial team member in putting together the instrumented vehicle data collection protocol and training the staff to collect the data.

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CHAPTER 1
INTRODUCTION

State departments of transportation (DOTs) are constantly investigating methods to improve safety along their respective roadway networks. As their roadway networks expand and become more complex, the costs associated with construction and maintenance grow as well, and so, state DOTs must try to find every low-cost alternative to improving safety. One of the low-cost alternatives state agencies are examining is to install wider pavement markings to enhance roadway delineation with the intent to reduce crashes (*1*). In the United States, the *Manual on Uniform Traffic Control Devices* (MUTCD) defines the purpose of longitudinal pavement markings as the delineation of the vehicle path along the roadway (*2*). Altering the color, pattern, and width of longitudinal pavement markings creates variations that can be used to enhance the delineation of the proper path for a driver. While the MUTCD defines standard longitudinal pavement markings as having a width of 4 to 6 inches, for this report, any pavement markings that are wider than 4 inches have been referred to as wider pavement markings. The research discussed in this report details the methods used to evaluate the potential benefit of wider edge line pavement markings and the associated findings.

OBJECTIVES

Many states use wider edge line pavement markings despite a void in solid research documenting their benefit (*1*). Policy makers and engineers seem to like the look and feel of wider edge line pavement markings and use engineering judgment with estimated costs to make decisions regarding their use. TxDOT commissioned this study to provide evidence of the benefit based on human factors visibility data as well as the latest safety data.

The primary objective of this research was to determine how nighttime drivers benefit from wider edge line pavement markings in horizontal curves. After researchers evaluated previous research efforts with regard to wider pavement markings, they set a goal to develop a codependent relationship with one or more measures of effectiveness (MOEs) (i.e., mean lateral position, standard deviation of mean lateral position, mean difference, eye glance, etc.) and pavement marking width. Figure 1 shows a theoretical relationship for pavement marking width, retroreflectivity, and one of the MOEs previously listed.

While the purpose of the study was to investigate the potential benefits of wider edge line pavement markings, the researchers decided to include retroreflectivity, or marking brightness, to investigate whether marking width or marking brightness had a greater influence on the previously mentioned MOEs. The researchers believed that there might be a cost-effectiveness trade-off between installing wider and/or brighter pavement markings. Could a wider marking have a lower brightness and still be as effective as or more effective than a narrow brighter marking?

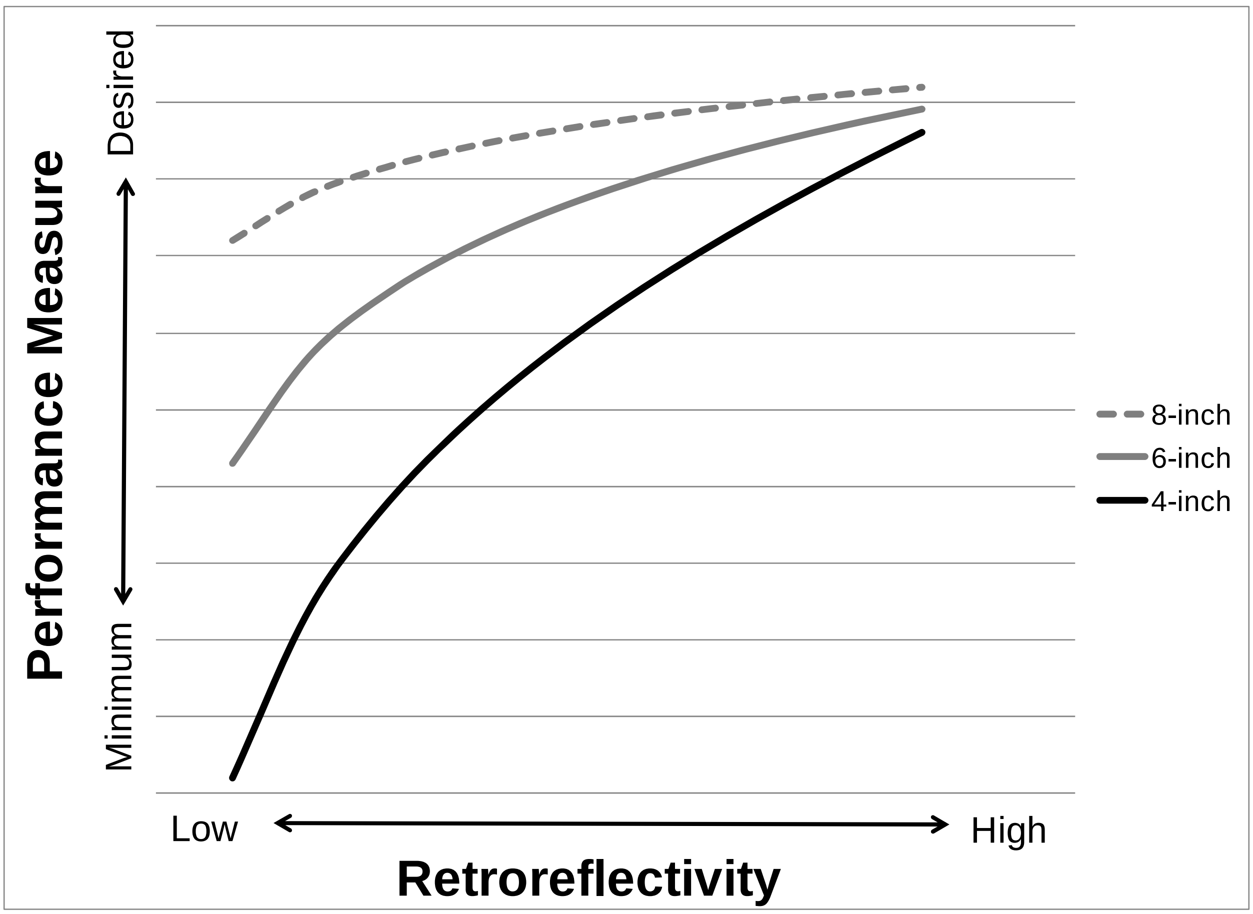


Figure 1. Theoretical Relationship between Retroreflectivity, Width, and MOE.

CHAPTER 2
LITERATURE REVIEW

There have been a number of research projects related to wider pavement markings, with particular emphasis in the last decade. Primarily, there have been four different approaches—subjective evaluations, safety evaluations, vehicle operational studies, and visibility studies. This chapter expands upon all four approaches and concludes with a general summary of the appropriate course of action for the current study.

SUBJECTIVE EVALUATIONS

Transportation agencies have used the opinions of the driving public to evaluate wider pavement markings and, in some cases, to assist in policy decisions. Subjective evaluations can serve as an indicator of customer desire, but the results are not always tied to improvements in safety or operations.

A public opinion survey published by the South Dakota DOT in 1997 showed that "keeping stripes visible" was the third-highest ranked attribute out of 21 for resource allocation (money and services) as rated by both 768 members of the driving public and 32 state legislators (*3*). A follow-up public opinion survey in 1999 showed that 81 percent of the 734 respondents felt that poor pavement markings would "somewhat interfere" or "very likely interfere" with safe travel (*4*).

The American Association of Retired Persons (AARP) had 18 of their instructors drive a test course during both the daytime and nighttime. The drivers were interviewed, and 94 percent of the respondents said that 8-inch edge lines affected the way they drove. The instructors emphasized that the wider markings aided in staying on the roadway and in their lane (*5*). Research by Ohme reported that drivers participating in a field detection distance evaluation generally judged wider markings as more favorable than 4-inch markings (*6*). Similar results were observed by Pietrucha et al. in simulator evaluations of 8-inch versus 4-inch edge lines (*7*). However, the researchers in both studies found that subjective evaluations did not correlate well with objective performance for markings of different widths.

One of the current weaknesses in the body of knowledge is that there appears to be little to no documented efforts describing how well the various DOTs' visual assessments correlate to measured retroreflectivity or other quantitative metric. TxDOT recently sponsored a study that was designed to evaluate the accuracy of DOT personnel's visual assessment with respect to retroreflectivity. The study was conducted at a closed-course site with a variety of nighttime roadway conditions (*8*).

State DOT personnel drove the course and were asked to visually assess the pavement marking brightness (*8*). The researchers compared the visual assessment against the measured retroreflectivity levels to determine if visual nighttime inspection would be a viable method to evaluate pavement marking retroreflectivity. The researchers found that subjective evaluations showed inconsistency in retroreflectivity rating when compared between different evaluators, marking colors, and retroreflectivity levels.

SAFETY OF PAVEMENT MARKINGS

Many agencies are utilizing enhanced pavement markings with the intent to reduce crashes and/or crash rates. Much of this emphasis has resulted from the Federal Highway Administration's recent focus on state safety data in an effort to reduce the national highway fatality toll. Other factors, such as the emphasis on accommodating older drivers, have also inspired states to evaluate their marking programs in terms of roadway safety. Regardless of the reason, safety analysis is a quantitative method to evaluate pavement markings.

Standard Edge Lines

One of the first studies to determine edge line safety benefits was conducted in 1957 by Musick (*9*). The study analyzed the crash data after the Ohio Department of Transportation mandated edge lines for all two-lane rural highways and for roadways with a width greater than 20 ft. A before-after analysis identified that edge lines contributed to a 19 percent net reduction in crashes. Fatalities and injuries were also reduced by 37 percent, and nighttime crashes decreased by 35 percent.

Basile obtained a similar trend to the Musick study when the researcher conducted a before-after study on Kansas roadways in 1959 (*10*). Edge lines were added to all rural two-lane highways with a pavement width of 20 to 26 ft and a minimum average daily traffic (ADT) of 1,000 vehicles per day (vpd). The study determined that edge lines contributed to a 78 percent net reduction in fatalities, and crashes at intersections/driveways were significantly decreased for both daytime and nighttime periods.

In a recent study, Tsyganov et al. examined crash data from the Texas Department of Public Safety to determine the current relationship between roadways with and without edge lines and the likelihood of a crash (*11*). The researchers reviewed data from 9,774 crashes on rural two-lane highways over a four-year time span. Besides edge lines, the researchers took into consideration lane width, shoulder width, and ADT. The results determined that edge lines may reduce crash frequency up to 26 percent, and the greatest safety benefit was observed on horizontal curves and on roadways with lane widths of 9 to 10 ft. The researchers reasoned that the reduction in speeding-related crashes during darkness may be a result of improving a driver's perception of the travel path and vehicle speed (*11*).

When conducting safety assessments, transportation agencies take the safety data and complete cost-effectiveness (or benefit/cost) analyses when trying to identify potential policy changes. Pavement markings have traditionally been viewed by most transportation agencies as a very low-cost device for improving highway safety. A commonly cited study completed in 1991 by Miller quantified the benefit/cost ratios of edge lines for various roadway situations (*12*). Analyzed crash statistics determined that, on average, pavement striping yielded a 60:1 benefit/cost ratio with average annual benefits estimated at $19,226 per line-mile. Miller showed that even on rural two-lane roads with an ADT as low as 500 vpd, edge lines yielded a benefit/cost ratio of 17:1. A benefit/cost analysis performed by Hughes et al. in the late 1980s determined that an annual reduction of eight edge line-related crashes for every 1,000 miles striped with 8-inch edge lines would allow for the wider lines to be cost-effective (*13*). With the general low cost of pavement markings versus the overall cost of installing and maintaining roadways, it is a logical next step for DOTs to investigate the potential improvements in safety from installing brighter and/or wider pavement markings.

Wider Edge Lines

Overall, research has repeatedly proven that the addition of edge lines reduces crash rates and improves roadway safety. It can be reasoned that if a 4-inch-wide edge line enhances roadway safety, then a wider edge line may offer some additional benefits from the increased target area, which should enhance conspicuity.

One of the first safety evaluations of wider edge lines was conducted by Cottrell in 1987. The study analyzed crash data on three two-lane rural roadways in Virginia (*14*). At the three test sections, treatment portions were striped with 8-inch-wide edge lines, and comparison sections were restriped with 4-inch-wide edge lines. A before-after analysis reviewed crash data from three years prior to restriping and two years after installing the treatment. The researcher focused specifically on run-off-road (ROR) crashes and hypothesized that a significant reduction in ROR crashes would warrant the use of wider edge lines. The analysis revealed that there was a 13.6 percent reduction in both ROR and opposite-direction (OD) crashes. Despite the decline, the treatment reductions were not statistically significant when compared to the comparison sites. In the end, the researcher concluded that there was no substantial evidence to support that 8-inch-wide edge lines significantly reduced the investigated crash rates (*14*).

A study in New Mexico yielded a similar conclusion. Hall in 1987 evaluated the rates of ROR and OD crashes along 530 miles of rural two-lane highway with unusually high crash rates (*15*). The study applied 8-inch edge lines on 176 miles of the studied roadway, and the remaining sections were utilized for comparison purposes. The crash data were acquired from a relatively short time frame of 41 to 52 months for the before period and 5 to 17 months for the after period. The findings showed that crash rates decreased approximately 10 percent at the treatment locations and 16 percent at the comparison sections. The researcher recommended that the State of New Mexico discontinue the use of wider edge lines.

In an ongoing FHWA study, commenced in 2006, researchers are taking a much more expansive look at the safety benefits of wider pavement markings (*16*). As part of the current study, a nationwide survey was conducted to identify states that have wider pavement markings (wider than 4 inches) on all or some of their highways. The convergence of all the necessary criteria was rare, but three states were identified as having the required information: Michigan, Illinois, and Kansas. To date, the researchers have focused their efforts on rural two-lane highways in Illinois and Michigan. In Illinois, data screening reduced the rural two-lane data set to 1,321 miles of 4-inch edge lines and 260 miles of 5-inch edge lines. In Michigan, before-after evaluations were conducted with three years (2001–2003) of before and two years (2005–2006) of after data, which was obtained from 852 miles of rural two-lane roadways.

The empirical Bayes before-after evaluations resulted in the following crash reduction estimates: total (7.1 percent), fatal and injury (17.1 percent), property damage only (PDO) (5.4 percent), daytime (10.0 percent), nighttime (2.4 percent), daytime fatality and injury (18.0 percent), nighttime fatality and injury (11.7 percent), wet (24.4 percent), wet and nighttime

(22.6 percent), single vehicle (2.0 percent), single vehicle and wet (20.0 percent), single vehicle and nighttime (−0.3 percent), and opposite direction (14.9 percent). All of these crash reduction estimates, except for nighttime, single vehicle, and single vehicle and nighttime crashes, were statistically significant at the 95 percent confidence level.

EFFECT OF PAVEMENT MARKINGS ON VEHICLE OPERATIONS

Safety benefits can be directly observed with a reduction in crash rates, but in some cases sufficient crash data may not always be accessible. Safety surrogate measures establish a relationship between vehicle operations and crashes rates. Surrogates are an accepted intermediate, but they are not a substitute for crash data. Speed and lateral position are accepted surrogate measures, and the following subsections describe recent research on these measures.

Vehicle Speed

While there have been a number of 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 strongly correlated with crash rates (*17, 18*). For instance, in 2004 van Driel et al. performed a meta-analysis of vehicle operating speeds based on edge line presence (*19*). The range of reported before-after results was −3 mph (reduction in mean speed) to +8.1 mph. An overall increase in mean speed after installing edge lines on roadways that previously only had a centerline was less than 0.5 mph. The researchers came to the conclusion that the net speed effect was essentially zero.

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

A recent study performed by Donnell et al. for FHWA 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 (*21*). Based on the results of the present nighttime driving 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 (*22*). 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 determined that there were no statistical differences in vehicle speeds when considering daytime versus nighttime conditions. The researchers' findings consistently showed that speeds slightly increased in all conditions after edge lines were applied, but the differences were not deemed statistically significant. They also showed that absolute speed standard deviations were less than 1 mph.

Many experts believe that drivers reduce speeds based solely upon 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.

Vehicle Lateral Lane Position

Previous research has determined that vehicle lateral position measures are strongly correlated with crash rates (*23, 24*). A meta-analysis of lateral vehicle position was performed by van Driel et al. (*19*). The analysis looked at research conducted in the United States after the installation of edge lines on roadways without previous markings. The compiled results found that the change in mean lateral position 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. The researchers came to the conclusion that the net lateral position effect was essentially zero.

The work previously described by Donnell et al. resulted in findings that indicate there was little evidence to show that wider pavement markings change the way in which motorists transition from a tangent into a curve (*21*). The researchers concluded that use of wider pavement markings does not improve driver lane position differential between an approach tangent and the midpoint of a horizontal curve.

On the other hand, Cottrell compared the lateral position using 4- and 8-inch-wide edge lines (*25*). The results indicated that lateral vehicle position variance was unchanged at locations with 4-inch-wide edge lines, but lateral vehicle position variance decreased during both daytime and nighttime for the locations marked with 8-inch-wide edge lines.

The research conducted in Louisiana investigated lateral position specific to narrow rural two-lane highways (*20*). Their before-after measurements showed that edge lines helped drivers to travel in a more centralized and uniform path. The results were prominent at nighttime, which was of particular interest because nighttime crash rates are traditionally higher than daytime crash rates.

Tsyganov et al. also evaluated the impact of installing edge lines along narrow two-lane highways (*22*). The researchers also measured a reduction in the variability of vehicle lateral position. The exact vehicle lateral placement depended on the overall lane width. For the 9-ft lane width, the vehicle path was closer to the newly installed edge line, especially in the curve sections. For 10-ft lane widths, drivers did not favor either the centerline or edge line pavement marking. However, for the 11-ft lane width highways, the majority of the drivers moved closer to the centerline, especially on the curve sections. The researchers deemed all modifications in lane position to be acceptable and that the addition of edge lines achieved beneficial vehicle operations.

Vehicle Operations Summary

The reviewed research offered differing and sometimes contradictory vehicle speed and lateral position findings. Standard 4-inch and wider 8-inch edge lines had little to no impact on vehicle speed, and results were not statistically significant. The meta-analysis by van Driel et al. revealed that mean speed values fluctuated greatly when edge lines were added, but in the end the researcher concluded that the net change was essentially zero (*19*).

Although similar mixed results were observed, there were some promising findings for vehicle lateral position. Three other studies observed more uniform and centralized lane position as a result of the installation or modification of edge line treatments (*20, 22, 25*). The findings from the reviewed studies would suggest that vehicle lateral placement might be a more useful dependent variable than speed when investigating the potential benefits of wider edge line pavement markings.

PAVEMENT MARKING VISIBILITY

Another area of pavement marking research has focused on the visibility of the markings with respect to crashes, detection distance, and driver perception.

Retroreflectivity

A significant challenge when studying pavement marking retroreflectivity has been that retroreflectivity degradation models have not been widely successful and the factors are rarely consistent (*26, 27*). In particular, a variety of different independent variables have been found to be significant in predicting the life of a pavement marking with respect to retroreflectivity. The oddity has been that no one model has been identical to another, and in fact, many predictors for one model were found insignificant in another. ADT has been the most consistently modeled predictor. Modeling pavement marking degradation then becomes even more complicated once weather, quality of installation, and even the condition of the pavement are considered. As a result, it has been difficult to associate a particular marking retroreflectivity level with a particular crash, and so researchers have had to make assumptions regarding the retroreflectivity levels for inclusion in their crash analysis models. Some researchers model retroreflectivity using various sources of measured data, while others make assumptions about the retroreflectivity without measurements.

Crashes

Recently, there have been attempts to statistically link pavement marking retroreflectivity levels to crash rates. Two of the earliest efforts showed no statistical correlation between retroreflectivity and safety; however, those studies had sites with retroreflectivity values around 200 mcd/m^2/lx or higher (*28, 29*). Abboud and Bowman investigated even lower retroreflectivity values with the assumption that there was probably a minimum threshold retroreflectivity value below which safety degrades, but above which safety does not improve significantly (*30*). Abboud and Bowman suggested that states wishing to consider safety in pavement marking practices should set a minimum retroreflectivity value of 150 mcd/m^2/lx.

In 2007, researchers reported results from another effort to develop a statistical association between measured pavement marking retroreflectivity and traffic crash frequency (*31*). The researchers reported that increased levels of the average pavement marking retroreflectivity on multi-lane highways may be associated with lower expected target crash frequencies; however, the association was small in magnitude and not statistically significant. On two-lane highways, the association between pavement marking retroreflectivity and crash frequency was larger in magnitude and marginally significant. While this study used measured retroreflectivity levels (recorded once per year), it should be noted that all the retroreflectivity data were well above what might be considered minimum levels, and even near what might be considered desirable levels (all data were above 100 mcd/m^2/lx with an overall average of 240 mcd/m^2/lx). These researchers are continuing to evaluate their data using innovative techniques such as modeling retroreflectivity using neural networking techniques.

In 2008, a similar effort was conducted by Smadi et al. that included three years of measured retroreflectivity (measured once per year) in Iowa (*32*). These data were analyzed along with crash records from the same year. The models of all roadways and two-lane highways did not show that pavement marking retroreflectivity correlated to crash probability. When truncating the data to only records with retroreflectivity values less than or equal to 200 mcd/m^2/lx, a statistically significant relationship was determined. However, the correlation was small. This research is also being continued using retroreflectivity thresholds near the generally accepted minimum levels of 100 mcd/m^2/lx.

Detection Distance

Pavement marking detection distances have been measured with two different techniques: static and dynamic. In a static setup, a stationary study participant counts the number of visible lane lines. In a dynamic setup, a study participant drives a vehicle and reports when he/she detects isolated lane lines (*33*) or modifications in pavement markings such as edge line breaks or tapers (*34*). The results have been reported in maximum nighttime detection distances.

The studies that focused on maximum detection distance have been conducted with pavement markings of various retroreflectivity levels, of different widths, of different profiles, and/or from different vehicles. These types of studies have repeatedly shown that pavement marking detection distances were correlated with retroreflectivity in a logarithmic fashion (*35, 36*). The correlation has shown that detection distance increases as the retroreflectivity increases.

The previous relationship has not necessarily held true for detection distance and wider edge lines. Some research efforts showed that wider edge lines increased subject detection distance (*6, 37, 38*), while other studies found that there were no statistical or practical differences between the detection of standard and wider markings (*7, 33*). Despite mixed results, it would be premature to conclude that wider edge line pavement markings do not improve visibility and aid detection. Since the addition of edge lines has been shown to improve lane keeping by reducing variance in lateral position, it could be hypothesized that wider edge lines would improve visibility in a similar manner as adding edge lines.

Lane Keeping

A study by McKnight in 1998 explored both lane keeping and the visual perception of pavement markings (*39*). The study evaluated the lane-keeping measures of 124 study participants by means of a driving simulation. Test variables included three edge line widths of 4, 6, and 8 inches along with 14 line-pavement contrast ratios. Lane keeping was evaluated in terms of heading error, position error, lane excursions, and roadway excursions. The results determined that differences in lane keeping for different test variables were practically inappreciable. The only notable exception occurred at extremely low contrast and luminance levels, which would be characteristic of driving in rain during nighttime. Under such conditions, the performance error for the 8-, 6-, and 4-inch-wide edge lines were 1.6, 1.8, and 2.2, respectively. These results signified that there was a correlation between lane-keeping performance and pavement marking width under poor visibility conditions.

One possible explanation for the McKnight results is that wider pavement markings provide heightened recognition and detection in the periphery. One theory has been that pavement markings provide two primary functions: previewing the roadway alignment (using far or foveal vision) and maintaining lane position (using near or peripheral vision). The peripheral vision system is capable of target recognition using low cognitive power. There are endless targets recognized in the periphery that somehow are processed as insignificant and therefore cause no need for our central vision focus. If wider markings can reduce the amount of time the foveal focus is needed on short-range pavement markings, then the potential benefits of wider markings could be realized. Drivers could then allocate more foveal vision to other critical targets, therefore ultimately providing a safer driving environment.

SUMMARY

In summary, there are four possible ways to evaluate the merit of wider pavement markings: subjective studies, safety studies, operational-based studies, and visibility studies. Subjective studies are pertinent, but they provide the least amount of scientific evidence. Safety studies would be the ultimate measure of effectiveness, but sufficient crash data are not always available, and designating adequate comparison sites is difficult. Despite mixed study results, operational and visibility studies appear to have advantages over subjective and safety studies.

In the operational studies, wider edge lines appeared to yield little to no effect on vehicle speed, which could be a direct result of increased driver comfort from the enhanced conspicuity of the treatment. On the other hand, there have been beneficial and significant changes in vehicle lateral position. The reviewed literature indicated that wider edge lines may decrease lateral position variance and promote a more centralized vehicle path (*25, 39*). The encouraging wider edge line results occurred at low luminance levels, revealing a meaningful connection between vehicle operations and pavement marking visibility.

Based on the past methodology, a study design that integrates both operational performance and visibility components may yield promising findings. Foveal detection tasks have already been explored, so it is reasonable to evaluate peripheral visibility measures as an indicator of wider pavement marking benefits. The research team believes that vehicle lateral position is acutely related to peripheral vision, and both metrics will serve as cornerstones for this investigation. Based on the reviewed literature, the work plan was designed to focus on how wider and brighter pavement markings may assist a study participant with vehicle lateral placement and/or allowing more time for conducting more critical foveal tasks associated with tracking curves and reading signs.

CHAPTER 3
STATE SURVEY

A survey was administered to traffic engineers at each state department of transportation to determine the current use of wider pavement markings. The survey was administered over the Internet and was followed up with telephone interviews of agency personnel. The design of the questions was based on researcher experience and findings from a review of existing literature on the subject of wider pavement markings. The answer categories were multiple choice, with several open-ended questions that allowed for detailed responses. It was estimated to take less than 15 minutes to complete the survey.

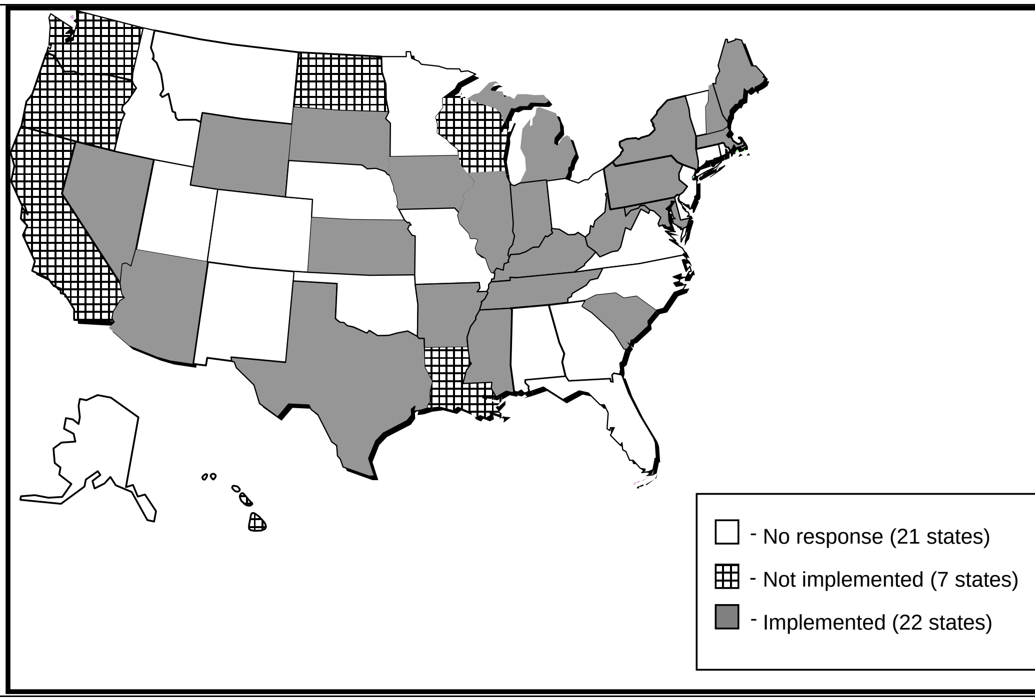
Out of the 50 state DOTs that were included in the survey, 29 responded. A discussion of the summary of the agency responses and individual state responses is presented in this chapter. The survey questionnaire and the full agency responses can be found in the appendix.

OBJECTIVES

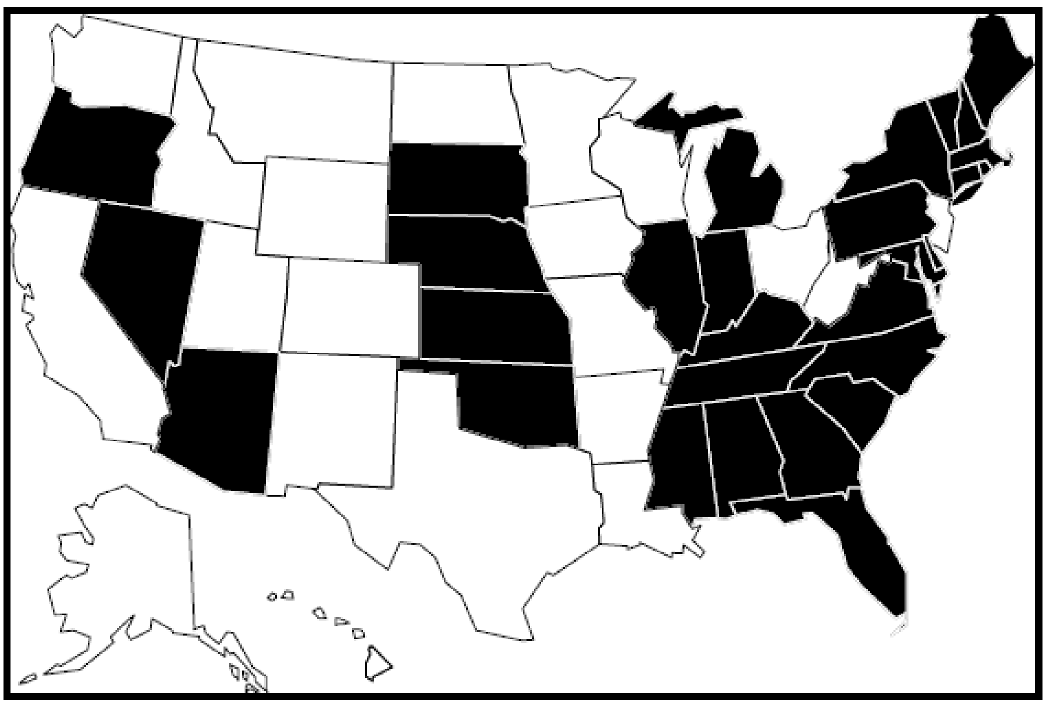
The main objective of the survey was to obtain information and identify potential data sources related to wider longitudinal pavement markings. The survey was to be used in combination with crash data to attempt to identify the safety impact associated with the usage of wider pavement markings. Another goal of the surveys was to compare the current usage trends of wider pavement markings with results obtained in a previous Texas Transportation Institute (TTI) research study by Gates and Hawkins (*1*).

EXTENT OF WIDER PAVEMENT MARKING USE

Based on the survey responses, 22 out of the 29 states that responded to the survey (about 76 percent) were currently using wider markings to an extent for some longitudinal pavement markings (centerline, lane line, and/or edge line). This number was an increase from the 58 percent usage reported by Gates and Hawkins (*1*). It should be noted, though, that while the 2002 report had a 100 percent response rate (i.e., all 50 DOTs responded), there was a 58 percent response rate to the current survey. Figure 2 shows which states responded to both surveys. As stated previously, the main goal of this survey was to identify states with wider line usage that could be combined with a well-maintained crash database in the same state. Hence, a 100 percent response rate was not required.



a) Responses to 2006 Survey



b) Responses to 2001 Survey (Solid Black Indicates Use of Wider Lines) (*1*)

Figure 2. Wider Line Usage Survey Response.

Figure 2a indicates which states responded to the survey and whether or not they were currently using wider pavement markings; the complete list of responses is in the appendix. Figure 2a can be compared to Figure 2b, which indicates the usage from the survey conducted in 2001. Even with less than 100 percent response, several states have added wider lines to some of their roads. This would indicate an interest and a trend toward wider line usage.

WIDER PAVEMENT MARKING WIDTHS USED

From the survey results, almost half of the 29 states (approximately 48 percent) that responded to the survey utilized 6-inch-wide pavement markings, while just 1 state used a 5-inch line width. Other wider line widths used across the United States included:

- 8-inch line widths,
- 12-inch line widths (used for areas intended for double lines), and
- 10- and 18-inch line widths.

The total mileage of wider pavement marking applications in the states that responded is shown in Table 1. From the results in Figure 3, it is clear that an overwhelming majority of current wider pavement markings applications is using 6-inch line widths. Figure 3 indicates the width of wider markings used in each state. Some states use wider markings of different widths, and many states still use the standard 4-inch-wide markings as well as wider markings.

Table 1. Wider Pavement Marking Usage with Respect to Mileage.

Wider Marking Type	Total Mileage	Total Reported Wider Marking Applications
5-inch	12,200	22%
6-inch	43,615	77%
8-inch	735	1%

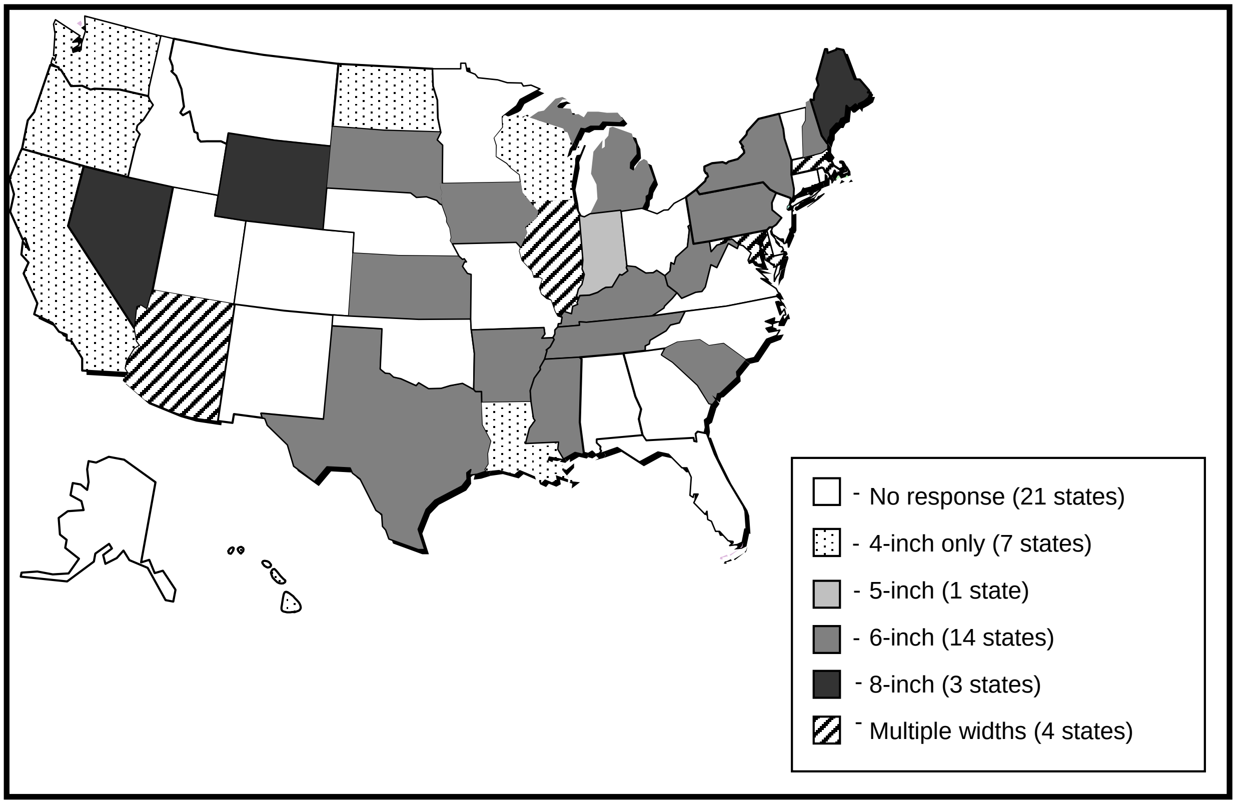


Figure 3. Wider Line Usage by Width and Mileage.

REASONS AND/OR BASIS FOR USING WIDER MARKINGS

Various reasons were given for the use of wider pavement markings by the various state agencies. The results are shown in Table 2. There was no predominant reason given out of the choices presented. Experimental usage and a state trend toward implementing wider lines were the two most common answers, as was other, which was mostly noted as visibility related. In the 2001 survey the most common response was to improve visibility.

Table 2. Reasons for Implementing Wider Markings.

Reasons for Implementing Wider Pavement Markings	Response*
Experimental	16%
For spot treatments (e.g., severe curves, bridge approaches, etc.)	11%
High-crash areas	11%
State trend	20%
Recommendations from other states	13%
Research results	9%
Other	20%

*Some respondents provided multiple reasons.

Other reasons given by the respondents for implementing wider pavement markings in some states included:

- a desire for wider lines on interstate highways,
- perceived safety and convenience benefits of the wider lines,
- to aid in reducing departure crashes,
- to help the older driver population, and
- as part of the state's highway safety plan.

HISTORIC TRENDS IN WIDER PAVEMENT MARKINGS

The survey was designed to determine recent trends in wider pavement marking implementation. As shown in Table 3, 82 percent of the states with existing wider pavement markings (of those who responded) first implemented wider markings more than three years ago, whereas 18 percent of the respondents implemented wider pavement markings for the first time within the past two years.

Also, 59 percent of responses with wider markings indicated that the majority of such markings were implemented more than three years ago, meaning that 41 percent implemented their wide pavement markings within the past three years. This shows that more states have started to use wider markings in recent years.

Table 3. Wider Pavement Marking Implementation History.

Time Frame of Implementation	First Wider Markings Application	Majority Wider Markings Application
Within the past year	9%	9%
Between 1 and 2 years ago	9%	18%
Between 2 and 3 years ago	0%	14%
Greater than 3 years ago	82%	59%

RECORD KEEPING

Researchers attempted to obtain information on record keeping with respect to locations of roadways with wider pavement marking implementation. Details of records on the location of such wider marking application, annual average daily traffic (AADT) values for such roadways, details of roadway improvement on such areas, etc. were surveyed. Table 4 shows the percentage of respondents with records of locations with wider markings, 4-inch markings, and areas and dates of work zones.

Table 4. Records Availability for Location of Wider Pavement Markings.

Record Type	Response		
	Yes No		Uncertain
Records of locations with wider marking	57%	29%	14%
Records of locations with standard 4-inch marking	61%	29%	10%
Records of areas and dates of work zones	45%	55%	-

The survey asked about details of records kept for locations where wider pavement markings have been implemented. The most-recorded detail for locations with wider pavement marking application was the location, beginning and end of the application, and number of miles installed. The least-recorded detail was the pavement edge drop-offs, terrain type, and curve and tangent locations.

Researchers also wanted to examine details of records that indicate areas of improvements made to roadways before and after being striped with wider markings. Based on responses received, the most-recorded detail of areas of improvements made to roadways before and after being striped with wider markings was the implementation of new surface treatment. Roadway expansion was the least-recorded detail on roadway improvements before and after wider marking application.

State agencies were asked about typical sources of data for information with regards to wider pavement marking application. Sources of information for two record types (A and B) are reported in Table 5. The following is a description of the two record types:

- Record Type A: source of data for AADT at sites where pavement marking width is known or for records indicating details of roadway locations with wider marking (location, beginning and end of wide marking, date of application, road type/class, number of miles installed, line type installed, AADT, speed limit, number of lanes, median type and width, lane width, shoulder width, pavement edge drop-offs, curve and tangent locations ,and terrain type); and

- Record Type B: source of data for records that indicate areas and dates of work zones on roadways or details of areas of improvements made to roadways before and after being striped with wider markings.

Table 5. Sources of Information Relating to Wider Marking Application Record.

Source of Data	Response*	
	Record Type A	Record Type B
Online database	15%	0%
Request DOT electronic files	22%	23%
Request DOT paper files	15%	19%
Request DOT maps	15%	12%
On-site visit	22%	19%
No records exist	11%	27%

*Some respondents selected both record types.

From the responses received, state DOT electronic files and on-site visits seemed to be the most popular sources of data available. The majority of state DOTs surveyed has no records available for areas and dates of work zones or details of improvements made to roadways before and after wider marking application.

AVAILABILITY OF AADT DATA

States also reported on the availability of AADT records at sites where pavement marking width is known, as well as the updating practice of AADT values for sites with wider markings. Of the respondents with existing AADT records for roads with 6-inch-wide markings, these records are updated at least once a year according to 67 percent of responses with such data available. The availability of AADT records is shown in Table 6.

Table 6. Availability of AADT Records.

At Sites with Known Pavement Marking Width, Do AADT Records Exist for:	Response
Several years before application date	28%
A time after application date	30%
Percent heavy vehicles	30%
Percent night traffic	12%
How Often Are AADT Values Updated for Roads with 6-Inch-Wide Markings?	
At least once a year	66%
Once every 2 years	17%
Once every 3 years	17%
Once every 5 years	0%
Once every 10 years	0%

PUBLIC RESPONSE TO WIDER LINE USAGE

The public response to the use of wider markings as reported by the state agencies is summarized in Table 7. All 59 percent of respondents, who indicated having received feedback from the public about wider pavement marking deployment, indicated a favorable public response. The results show that the general public provides a positive subjective response to the effectiveness of wider lines. Currently most of the benefits measured by agencies are subjective in nature if any are measured at all. Quantifying the benefits associated with wider markings, especially those used in cost-effectiveness evaluations, has proven to be a difficult task for agencies and researchers alike. The purpose of this research is to improve upon the subjective responses by providing objective values of the effect of wider pavement markings. These objective values may be based on operational or crash studies.

Table 7. Public Response to the Installation of Wider Pavement Markings.

Public Response	Respondents	
	Yes No	
Any public response	59%	41%
Favorable public response*	100%	0%

*Percentage of states that have received public feedback.

FUTURE OUTLOOK FOR WIDER PAVEMENT MARKINGS

Eighteen out of the 22 state agencies using wider markings indicated that they intend to continue using wider markings. Three other states noted that future use of wider markings is subject to performance results from current testing. The remaining state indicated that further use is not deemed necessary due to relatively low traffic volumes. For state agencies planning further use of wider pavement markings, several reasons were given. These reasons have been grouped into general categories, which are included in Table 8.

The reasons given for future implementation are overwhelmingly weighed toward state policy or state trends. This was usually either a policy of the state or a general decision made by state employees to continue implementing wider markings based on a subjective benefit not directly stated. Most of the other reasons were based mainly on a subjective assessment of improved safety and not on traditional objective measures, such as benefit/cost, crash, or service life analyses.

Table 8. Reasons for Continuing Installation of Wider Pavement Markings.

Reasons for Further/Continued Deployment of Wider Markings Observed Benefits	Response*
State policy/state trend	53%
Favorable public response	5%
Improved visibility (subjective)	5%
Improved safety (subjective)	16%
Potential for lower maintenance with higher target value/service life improvement	5%
No response/no reason	16%

*Some respondents provided multiple reasons.

REASONS FOR NOT CURRENTLY USING WIDER PAVEMENT MARKINGS

States that did not currently use wider pavement markings were asked for reasons why they have not implemented them. The following reasons were given for why they are only using the standard 4-inch line width instead of including wider markings:

- budget limitations,
- need for published research or study on safety benefits of wider markings,
- currently improving striping procedures (for standard 4-inch and wet-reflective materials for instance), and
- higher priority on supplementing centerline markings with raised pavement markers.

COMPARISON OF CURRENT WIDER MARKING USAGE WITH PREVIOUS STUDY

Based on the survey responses, 22 out of the 29 states that responded to the survey (approximately 76 percent) were currently using wider markings to an extent for some longitudinal pavement markings (centerline, lane line, and/or edge line). This number was an increase from the 58 percent usage reported by Gates and Hawkins in 2002 (*1*). It should be noted, though, that while the 2002 report had a 100 percent response rate (all 50 DOTs responded), there was a 58 percent response rate for the survey conducted for this report.

Line width usage by state DOTs seemed to follow a similar trend from the previous study (*1*). The majority of state transportation agencies were using 6-inch-wide lines for wider marking applications. There was an increase from 34 to approximately 48 percent of state DOTs who currently use 6-inch-wide lines.

In the earlier research conducted, subjective visibility improvement was the dominant reason for using wider markings across the United States, whereas this survey indicated state trends, experimental studies, and visibility improvements as the main reason for using wider marking stripes (*1*). For both studies, literature review or past research appears to rank very low as reason or basis for implementing wider markings. This is either due to little conclusive research on the subject area or a lack of documented quantifiable benefits based on sound research on wider marking implementation.

In Gates and Hawkins' report, they noted that most of the benefits measured by agencies were subjective in nature, and this seems to still be the practice across the country. Few, if any, quantifiable benefits were cited in the responses to the survey.

TXDOT DISTRICT WIDER PAVEMENT MARKING USAGE

In the fall of 2007, each TxDOT district was called and asked several questions about wider pavement markings. This information was also combined with an internal TxDOT wider pavement marking survey that was conducted the previous year. The results were similar, with only Abilene indicating new usage and Beaumont indicating reduced usage. The results of the survey can be seen in Table 9.

Nine of the 25 TxDOT districts (36 percent) indicated that they have implemented wider pavement markings, representing a usage of 36 percent for TxDOT. All nine districts deployed a 6-inch-wide pavement marking. Of the remaining 16 respondents who do not use wider pavement markings, almost half of them (44 percent) cited budget as a concern for implementing wider pavement markings, while the rest had no problem with using 6-inch-wide pavement markings. Of the nine districts that have implemented wider pavement markings, half of them explicitly indicated their satisfaction with the increased visibility and perceived performance benefits of the wider markings.

Table 9. Texas DOT Districts and Wider Lines Status.

District	Wider Marking Use	Wider Marking Width	Comments
Abilene	Yes	6 inches	Currently uses 6-inch markings on interstate and construction projects.
Amarillo	No	-	Standard 4-inch lines; no problem with 6-inch usage (uses contrast markings on concrete, 4 inches of white with black stripe).
Atlanta	Yes	6 inches	Uses 6-inch lines on Interstate Highway 20 and dashes on Interstate Highway 30; satisfied with implementation.
Austin	Yes	6 inches	Uses both 4- and 6-inch striping where applicable. I-35 is currently being restriped with 6-inch markings as part of a resurfacing project.
Beaumont	Yes	6 inches	Uses 6-inch edge lines on all new construction and new seal coat; TxDOT headquarters to decide on use of 6-inch skips.
Brownwood	No	-	Standard 4-inch lines; only concern with 6-inch usage is budget.
Bryan	No	-	Uses standard 4-inch lines; no problem with 6-inch usage.
Childress	No	-	Uses standard 4-inch lines; no problem with 6-inch usage.
Corpus Christi	No	-	Standard 4-inch lines; only concern with 6-inch line is budget.
Dallas	Yes	6 inches	Deployed 6-inch lines on interstate highways and edge lines; satisfied with implementation.
El Paso	No	-	Uses standard 4-inch lines; no problem with 6-inch usage.
Fort Worth	Yes	6 inches	Deployed 6-inch lines on interstate highways; satisfied with implementation.
Houston	Yes	6 inches	Deployed 6-inch lines on interstate highways and edge lines; satisfied with implementation.
Laredo	No	-	Uses standard 4-inch lines; no problem with 6-inch usage.
Lubbock	Yes	6 inches	Deployed 6-inch skips and 4-inch edge lines; no problem with all 6-inch line application if TxDOT headquarters approves.
Lufkin	No	-	Uses standard 4-inch lines; has budget concerns.
Odessa	No	-	Standard 4-inch lines; only concern with 6-inch usage is budget.
Paris	No	-	Standard 4-inch lines; only concern with 6-inch usage is budget. One site on a two-lane highway (no shoulders) has 6-inch lines.
Pharr	No	-	Uses standard 4-inch lines; no problem with 6-inch usage.
San Angelo	No	-	Uses standard 4-inch lines; no problem with 6-inch usage.
San Antonio	No	-	Uses standard 4-inch lines (performance-based 4-inch striping effective for 5 years for Flasher); no problems with 6-inch usage.
Tyler	No	-	Standard 4-inch lines; only concern with 6-inch usage is budget.
Waco	No	-	Has three or four sites with 6-inch lines and will continue to go that direction in the future on freeways.
Wichita Falls	Yes	6 inches	Deployed 6-inch lines in Gainsville on I-35; very bright; future construction to use 6-inch lines.
Yoakum	No	-	Uses standard 4-inch lines, no problem with 6-inch usage.

CHAPTER 4
INDEPENDENT CRASH ANALYSIS

Longitudinal pavement markings provide a continuous stream of information to road users by assisting them in selecting the appropriate lane and maintaining the appropriate lane position. This is true in both day and night conditions. It seems logical that increasing marking visibility will better enable drivers to maintain the appropriate lane position and to see and react to changes in road alignment earlier, resulting in an improvement in safety. In recent years, the use of wider pavement markings has been one method by which transportation engineers have tried to increase safety since it is believed that wider pavement markings benefit drivers by increasing the visibility of the pavement markings.

Across the United States, the use of 4-inch markings is the basic application, with wider lines being used when deemed necessary. As part of a study conducted in 2001 the results from a nationwide survey indicated that 58 percent (29 states) use wider pavement markings to some degree (*1*). All 50 states responded to this survey, providing a solid baseline for establishing usage. The survey results also indicated that the various states' primary reason for the use of markings wider than 4 inches was to improve visibility and thereby improve safety.

The 2001 study also found that there is limited research on the safety effects of using wider edge line markings. The existing research does not provide conclusive results on the benefits of wider markings, and the results of various studies often conflict. Despite these inconclusive findings, the survey summarized in the previous chapter shows that the use of wider pavement markings in the United States is on the rise.

This chapter presents preliminary findings from an ongoing study evaluating the effectiveness of wider edge lines in the United States (*16, 40*). While there are several objectives of the study, this chapter describes the findings related to the safety of edge lines on two-lane highways. Under the larger study, additional work is being completed on other aspects of pavement markings, including the safety of wider edge lines on other facility types such as freeways and expressways.

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

DATA COLLECTION

An electronic survey was distributed to identify states that install pavement markings wider than 4 inches on all or some of their state-owned highways. It was sent through several different media, including:

- a list of state transportation agency representatives manually developed using rosters for the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Safety Management and Subcommittee on Traffic Engineering, as well as other research team contacts with pavement marking responsibilities;
- the listserv for the AASHTO Subcommittee on Traffic Engineering;
- the listserv for the Institute of Transportation Engineers (ITE) Traffic Engineering Committee;
- the listserv for the National Committee on Uniform Traffic Control Devices (NCUTCD) Markings Technical Committee; and
- the listserv for the Transportation Research Board (TRB) Traffic Control Devices Committee.

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

- locations (by route number and linear reference) of the wider pavement markings could be determined;
- use of wider pavement markings was extensive on roadway segments (i.e., not spot treatments, such as isolated to horizontal curves with high crash rates);
- approximate dates of wider pavement marking installation were known; and
- sufficient crash, traffic, and roadway databases existed in formats that could be merged with each other and with pavement marking information.

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

Illinois Data

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

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

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

1. total number of crashes,
2. total number of fatal plus injury (F+I) crashes,
3. total number of PDO crashes,
4. total number of daytime crashes,
5. total number of nighttime crashes,
6. total number of daytime fatal plus injury crashes,

7. total number of nighttime fatal plus injury crashes,
8. total number of wet weather crashes,
9. total number of wet and nighttime crashes,
10. total number of single vehicle crashes,
11. total number of single vehicle and wet crashes,
12. total number of crashes with at least one driver 55 years of age or older,
13. total number of opposite direction crashes (includes opposite direction sideswipe and head-on collisions), and
14. total number of fixed object crashes.

Roadway segments and associated crash counts for rural two-lane highways were identified using area type and roadway classification indicators. Rural two-lane segments coded with the presence of traffic signals, stop signs, or yield signs were deleted from the database to minimize the influence of intersection presence on the analysis. Additional segments coded as having extremely short segment lengths or atypical rural two-lane highway features (e.g., medians and auxiliary lanes) were also eliminated. Finally, segments that showed any change in physical features during the observation period (2001 through 2006) were deleted to try and minimize the influence of any major reconstruction project on the analysis results. The final rural two-lane data set for Illinois consisted of 3,439 segments (1,581.1 miles): 2,810 segments (1,321.4 miles) with 4-inch-wide edge lines and 629 segments (259.7 miles) with 5-inch-wide edge lines. Six years of data (2001 through 2006) were available for each segment. Descriptive statistics for the primary segment variables considered in the analysis are summarized in Table 10 and Table 11.

Table 10. Descriptive Statistics for Continuous Illinois Segment Variables.

Segment Variable	2,810 Segments (1,321.4 Miles) 4-Inch-Wide Edge Lines			629 Segments (259.7 Miles) 5-Inch-Wide Edge Lines		
	Minimum	Maximum	Average	Minim um	Maximum	Average
Length (miles)	0.12	5.45	0.47	0.12	2.51	0.41
ADT (vehicles per day)	100	25,900	3,300	100	11,100	2,180
Daily commercial traffic (trucks per day)	0	4,500	390	0	1,000	260
Lane width (feet)	8	16	11.7	9	16	11.5
Shoulder width (feet)	0	14	6.5	0	12	5.9
Paved shoulder width (feet)	0	12	3.7	0	12	4.3

Table 11. Descriptive Statistics for Categorical Illinois Segment Variables.

Segment Variable	2,810 Segments (1,321.4 Miles) 4-Inch-Wide Edge Lines		629 Segments (259.7 Miles) 5-Inch-Wide Edge Lines	
	Frequency	Percent	Frequency	Percent
Posted speed = 25 mph	1	< 0.1	1	0.2
Posted speed = 30 mph	43	1.5	16	2.5
Posted speed = 35 mph	80	2.8	27	4.3
Posted speed = 40 mph	72	2.6	14	2.2
Posted speed = 45 mph	116	4.1	34	5.4
Posted speed = 50 mph	76	2.7	8	1.3
Posted speed = 55 mph	2422	86.2	529	84.1
Presence of horizontal curve sharper than 2.5 degrees of curvature	223	7.9	44	7.0

Michigan Data

Michigan edge lines were 6 inches wide on all state-owned roadways without curbs and gutters. The change was made from 4-inch-wide edge lines on almost all of the state-owned systems during 2004. A Michigan Department of Transportation (MDOT) pavement marking engineer estimated that 6-inch-wide edge 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-inch to 6-inch-wide edge lines minimizes the concern of selection bias or regression to the mean. However, it also does not allow a before-after analysis using comparison sites within the same state. The research team examined several comparison site alternatives. Additional detail is provided in the analysis section below.

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

Roadway segments and associated crash counts for rural two-lane highways were identified using an area type indicator and a variable for total number of through lanes. Similar data screening techniques and criteria as those employed for Illinois data were used for Michigan, including those for intersections, atypical rural two-lane highway features, and observed changes in physical features during the observation period. The final rural two-lane data set for Michigan consisted of 253 segments (851.5 miles). Each segment was observed for three years with 4-inch-wide edge lines (2001–2003) and two years with 6-inch-wide edge lines (2005–2006). Descriptive statistics for the primary segment variables considered in the analysis are summarized in Table 12 and Table 13.

Table 12. Descriptive Statistics for Continuous Michigan Segment Variables.

Segment Variable	253 Segments (851.5 Miles) 4-Inch-Wide Edge Lines for 3 Years 6-Inch-Wide Edge Lines for 2 Years		
	Minimum	Maximum	Average
Length (miles)	0.04	12.69	3.37
ADT—before period	197	17,633	4,497
ADT—after period	299	18,597	4,433
Daily commercial traffic (trucks per day)	20	2,100	360
Lane width (feet)	10	12	11.5
Shoulder width (feet)	3	12	8.1
Paved shoulder width (feet)	0	11	4.2

Table 13. Descriptive Statistics for Categorical Michigan Segment Variables.

Segment Variable	253 Segments (851.5 Miles) with 4-Inch-Wide Edge Lines for 3 Years and 6-Inch-Wide Edge Lines for 2 Years	
	Frequency	Percent
Posted speed = 25 mph	5	2.0
Posted speed = 30 mph	1	0.4
Posted speed = 35 mph	4	1.6
Posted speed = 40 mph	3	1.2
Posted speed = 45 mph	10	4.0
Posted speed = 50 mph	4	1.6
Posted speed = 55 mph	226	89.3
Level terrain	165	65.2
Rolling terrain	88	34.8

DATA ANALYSIS

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

Cross-Sectional Analysis of Illinois Data

In Illinois, data screening reduced the rural two-lane data set to 3,439 segments (1,581.1 miles) consisting of 2,810 segments (1,321.4 miles) with 4-inch-wide edge lines and 629 segments (259.7 miles) with 5-inch-wide edge lines. Crashes occurring at the segments with 4-inch-wide edge lines were compared to crashes occurring at the segments with 5-inch-wide edge lines. Table 14 shows the average crash rates computed as crashes per million vehicle miles of travel averaged over the segments considered in the study.

The crash rates shown in Table 14 might be useful if all the segments included in the study were identical except for edge line width, segment length, and traffic volumes (ADT), and also if crashes increased linearly with ADT. However, the road segments were different not only in edge line width, segment length, and ADT, but also in lane width, shoulder width, presence of curves, etc., and the relationship between crashes and ADT 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-inch and 5-inch-wide edge line segments shown in Table 14.

Table 14. Average Crash Rate Illinois Rural Two-Lane Highways.

Edge Line Width (Inches)	**4**	**5**
Number of Segments	2,810	629
Total Segment Length (Miles)	1,321.4	259.7
Crash Type[a]		
Total	1.76	1.86
Fatal injury	0.44	0.33
PDO	1.32	1.53
Daytime	0.74	0.64
Nighttime	0.87	0.98
Daytime fatal injury	0.26	0.19
Nighttime fatal injury	0.15	0.13
Wet	0.19	0.14
Wet and nighttime	0.10	0.08
Single vehicle	1.31	1.55
Single vehicle and wet	0.14	0.12
Older driver	0.40	0.38
Opposite direction	0.04	0.05
Fixed object	0.34	0.30

[a] Measured in million entering vehicles per 1-mile segment.

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

$$\mu_i = \exp(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_k X_{ki}) \qquad \text{Equation 1}$$

where μ_i is the expected number of crashes at segment i, X_{1i}, …, X_{ki} are the covariates/predictors corresponding to roadway characteristics of segment i, and β_0,, β_1, β_2,…, β_k are the regression coefficients. A model that included edge line width, lane width, shoulder width, presence of horizontal curve (1: present, 0: not present), and log of ADT as predictors and the log of the segment length as an offset variable provided the closest fit to the Illinois data.

Table 15 shows the estimates of the negative binomial regression model coefficients. The regression coefficient for edge line width was negative and statistically significant at $\alpha = 0.05$, which indicates a positive safety effect of wider edge lines (i.e., a smaller number of crashes is associated with wider edge lines) for the following crash types: fatal and injury (−0.3555), daytime (−0.1710), daytime fatal and injury (−0.3684), nighttime fatal and injury (−0.2900), wet (−0.2953), single vehicle and wet (−0.2560), and fixed object (−0.2808) crashes. It can also be observed that the signs of the coefficients for lane width, shoulder width, log of ADT, and curve presence are consistent with intuition. For example, the negative signs of lane width and shoulder width coefficients imply that crashes tend to decrease as lane width or shoulder width increases, and the positive sign of curve presence implies that crashes tend to increase when there is a curve or curves as compared to when there is no curve.

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

Table 15. Estimates of Regression Coefficients[a,b,c,d] of the Negative Binomial Regression Model Applied to Illinois Rural Two-Lane Highway Crash Data.

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

[a] Crash data from 3,439 Segments (1,581.1 Miles) aggregated for six years.
[b] Significant (at α =0.05) effects are shown in **bold**.
[c] An asterisk (*) indicates there was an extreme outlier in the opposite direction crash data for a 0.27-mile segment with 5-inch edge lines, which greatly affected an estimate of the edge line width coefficient for opposite direction crashes. When this outlier was removed, the opposite direction coefficient for edge line width changed from 0.3295 to 0.1768 and became insignificant.
[d] DF stands for degrees of freedom.

Before-After Analysis of Michigan Data

In Michigan, changes to 6-inch-wide edge lines occurred in 2004 for about 95 percent of road segments statewide. Before-after evaluations were conducted with three years (2001–2003) of before and two years (2005–2006) of after data obtained from 253 segments corresponding to 851.5 miles of rural two-lane highways. Crashes that occurred during the before period were compared to crashes that occurred during the after period. Table 16 shows the average crash rates computed as crashes per million vehicle miles of travel averaged over the segments considered in the study for each of the before and after periods. Table 16 shows that crash rates decreased overall. However, this direct comparison of before and after crash rates is valid only when it can be absolutely assured that there have been no changes from before to after periods other than edge line width and traffic volumes, and that the relationship between crashes and traffic volumes is linear. As a matter of fact, both of these assumptions are often violated when the crash data of multiple years are analyzed. There will almost always be changes over time in weather, vehicle fleet, driver characteristics, economic conditions, etc., and crashes may increase with traffic volume in a nonlinear fashion.

To distinguish the effect of edge line width from the effects of other factors that might have also changed from the before to the after period, an advanced statistical before-after evaluation method known as the empirical Bayes approach for safety evaluation was employed (*41*). The empirical Bayes method estimates changes in crashes (due to wider edge lines) by comparing the observed number of after-period crashes to the predicted number of crashes during the after period that would have occurred had wider edge lines not been installed, rather than to the observed number of before-period crashes. Predicted crash frequencies by the empirical Bayes method are obtained in such a way that they account for a potential nonlinear relationship between crashes and traffic volume (through the regression function called the safety performance function [SPF]) as well as changes in general underlying trends caused by extraneous factors such as weather, vehicle fleet, driver characteristics, etc., between the before and after periods.

The SPF, which describes the relationship between crashes and traffic volume as well as other roadway characteristic variables such as lane width, shoulder width, terrain, etc., were derived from the before-period Michigan data. The changes in general trend would typically have been estimated based on crash counts from road segments on which edge line width remains at 4 inches throughout the study period. Because no such segments remained in Michigan, due to statewide installation of 6-inch edge lines during the study period, an alternative approach of deriving the trend factor based on another entity set was taken in which the general trend between the before and after periods was derived from the Illinois fatal and injury crash data obtained from rural two-lane segments with 4-inch-wide edge lines (*42*). Using the Illinois data to provide a comparison group yielded results that are comparable to the cross-sectional analysis conducted with the Illinois data. Additional analyses are being conducted to further verify this approach.

Table 16. Average Crash Rate of Michigan Rural Two-Lane Highways for Before (2001–2003) and After (2005–2006) Period.

Number of Segments	253	
Total Segment Length	851.5	
Period Before		**After**
Crash Type[a]		
Total	3.06	3.00
Fatal injury	0.44	0.40
PDO	2.63	2.60
Daytime	1.29	1.22
Nighttime	1.41	1.41
Daytime fatal injury	0.29	0.25
Nighttime fatal injury	0.12	0.12
Wet	0.28	0.24
Wet and nighttime	0.14	0.12
Single vehicle	2.26	2.24
Single vehicle and wet	0.21	0.19
Single vehicle and nighttime	1.29	1.29
Opposite direction	0.08	0.07

[a] Measured in million entering vehicles per 1-miles segment.

Table 17 presents the result of empirical Bayes before-after evaluations based on the crash data from 253 segments (851.5 miles) of Michigan rural two-lane highways. The table shows the observed number of after crashes over 253 segments, the predicted number of crashes during the after period that would have occurred without installing wider edge lines, and an estimate of the percent change in crashes from the before to the after period. All of these crash reduction estimates, except for nighttime, single-vehicle, and single-vehicle nighttime crashes, were statistically significant at the 95 percent level.

Table 17. Empirical Bayes Before-After Safety Evaluations Based on Michigan Rural Two-Lane Highway Crash Data.

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

[a] Crash data with three years of before and two years of after data obtained from 253 Segments (851.5 Miles) of rural two-lane highways.
[b] Statistically significant results (at 95% confidence level) are shown in **bold**.

SUMMARY

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

- For Illinois, the negative binomial regression analysis based on the crash data aggregated for six years resulted in positive safety effect estimates for the following types of crashes:
  - fatal and injury,
  - daytime,
  - daytime fatal and injury,
  - nighttime fatal and injury,
  - wet,
  - single vehicle and wet, and
  - fixed object.

- For Michigan, an empirical Bayes before-after evaluation resulted in positive safety effect estimates for the following types of crashes:
  - total,
  - fatal and injury,
  - PDO,
  - daytime,
  - daytime fatal and injury,
  - nighttime fatal and injury,
  - wet,
  - wet and nighttime,
  - single vehicle and wet, and
  - opposite direction.

CHAPTER 5
RESEARCH DESIGN AND DESCRIPTION

The research described in this chapter was conducted to quantify the potential benefit of wider edge line pavement markings using operational metrics and eye-tracking data. The goals of this research were to: 1) identify any benefit of wider edge line pavement markings with respect to vehicle lateral position and/or eye tracking and 2) see if pavement marking brightness impacted these same measures of effectiveness.

OVERVIEW

Nighttime driving data (i.e., vehicle lateral placement, vehicle speed, and eye-tracking data) were collected through several horizontal curves at the Texas A&M University Riverside Campus facility (see Figure 4). The horizontal curves varied with respect to geometry, pavement marking width of the edge line, and pavement marking brightness. Data were also collected along tangent segments. The variety of horizontal geometries and pavement marking widths warranted the need for this study to be conducted in two phases. The first phase exposed study participants to 4-inch and 6-inch-wide edge line pavement markings. The second phase exposed study participants to 6-inch and 8-inch-wide edge line pavement markings. As shown in Figure 1, the researchers intended to describe the relationship between pavement marking width and brightness with regard to their impact on driver performance while navigating a variety of horizontal curves and tangent segments.

Figure 4. Riverside Campus.

PROCEDURE

Participants were scheduled to drive through a closed course route at the Riverside Campus. The participants were met at the entrance to the Riverside Campus by TTI staff and then escorted to an office where they completed an informed consent form, a demographics questionnaire, and a visual-acuity test. All of the testing was conducted at nighttime.

Prior to starting the study, the participants completed a few additional tasks. First, they were given some brief instructions about what was required of them. Provided they did not have any reservations about conducting the tasks described to them, a participant was then escorted to the instrumented vehicle (see Figure 5). The instrumented vehicle contains several pieces of state-of-the-art equipment required for the study.

Figure 5. Instrumented Vehicle.

Only one participant at a time was tested because there was only one instrumented vehicle and eye-tracker. The eye-tracker is a device designed to quantify where participants look or fix their gaze while driving. Once in the vehicle, the participant was instructed to make the necessary adjustments to the mirrors, seat, and climate controls. The radio was turned off during all of the testing. After the participant was comfortable, the eye-tracker was calibrated.

Once the calibration was complete, study participants were directed to the study course to start data collection. The data collection consisted of having the study participant drive through several horizontal curve segments, tangent segments, and lane shift segments. Several laps were conducted through the study course to obtain a complete sample of data, whereby each participant viewed all of the study segments at least once in both directions and under two different marking brightness levels. Two levels of marking brightness were created by adjusting the headlight illumination of the study vehicle.

The participants were instructed to indicate the direction of each horizontal curve (i.e., left or right) and to read the legends of several study signs. The legibility task was meant to minimize the likelihood of the study participants looking down at the pavement markings by giving the study participants a long-range driving task. It also enabled the researchers to avoid alerting the study participant to the fact that the real purpose of the study was to see how wider and/or brighter edge line pavement markings affected their driving, thus minimizing potential bias. The researchers considered using the curve detection data as another potential MOE; however, the methods used to collect the curve detection data and the secondary task data did not allow for these data to be reduced. The data collection took approximately one hour to complete for each participant.

Course Layout

Each study participant drove through at least eight different horizontal curves in both directions and with at least two different headlight illumination levels. The curve characteristics are detailed in Table 18. In general, there were four horizontal curves with 500-ft radii and four with 200-ft radii. All of the 500-ft-radius curves had approximately 45-degree deflection, while the 200-ft-radius curves were split, with two at approximately 45-degree deflection and two at 90-degree deflection. Each of the curves consisted of edge lines and a double solid centerline with an average lane width of 12 ft. These curves were striped on the Riverside Campus runways (see Figure 6).

The 4-inch and 6-inch-wide edge line segments are also indicated in Table 18. All 6-inch segments were restriped with 8-inch-wide edge lines in the second phase, and a portion of the 4-inch-wide segments were restriped with 6-inch-wide edge lines in the second phase of the study. This allowed for a direct comparison between 4 versus 6 inches and 6 versus 8 inches. Curve 8 was a curve with 4-inch-wide edge lines that was restriped with 8-inch-wide edge lines to investigate if a more noticeable change in lateral placement resulted. Curve 1 was left with 4-inch-wide edge lines throughout the study to test for a heuristic effect.

In addition to the horizontal curves, gradual lane shifts were added (see Figure 6 and Table 19). It was believed that wider edge lines may also help drivers better assess gradual changes in alignment. In one direction, a study participant would shift left, right, right, and left over approximately 0.5 miles. In the opposite direction, he/she would shift right, left, left, and right over approximately 0.5 miles. The purpose of a gradual lane shift was to ensure that the study participant would be unable to view the complete alignment shift under nighttime illumination. All tangent segments were 500 ft long. Tangents 2 through 6 were used to assess the impact of wider edge lines on gradual alignments changes. The adjacent 250-ft segments of tangent 7 and 8 were combined to form the 500-ft tangent 7'. It was decided to stripe tangent 7 and 8 in the same manner, so there was no need to have two separate tangent segments and they were combined to form tangent 7'. Tangent 7' was initially striped with 4-inch-wide edge lines, and then, restriped with 8-inch-wide edge lines to investigate if a more noticeable change in lateral placement resulted. Tangent 9 was left with 4-inch-wide edge lines throughout the study to test for a heuristic effect. Tangent 1 was not reduced.

The researchers conducted pilot studies to determine the amount of lane shift that would not be perceptible to study participants. The researchers selected a conservative lane shift of 2 ft from the original alignment over a distance of 750 ft. The effective pavement marking visibility was about 400 ft headlights with the study vehicle's headlights in low beam position.

Table 18. Curve Geometry.

Curve	Radius (Feet)	Deflection Angle (Degrees)	Marking Width (Inch/Inch)*
1	500	45	4/4 (Control)
2	200	90	6/8
3	500	45	4/6
4	200	45	6/8
5	500	45	6/8
6	200	90	4/6
7	200	40	4/6
8	500	50	4/8

*Indicates that for value *b/a* the marking width was *b* in the first phase and *a* in the second phase. Also, curve 1 served as a control curve between the two phases.

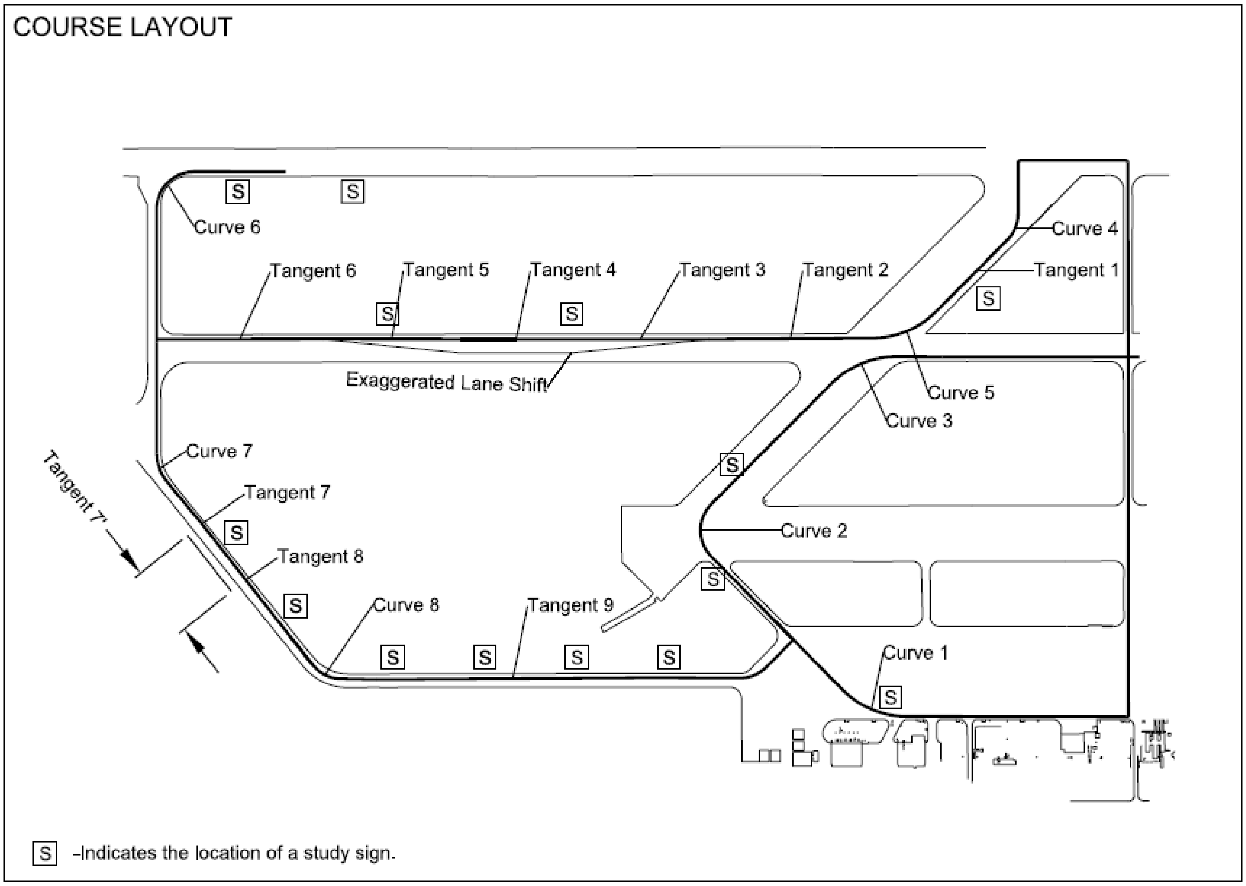


Figure 6. Study Course Layout.

Table 19. Tangent Geometry.

Tangent[a]	Condition	Marking Width (Inch/Inch)[b]
1	Normal	6/8
2	Normal	6/8
3	Lane shift	6/8
4	Transition	6-4/8-6
5	Lane shift	4/6
6	Normal	4/6
7'	Normal	4/8
9	Normal	4/4 (control)

[a]Indicates that tangent 7 was the center, 500 ft between tangents 7 and 8.
[b]Indicates that for value *b/a* the marking width was *b* in the first phase and *a* in the second phase. Also, tangent 9 served as a control tangent between the two phases, and tangent 4 was a transition tangent between 6- and 4-inch-width edge lines for the first phase and 8- and 6-inch-width edge lines for the second phase.

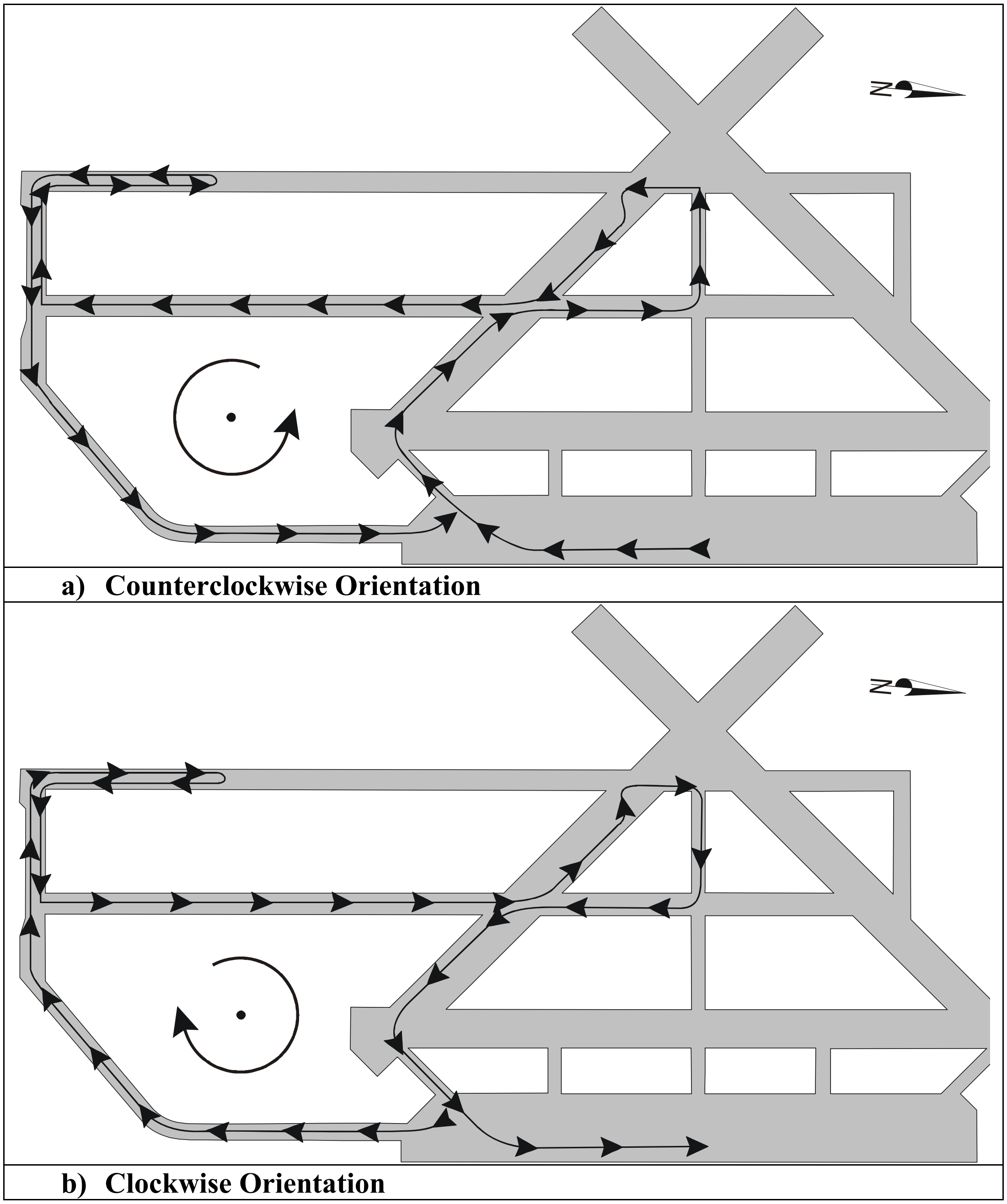
The edge line pavement markings were striped with a standard paint at approximately 7 mil dry thickness with AASHTO M247 beads that achieved a retroreflectivity value of approximately 200 $mcd/m^2/lx$ for the white edge lines and approximately 150 $mcd/m^2/lx$ for the yellow centerlines. The headlights were then adjusted using pulse width modulation to obtain a marking brightness approximately half the luminance under normal low-beam original equipment manufacturer (OEM) illumination. The adjustment in the headlights did not change the headlight lighting distribution or color temperature. From this point forward, the lighting levels will be referred to as "normal" and "half" for the normal low-beam OEM level and the adjusted headlight level, respectively. Nighttime images of the two different lighting conditions are in Figure 7.

a) Normal Light Level **b) Half Light Level**

Figure 7. Sample Headlight Illumination Images.

Course Route

The entire course was approximately 5 miles long. Each participant completed four total laps. There were four different combinations of individual laps that were used to change the order that study participants saw each lap and curve combination and lighting level. Each lap differed by whether the study participant started driving through the course in one direction or the other. Figure 8 contains two possible course routes.



a) Counterclockwise Orientation

b) Clockwise Orientation

Figure 8. Example Course Routes.

EQUIPMENT

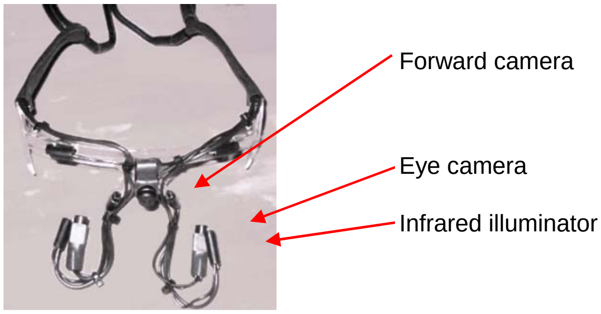
The primary pieces of data collection equipment were the eye-tracker and the instrumented vehicle.

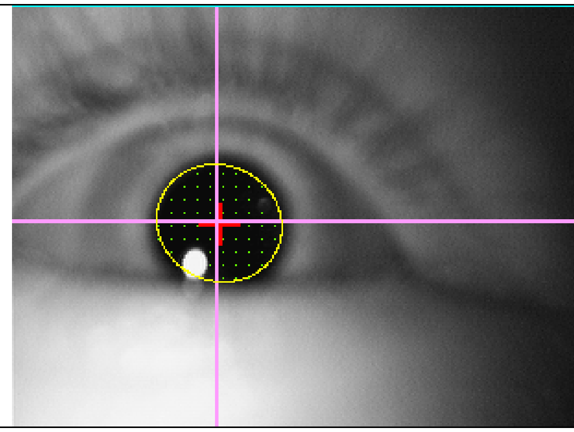
Eye-Tracker

The ViewPoint EyeTracker® combined video data and eye-tracker data. The eye-tracker is depicted in Figure 9a, with the various components of the system listed. The video data were collected using a forward-facing miniature video camera attached to the eye-tracker at 30 frames per second (30 Hertz). The eye-tracker fixations were captured through two additional miniature video cameras at 60 Hertz. Two infrared lights were used in conjunction with the eye-tracker cameras to illuminate the iris of a study participant's eyes (see Figure 9b). It was the point of convergence of the two illuminated irises, the point where a study participant was fixating, that was overlaid with a red dot onto the video from the forward-facing video camera. The images in Figure 9c show a progression from left to right of an example of a study participant looking at a sign in the distance and then moving his fixation off the sign to the next sign. The ability of the eye-tracker to accurately record a study participant's eye fixations was the direct result of the calibration procedure described in the previous section.

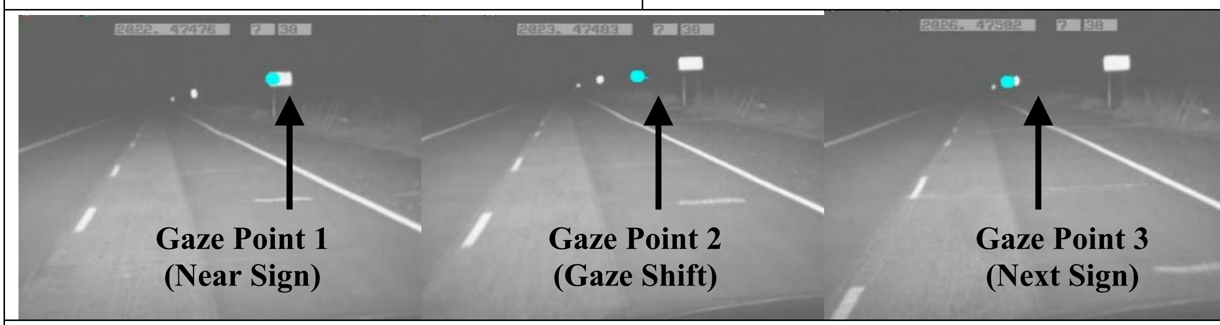
The eye-tracker required a few additional pieces of equipment to gather all of the data required for the study. There was a distance-measuring instrument (DMI), a customized DMI control box, video titling equipment, and a laptop computer.

The DMI was integral to the data collection because it provided the experimenter with an easily quantifiable relationship between the eye-tracker data and a study participant's proximity to test treatments. The DMI generated distance measurements from electronic pulses sent to the device from transmission sensors. For every revolution of the transmission flywheel, there are six electronic pulses and a specific number of revolutions of the tires. This relationship was quantified through a DMI calibration procedure, and then travel distances were measured with the DMI to within 1 ft per mile traveled. The customized DMI controller converted the distance data output from the DMI and exported it to the video titling equipment. Distance data were overlaid into the recorded eye-tracker footage in real time at 10 Hertz as the data were exported to the laptop. The refresh rate of 10 Hertz was the limiting factor for the data collection, but this rate was considered acceptable. An example of the final image is shown in Figure 9c.





a) Eye-Tracker b) Iris Tracking

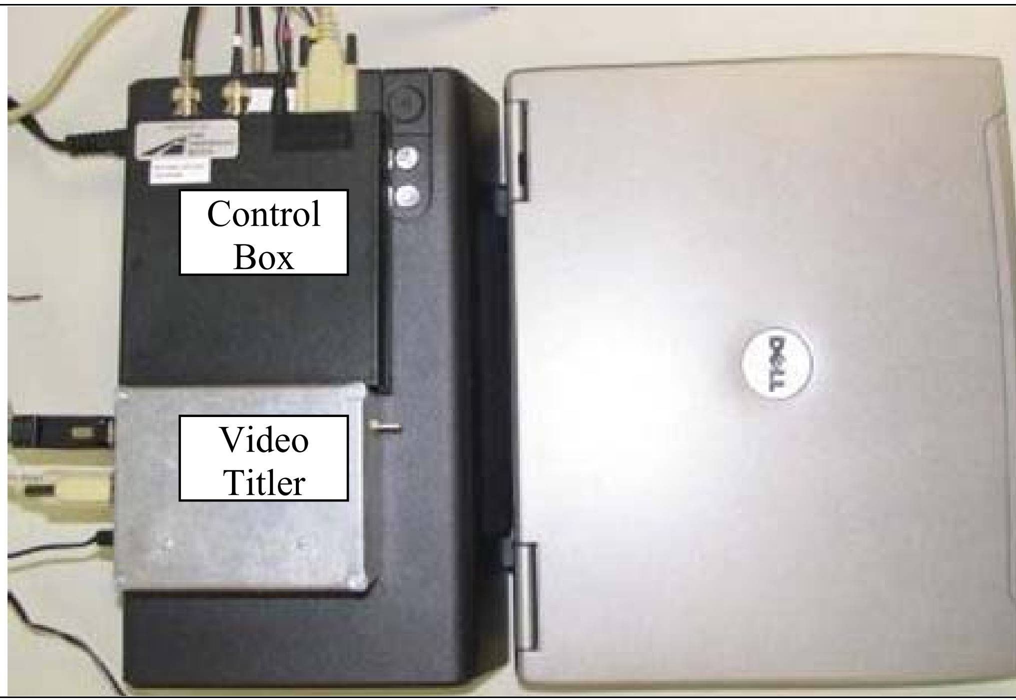


c) Typical Eye-Tracker Glance

Figure 9. Eye-Tracker.

The laptop operated the eye-tracker and stored the incoming data simultaneously. The laptop was actually attached to a docking station to incorporate the different pieces of hardware such as the video card needed to import the video data (see Figure 10). The video files were around 1 Gigabyte of data for every minute, so an external backup storage device was also connected to the laptop through the docking station. This allowed for data to be backed up nightly between study participants to minimize the loss of data from equipment problems. This also improved the portability of the data from the field data collection back into the office to another set of backup drives, which would also allow other staff to start reducing already collected data throughout data collection.

a) DMI



b) Laptop, DMI Control Box, and Video Titler

Figure 10. Additional Equipment Used with the Eye-Tracker.

Instrumented Vehicle

The TTI instrumented vehicle was a 2006 Toyota Highlander that had been upgraded with several different state-of-the-art sensors (see Figure 11). The heart of the instrumented vehicle was a Dewetron DEWE5000 data acquisition system (DAS) that had several different sensory inputs that could be programmed for different devices. One device was the Trimble DSM 232 system that used a single frequency antenna to gather global positioning system (GPS) data at a rate of 10 readings per second, or 10 Hertz. This device also had sub-meter accuracy.

Three video feeds relayed video data directly into the DAS. Lateral position data were collected using a video camera mounted on the driver side of the vehicle, and those data were recorded by the DAS. The video data collected using the eye-tracker was also ported into the DAS. The third video camera recorded the forward view in front of the instrumented vehicle to continuously capture the forward view regardless of where the study participant was looking. As the DAS simultaneously recorded GPS data, all the data recorded by the DAS were geocoded.

The headlight controller depicted in Figure 11 was tied directly into the instrumented vehicle, but it was not connected to the DAS. The headlight controller regulated the power that reached the OEM low-beam headlights through pulse width modulation. The use of pulse width modulation ensured that the light from the headlights did not shift in color or temperature.

a) DEWE5000

b) Trimble DSM 232

c) In-Vehicle Setup

Figure 11. Study Vehicle Instrumentation.

Experimental Factors

Each study participant drove through each scenario at least once, and the order was counterbalanced to minimize the likelihood of heuristic responses.

The study factors are detailed as follows:

- dependent variables
  - lateral position (with respect to the centerline pavement markings)
  - encroachments
  - speed
  - eye glances (quantity and duration of glances at the right edge line markings within a study region, i.e., horizontal curve, taper, or tangent segment)
- independent variables
  - edge line pavement marking width
    - 4-inch
    - 6-inch
    - 8-inch
  - marking brightness (retroreflectivity, simulated using two light levels)
    - half light level (~100 mcd/m^2/lx)
    - normal light level (~200 mcd/m^2/lx)
  - geometry
    - horizontal curves
      - curve radius (two levels)
        - 500 ft
        - 200 ft
      - deflection angle (two levels)
        - 45 degrees
        - 90 degrees
    - tangents
      - standard
      - lane shift
        - right
        - left
  - study participant

DATA REDUCTION

There were two primary data reduction tasks completed on this project. The first effort was in reducing the lateral position and speed data. In the second effort, the researchers reduced the eye-tracker data. Both efforts required identifying common reference points to ensure that the lateral position data could be synchronized with the eye-tracker data.

The researchers created a merged data set from various pieces of data. All of the data collected through the DAS was geocoded. The researchers separately recorded GPS points of interest associated with specific treatment locations, such as the starting and ending points of horizontal curves and tangent segments along the study course. A routine was developed using MATLAB to extract time stamps from the DAS data sets from the GPS points of interest. The researchers then created a macro that used the time stamp data from the DAS to populate a spreadsheet with the following base data: 1) time stamp, 2) GPS coordinates, and 3) vehicle speed. With these data the researchers were then able to merge the treatment (i.e., edge line marking width and roadway geometry), lap (i.e., which lap and lighting level), and subject demographic information (i.e., age and visual acuity) to the DAS data. The researchers used the merged data set when reviewing the video data from the DAS to manually extract the lateral position data and the time stamp data associated with the eye-tracker.

A separate time stamp associated solely with the eye-tracker data was recorded to be used later in reducing the eye-tracker data. This was done because the video data from the eye-tracker recorded into the DAS did not include the overlaid eye-tracker tracking gaze. The amount of computer processing power required to continually record eye-tracker data requires a separate computer to record a forward-facing video camera feed and superimpose the eye-tracking gaze. The researchers used a video titler to overlay time stamp data into the forward-facing video camera feed prior to importing into the eye-tracker computer. It was able to simultaneously record this video feed in the DAS, which guaranteed that the vehicle data, lateral position data, and eye-tracker data could be directly related with respect to time.

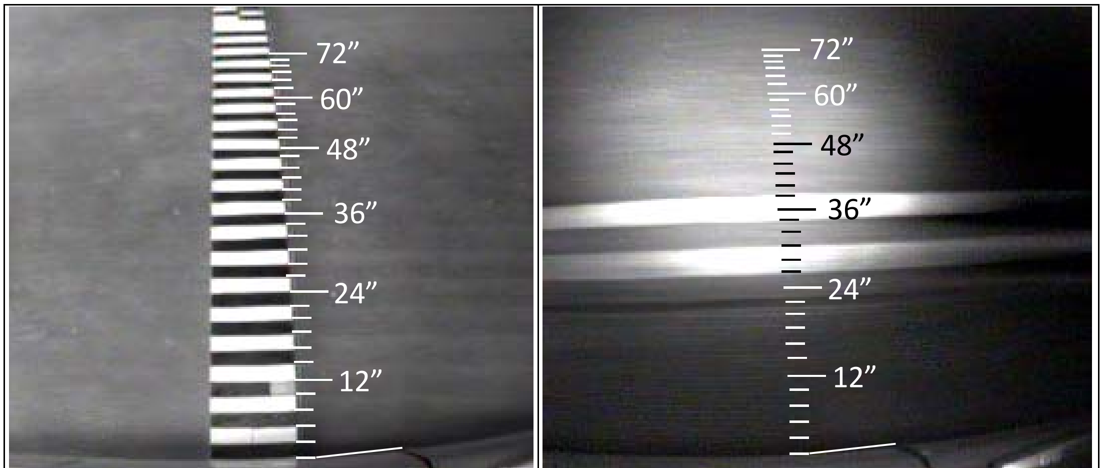
Lateral Position Data Reduction

Once the merged data set was created, the lateral position data reduction procedure required two additional steps. The first step focused on creating a lateral position video overlay to measure lateral position. The second step was advancing through each lateral position video to the extracted time stamps associated with the DAS data and measuring the lateral offset.

The lateral position video overlay was created from a calibration procedure conducted at least once every night of data collection. At least once a night, an 8-ft-long board marked in 2-inch increments out to 80 inches was placed perpendicular to the back driver-side tire and recorded onto the DAS using the lateral position video camera (see Figure 12a). A piece of silver tape was placed on the mark covering the range of 10 to 12 inches as a reference point and to remind the reviewer that the side of the vehicle occluded the first 2 inches of the board. As a result, the researchers assumed any marking occluded by the side of the vehicle indicated an encroachment on the marking. It should also be noted that while the board was 8 ft long, it was decided to only mark the board out to 80 inches (6 ft 8 inches) because the study vehicle would start encroaching on the right edge line if the inside edge of the centerline was beyond 69 inches, based on the width of the lane and the width of the study vehicle. The researcher reducing the lateral position data then marked off the 2-inch increments on a transparency placed over the monitor used to review the video data. Figure 12b shows an example of the overlay, and for this particular image a value of 26 inches was recorded for the lateral position. Black and white were used for this overlay for viewing purposes in this document, but the actual overlays used in the measurements were all black because the black provided a better contrast with the illuminated background. With the ability to discern the halfway mark in-between each mark, the 2-inch increments allowed for accuracy to 1 inch. The lateral position data were added directly into the merged data set.

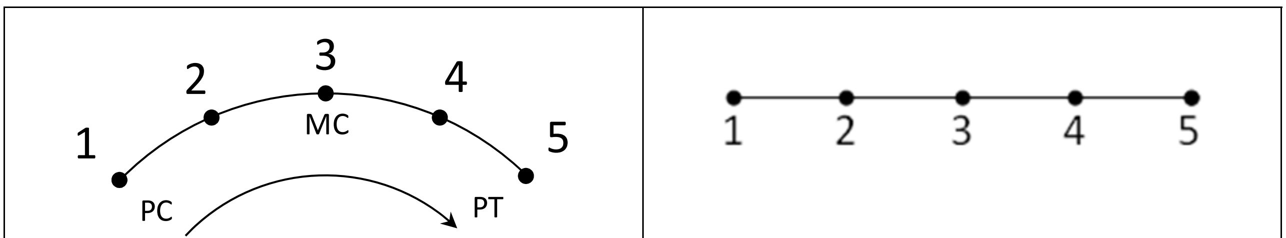
Lateral position data were collected at five points along horizontal curves and tangents (see Figure 13). The first and last points always corresponded with the start and end of a study segment, such as the point of curve (PC) and the point of tangent (PT) for the curves. Then, lateral position data were also collected at three equidistant points within the study segment. For example with the horizontal curve condition, one point was at the midpoint of curve (MC), and then two additional points between the PC and MC and the MC and PT were selected. The tangent segments were all 500 ft long, and that resulted in five points with four 125-ft segments between each point. The lengths of the horizontal curves varied, and so the distances between these points varied from horizontal curve to horizontal curve. For instance, two curves had a

500-ft radius with a 45-degree deflection, which resulted in segment lengths of 88 ft, while two other curves had a 200-ft radius with 90-degree deflection, resulting in 78.5-ft segment lengths.



a) Calibration Setup | **b) Measurement Setup**

Figure 12. Lateral Position Data Reduction Scale.



a) Curve Points of Interest | **b) Tangent Points of Interest**

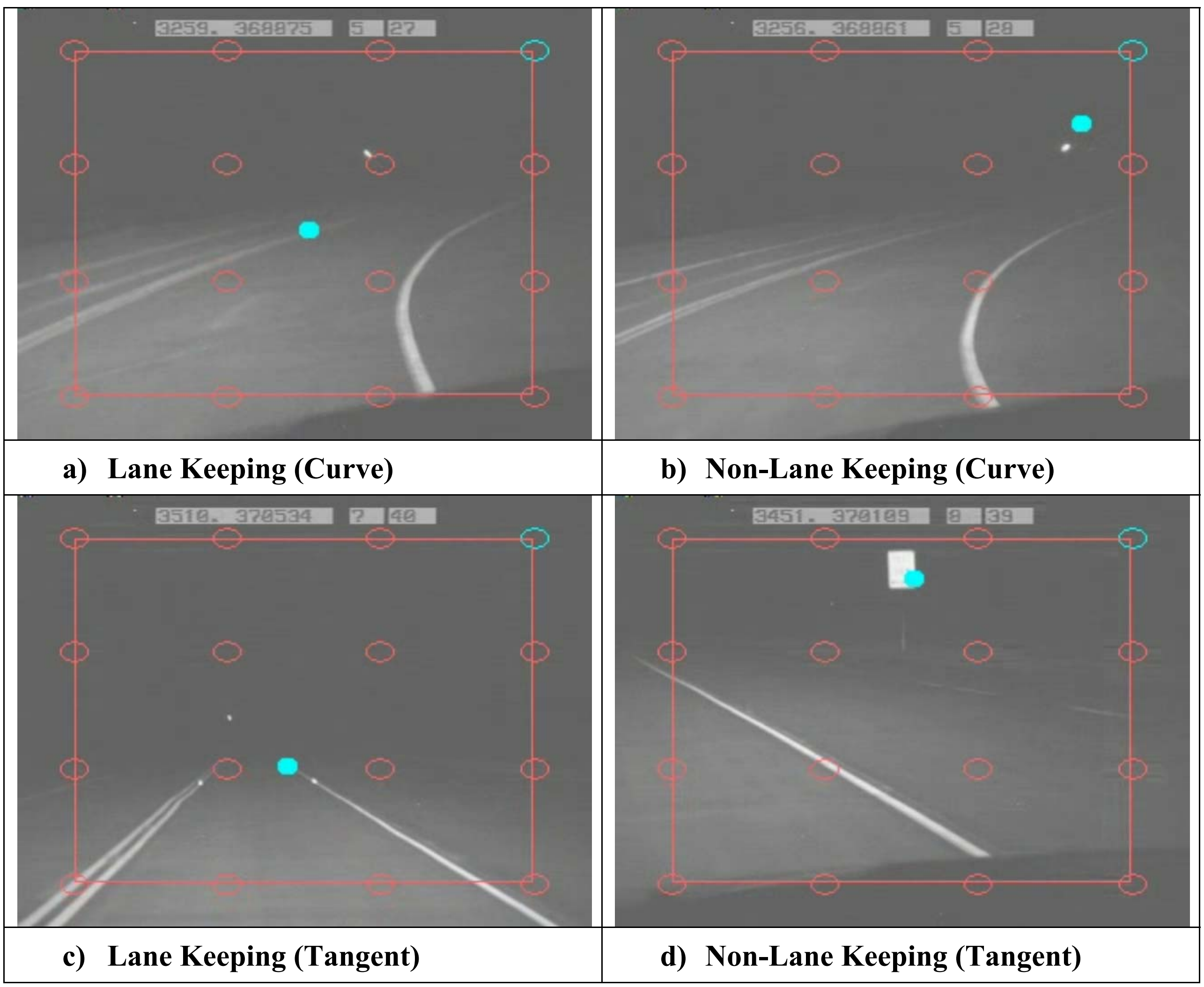
Figure 13. Lateral Position and Speed Points of Interest.

Eye-Tracker Data Reduction

Eye-tracker data were reduced continually along the same horizontal curve and tangent segments where the lateral position data were collected. The only exception was that the eye-tracker data reduction started from one second prior to the start of each treatment segment and continued until one second prior to the end of each treatment. In general, study participants would gaze along the drive path, and their gaze consisted of several glances and shifts from one glance to another. The duration of a glance was recorded out to a 10th of a second. Each glance was reduced with respect to the length of the glance and the interpreted purpose of the glance.

The purpose of a glance for this study was categorized as "lane-keeping" and "non-lane-keeping" tasks. A lane-keeping glance (LKG) was denoted as a glance focused between the adjacent and opposing edge line pavement markings with the intent to maintain adequate lane position. Any glance outside of this region was denoted as a non-lane-keeping glance (NLKG). Some examples of non-lane-keeping glances were gazes at signs along the study course, at the vehicle instrumentation, and in some instances at animals in or near the vehicle path.

Figure 14 contains four still shots taken from the eye-tracker video and show examples of lane-keeping and non-lane-keeping glances. Figure 14a and Figure 14c show lane-keeping glances. Figure 14b and Figure 14d show non-lane-keeping glances, such as looking at a light in the distant background or a shoulder-mounted sign, respectively.



a) Lane Keeping (Curve) | **b) Non-Lane Keeping (Curve)**

c) Lane Keeping (Tangent) | **d) Non-Lane Keeping (Tangent)**

Figure 14. Examples of Lane-Keeping and Non-Lane-Keeping Glances.

LKGs are used by the driver to preview the roadway alignment ahead and to maintain lane position. For a tangent, LKGs were focused at the forward expanse of the test course, which could be approximately 500 to 1,000 ft downstream. Tangent LKGs typically remained in the same downstream area. The glances ended when the glance deviated from the original area and relocated to a new position. Curve LKGs were noticeably different from tangent LKGs.

Nighttime drivers traversing horizontal curves are required to continuously move and readjust their view. As a result, glances continue to move downstream, tracking the roadway delineation until the point of tangent and downstream tangent enter the driver's view. Overall, LKGs in horizontal curves were consistent in that a single glance might shift horizontally along the change in the roadway alignment as a participant traversed a curve, but little vertical shift occurred. A curve LKG ended when the rate of horizontal movement abruptly changed, such as for a look at a sign or when the glance deviated from the vertical position, as it might for glancing at the vehicle instrumentation.

NLKGs may have included glances at objects included in the study design or unrelated to the study, but in either case, the glances were not associated with lane keeping. NLKGs would include fixations at signs, a quick look at an object on the side of the test course, or a glance down at the speedometer. Research personnel classified looks as NLKGs when the participant's gaze shifted away from the drive path and moved toward a particular object or target.

The sum of the LKGs and NLKGs within a particular study segment never equaled the total duration within a study segment. The primary reason for this discrepancy was that the eye-tracker data reduction disregarded all of the transition time between glances. When the participant's gaze was shifting from one location to another, eye-tracker data were not recorded. In addition, if a purpose for a glance could not be determined, it was not reduced. Examples are provided in the next subsection. The researchers calculated the total number of glances and total duration for LKGs and NLKGs, and merged these data with the data set containing the lateral position, vehicle, and subject data for analysis. The completed data set was then ready for analysis.

Eye-Tracker Issues

No standards or practices existed that the researchers could use when reviewing and reducing eye-tracker data; hence, the researchers established specific criteria and controls to minimize subjectivity. This section describes challenges with the eye-tracker data reduction related to the analyses and how the research team addressed each challenge.

During the initial stages of data collection, research personnel carefully calibrated the eye-tracker equipment so the gaze was precisely in sync with the participant's focus. During the hour of driving, the eye-tracker equipment could shift or move on the participant's head. Equipment movements could be attributed to study participant head movements, scratching one's head, or adjusting a pair of eyeglasses. An equipment shift created a shift in the calibration between the gaze recorded by the eye-tracker and the study participant's actual gaze. An example of this shift is depicted in Figure 15. If shifting equipment or video discrepancies were detected early, then research personnel readjusted and recalibrated the eye-tracker equipment during the study.

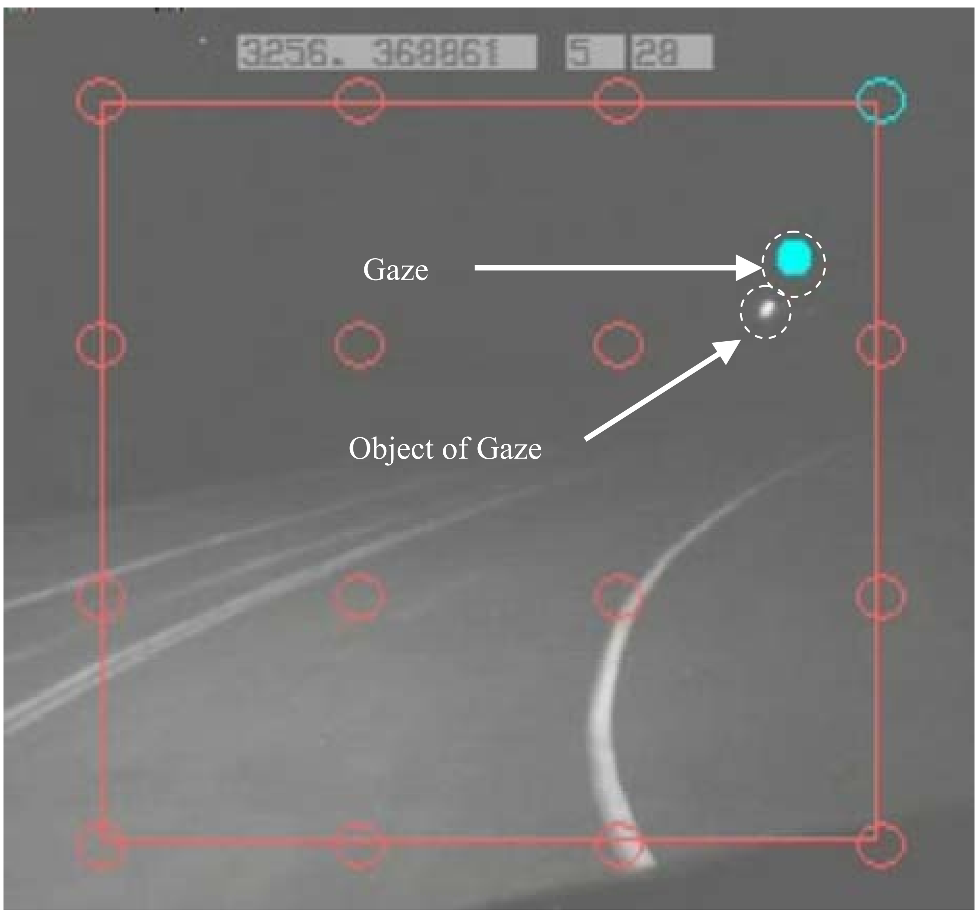


Figure 15. Calibration Shift.

The eye-tracker video was pre-screened to assess the amount of calibration shift. One way of detecting the calibration shift was through NLKGs associated with the study signs used as a distracter task. Test sign NLKGs lasted approximately one to two seconds and were fixed near the center of the sign. If a participant's glance was slightly off-center on the sign but exhibited the same sign NLKG characteristics, then video reviewers considered it a study sign NLKG. The deviation between each glance and the study sign allowed the video reviewer to gauge the degree and orientation of the calibration shift. Video reviewers only reduced video with small or moderate calibration shifts.

During the eye-tracker reduction, the gaze would occasionally leave the video screen's perimeter. This occurred when participants focused on something in the far corners of their eyes that was not in view of the forward-mounted camera. An example is when participants checked their speedometer. Glances departing from the bottom of the video screen were assumed to be speedometer NLKGs. If the gaze moved off the right side of the video screen and the video reviewer knew there was a test sign in that immediate area, then it was reasonable to assume that the participant completed a test sign NLKG. Video reviewers took the same approach to test course objects and other targets that might attract the participants' attention. If the gaze moved off the screen and there were no test signs or objects within the area, then the video reviewer disregarded that glance completely since the purpose was unknown.

CHAPTER 6
ANALYSIS

The analysis was carried out in two phases. A preliminary analysis of general descriptive statistics was conducted to better understand the data and to more efficiently design the in-depth model analyses. For the in-depth effort, mixed model analyses were completed with respect to lateral position, speed, and encroachment data as the dependent variables. Hence, there are two separate subsections within this chapter that cover both phases of the analysis.

PRELIMINARY ANALYSIS

Descriptive statistics were generated for several different potential MOEs and then graphed with the intent to investigate trends. Mean and standard deviations were the primary focus in this initial analysis, and the graphs included bar charts and histograms. While several graphs and tables were generated, only the key graphs that best explain the preliminary findings are presented in this section. The initial MOEs were:

- lane position in inches with respect to the distance between the rear driver-side tire and the outside edge of the adjacent centerline pavement marking at five different equidistant points along each treatment segment,
- encroachments along the edge lines and centerlines at five different equidistant points along each treatment segment,
- speed at five different equidistant points along each treatment section, and
- eye glances measured continuously starting approximately one second prior to entering each treatment section and stopping approximately one second prior to exiting each treatment segment.

Speed

An initial review of the aggregated vehicle curve speed data shows trends indicating that speed was reduced with the installation of wider edge line pavement markings. Figure 16 shows that mean speed values reduced by approximately 3 mph at the midpoint of curve when going from a 4-inch-wide edge line pavement marking to an 8-inch-wide edge line pavement marking. The terms 0.25L, 0.50L, and 0.75L represent the approximate points that were one-quarter, one-half, and three-quarter the way through the horizontal curve. While the tails in Figure 16, based off of one standard deviation, may indicate that the differences in the mean values are not significant, previous research has suggested that a change of 3 mph or more should be considered significant based on the idea that this could impact posted speed limits and advisory speeds (*37*).

However, it is important to note that speeds in general were slightly lower in phase II. The researchers had installed a control curve segment and tangent segment where the edge line width remained 4 inches during both phases of the study. Along these control segments, speeds reduced on average by approximately 2 mph from phase I to phase II (see Figure 17). Subsequently, the researchers used this information in the in-depth analyses to avoid bias.

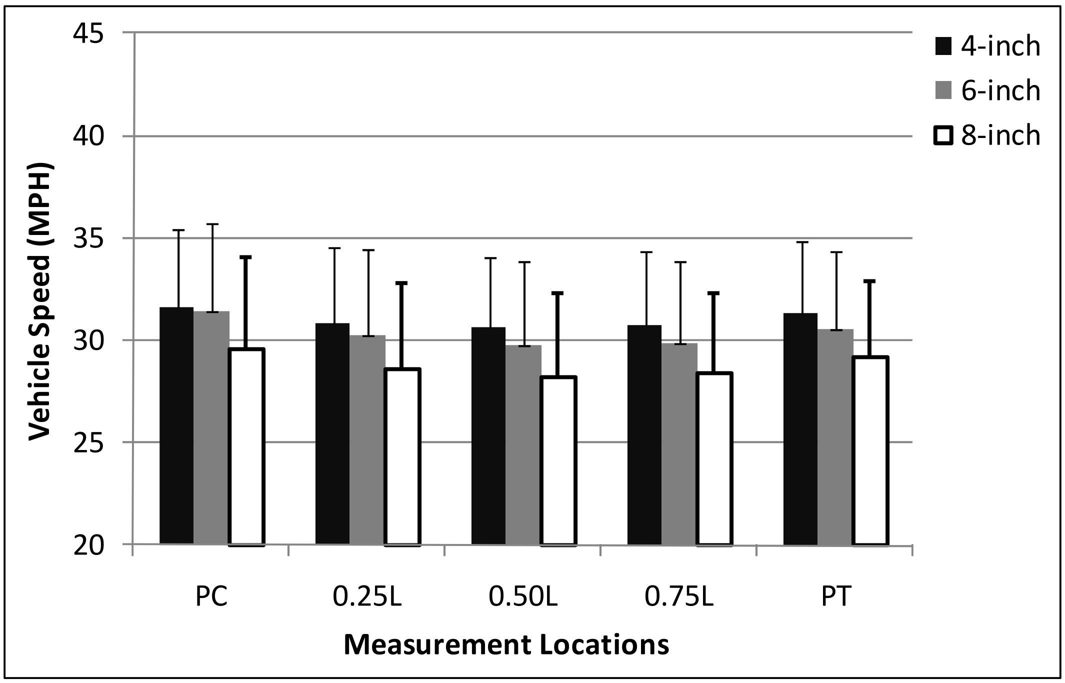
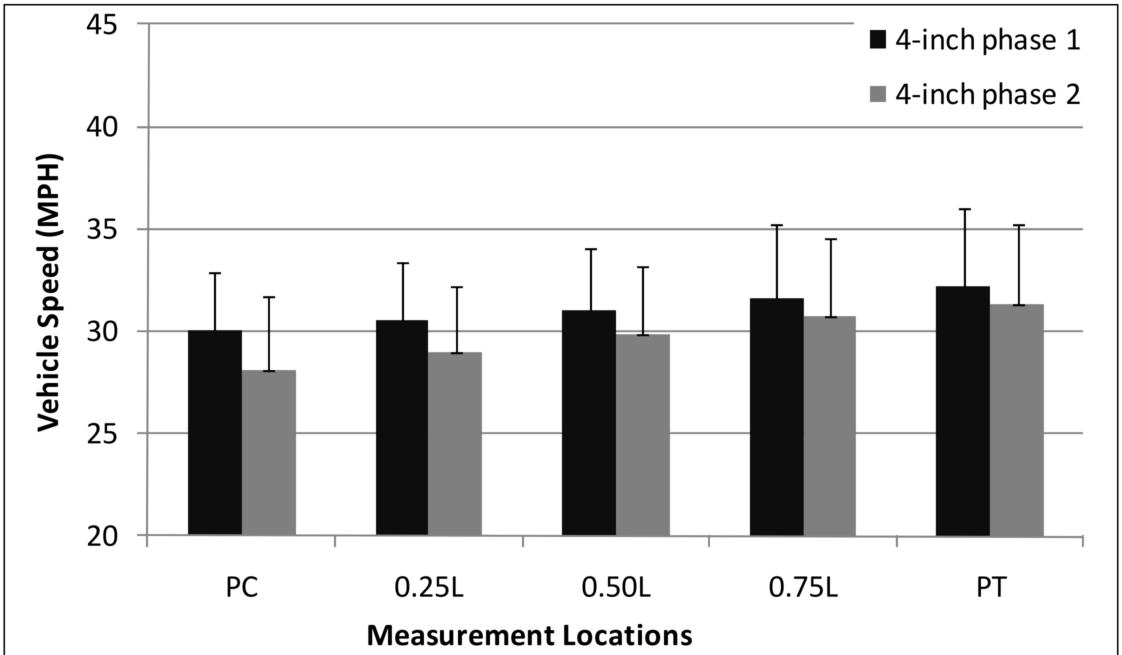
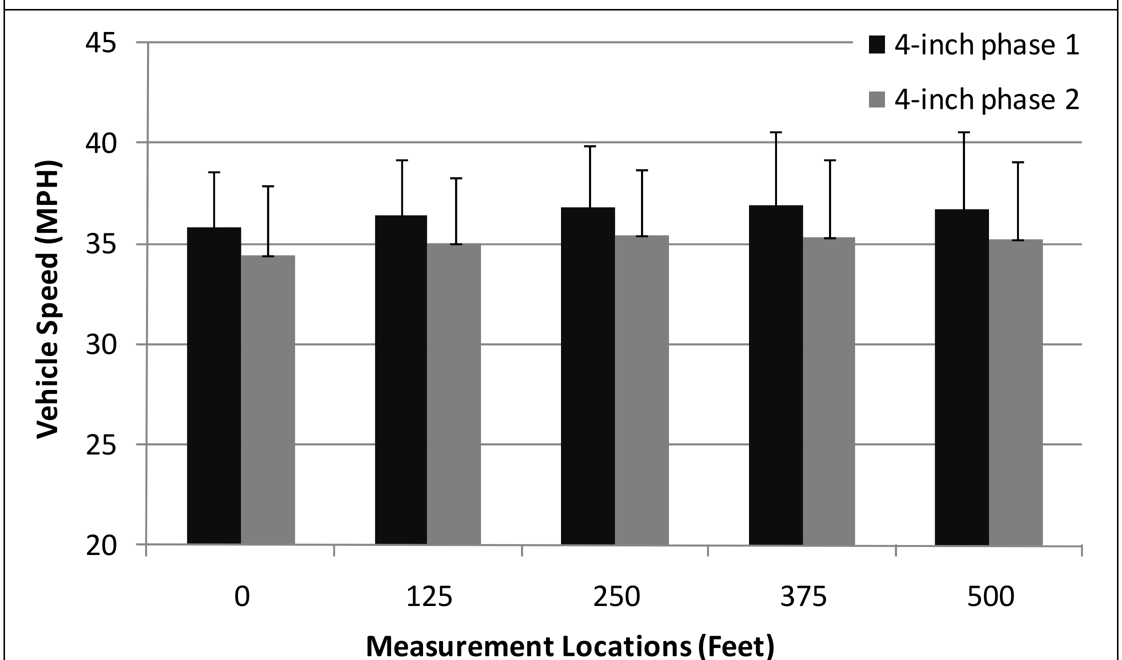


Figure 16. Vehicle Speed along Curves.



a) **Control Curve**



b) **Control Tangent**

Figure 17. Vehicle Speed along Control Segments.

Lateral Placement

The researchers investigated lateral position trends associated with the control tangent and curve segments. The marking width did not change along the control segments. Vehicle lateral placement was defined by the placement of the outside edge of the rear driver-side tire to the outside edge of the centerline. Figure 18 shows the lateral placement along the control tangent. The data were collapsed by direction and marking brightness. The dashed line indicates where the rear driver-side tire lateral placement would be for the study vehicle to be centrally located within the travel lane. While there does appear to be a shift in the lateral placement, there does not appear to be a difference between phase 1 and phase 2 with respect to lateral placement along the control tangent.

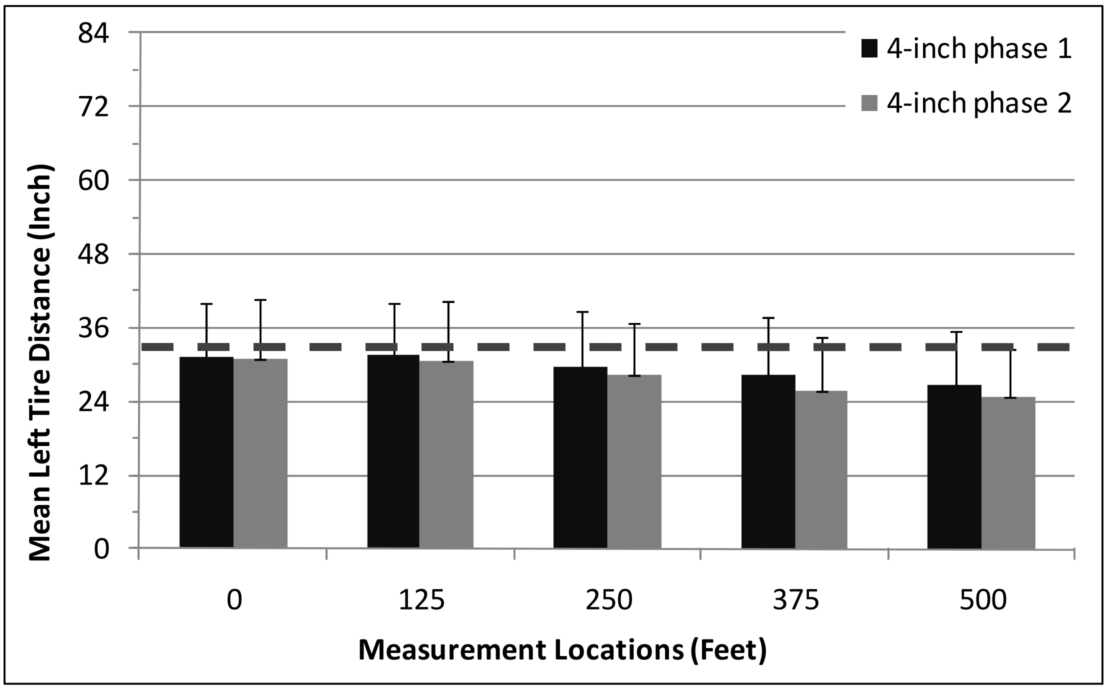


Figure 18. Overall Lateral Placement along Control Tangent.

In Figure 19, the researchers investigated lateral position across all tangent segments with respect to pavement marking width and brightness. Marking brightness was defined as either normal light level or half light level. While the data do suggest that edge line pavement marking width may shift study participants toward the centerline, the trends do not appear consistent when collapsing the data across all tangent treatment segments. Marking brightness did not appear to impact lateral position.

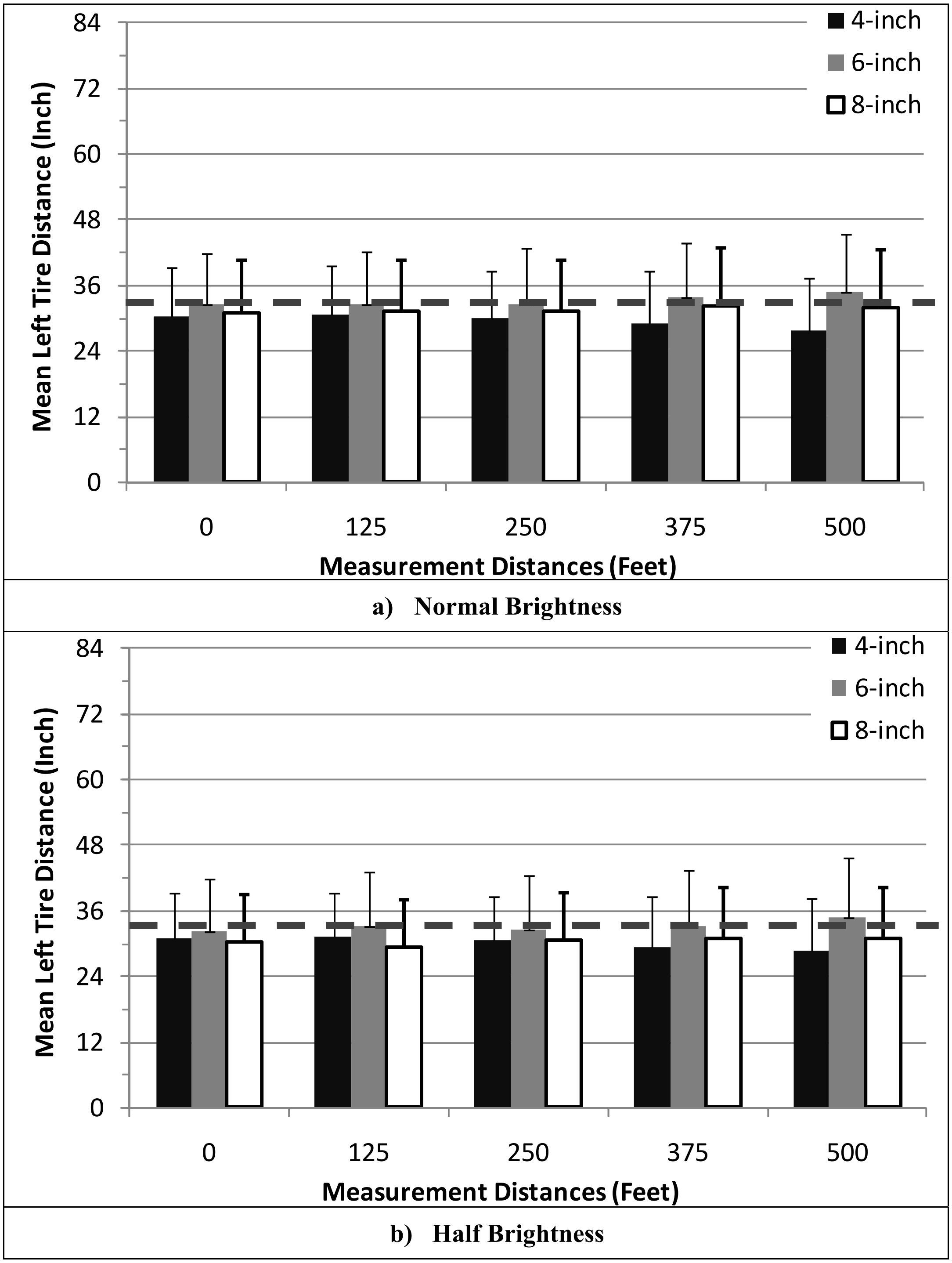


Figure 19. Overall Lateral Placement by Brightness along Treatment Tangents.

Figure 20 shows the results of lateral position along the control curve (curve 1) and shows that drivers travel through the inside of a curve differently than the outside of a curve. Again, a dashed line has been constructed on each graph that denotes where a vehicle's rear driver-side tire would have to be in order to be approximately centered in the travel lane.

Figure 20 shows that drivers start relatively centered in the lane at the beginning of the curve and shift in the lane to flatten the curve. Flattening the curve allows the driver to effectively increase the radius of the curve and reduce the amount of lateral acceleration felt by the driver. Flattening the curve also results in the driver in the inside lane driving closer to the edge line and the driver in the outside lane driving closer to the centerline. When considering the mean values and the tails based on one standard deviation, it would appear that there was not a difference in the lateral placement of vehicles between phase I and II along the control curve.

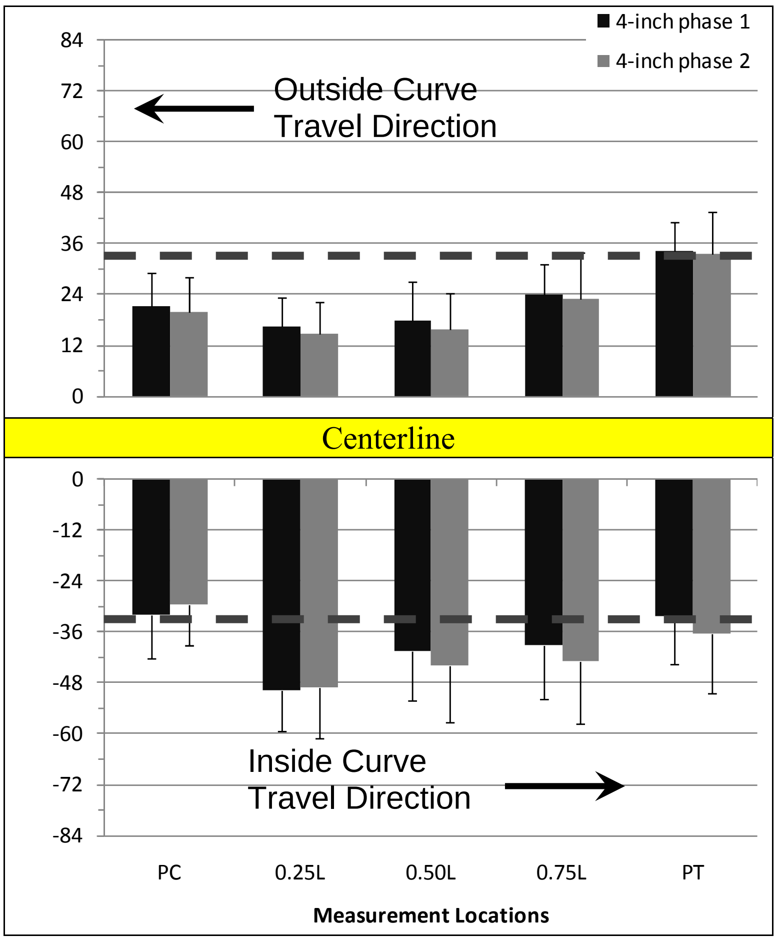
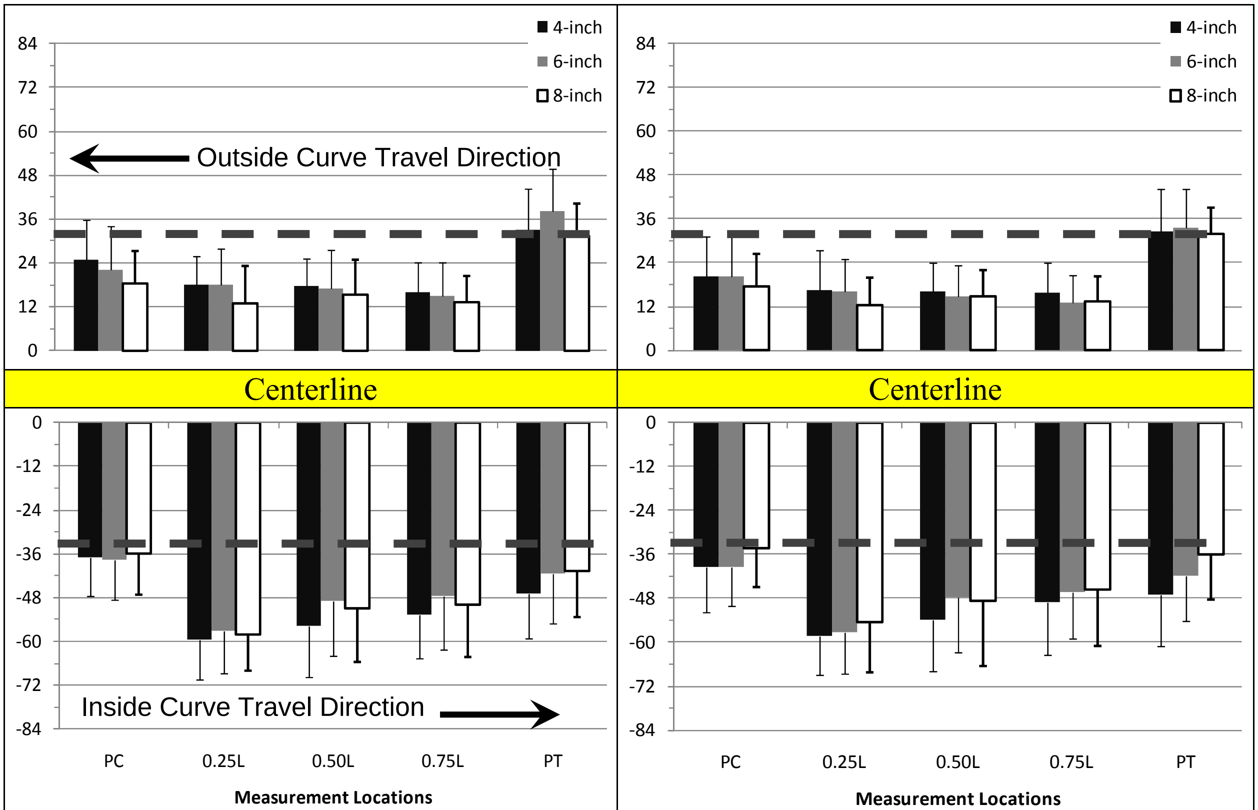


Figure 20. Mean Left Tire Distance (Inches) from Centerline along Control Curve.

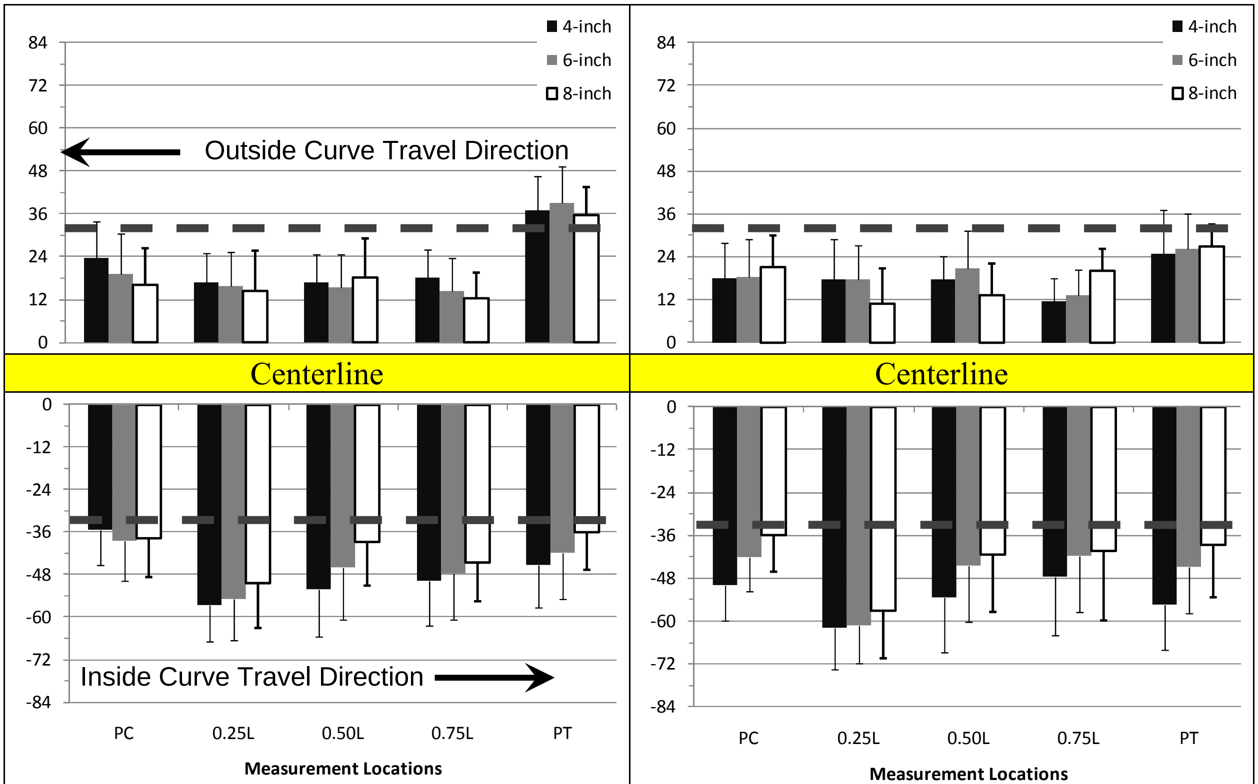
Figure 21 was created to investigate the impact of marking width and brightness in curves. Once again, curving flattening appears to occur. It would also appear that edge line pavement marking width impacts lateral position while marking brightness does not. As edge line pavement marking width increased, the study participants appeared to shift away from the wider edge line pavement marking and toward the centerline. However, when considering the tails, it would appear that the impact was not significant.



a) **Normal Brightness**	b) **Half Brightness**

Figure 21. Mean Left Tire Distance (Inches) from Centerline by Brightness along Treatment Curves.

The researchers investigated the possible impact of curve geometry and whether marking width or brightness had more impact on a particular curve geometry. Figure 22a shows the lateral position data for curves with a 500-ft radius and 45-degree deflection, which were considered easier to navigate than curves with a 200-ft radius and 90-degree deflection, as represented in Figure 22b. From Figure 22, it appears that as marking width increases, drivers shifted away from the wider edge line pavement marking, closer to the centerline. Once again, when considering that the mean values at each location were all within one standard deviation of the 4-inch-wide edge line pavement markings, it is questionable whether the impact was significant.



a) **500-Ft Radius, 45-Degree Deflection** b) **200-Ft Radius, 90-Degree Deflection**

Figure 22. Mean Left Tire Distance (Inches) from Centerline by Deflection along Treatment Curves.

Encroachment

The encroachment data from the horizontal curves show similar results as the lateral placement data. Figure 23 shows that the likelihood of encroachment increases as drivers approach the midpoint of curve and decreases as they exit the curve. The drivers in the outside curve are moving away from the wider edge line pavement marking cutting toward the 4-inch-wide centerline marking, while encroachments along the edge line of the inside curve appeared to decrease as the edge line marking width increased. Drivers were least likely to encroach at the PC and the peak encroachments generally occurred at 0.25L, or one-quarter the way into the curve. Only the 8-inch wide edge line resulted in no encroachments at the PC.

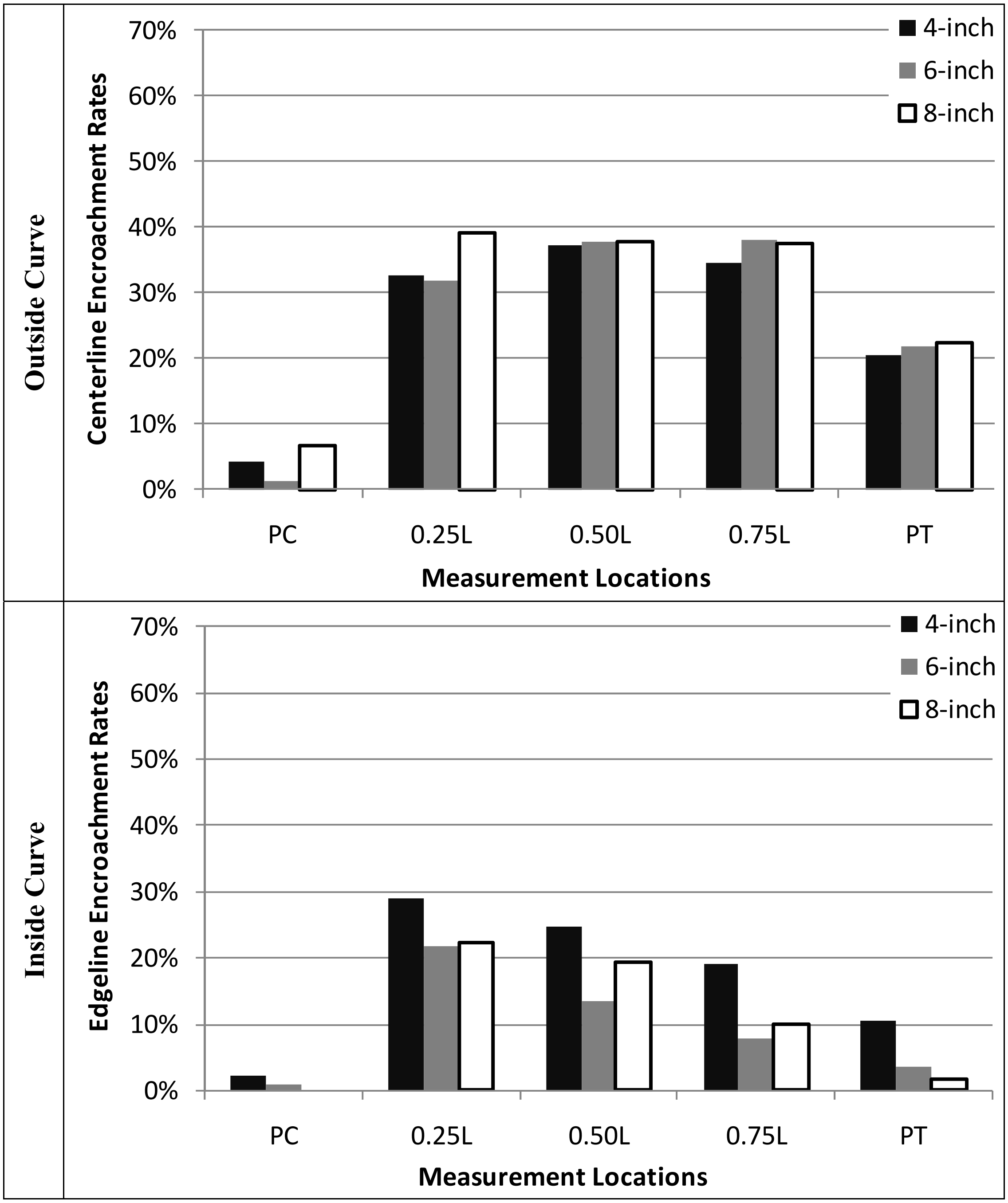


Figure 23. Encroachment for All Treatment Curves.

To further investigate these potential findings, the researchers focused solely on the sharpest horizontal curves with a 200-ft radius and 90-degree deflections. Figure 24 indicates a reduction in edge line encroachments in the inside lane as the width of the edge line pavement marking increased. The 8-inch wide edge lines in the inside of the curve resulted in the lowest number of encroachments throughout the curve, including no encroachments at the PC and PT.

It would also appear that the wider edge line along the outside of the curve shifted drivers away from the edge line and closer to the centerline, which resulted in higher centerline encroachments.

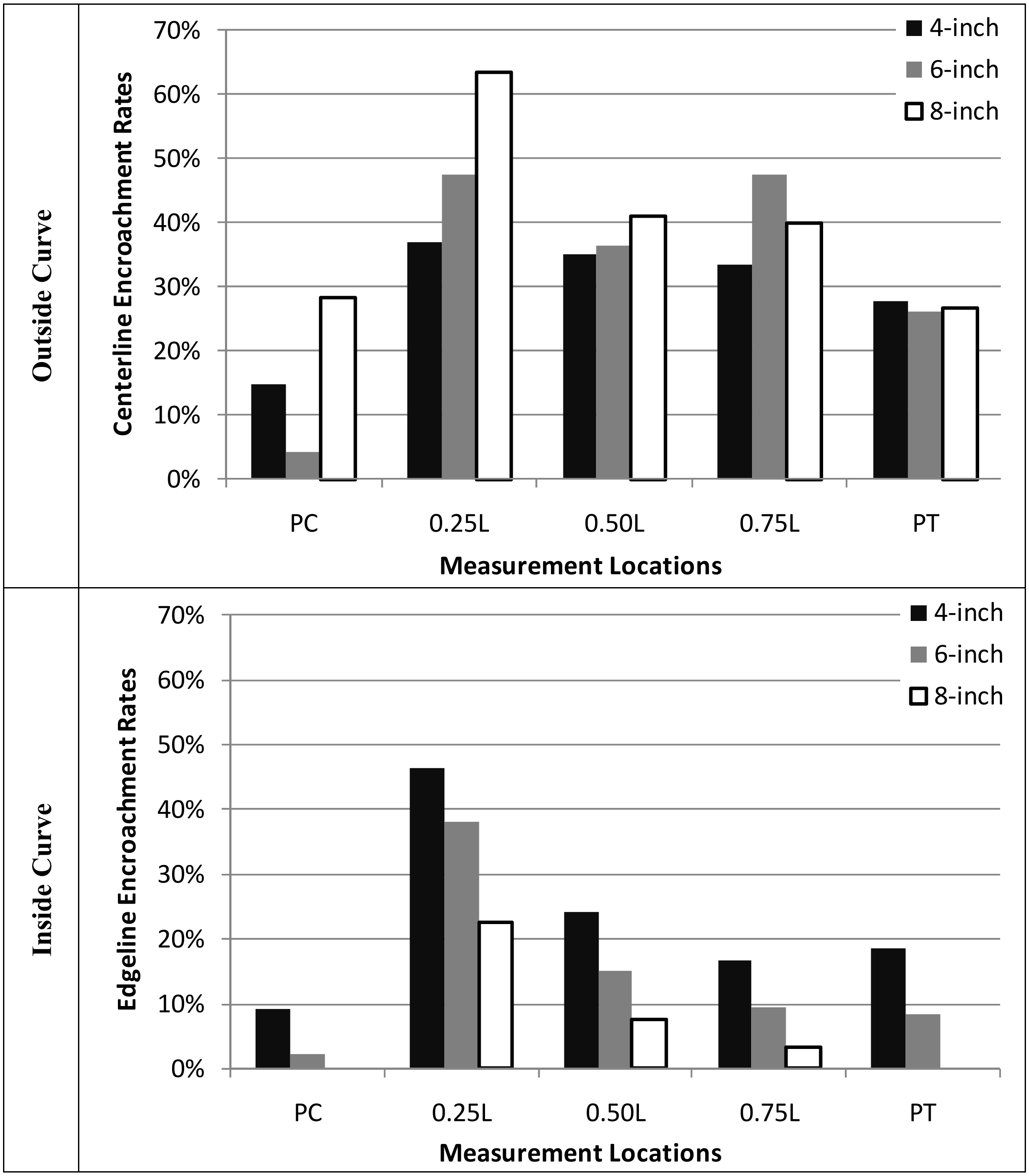
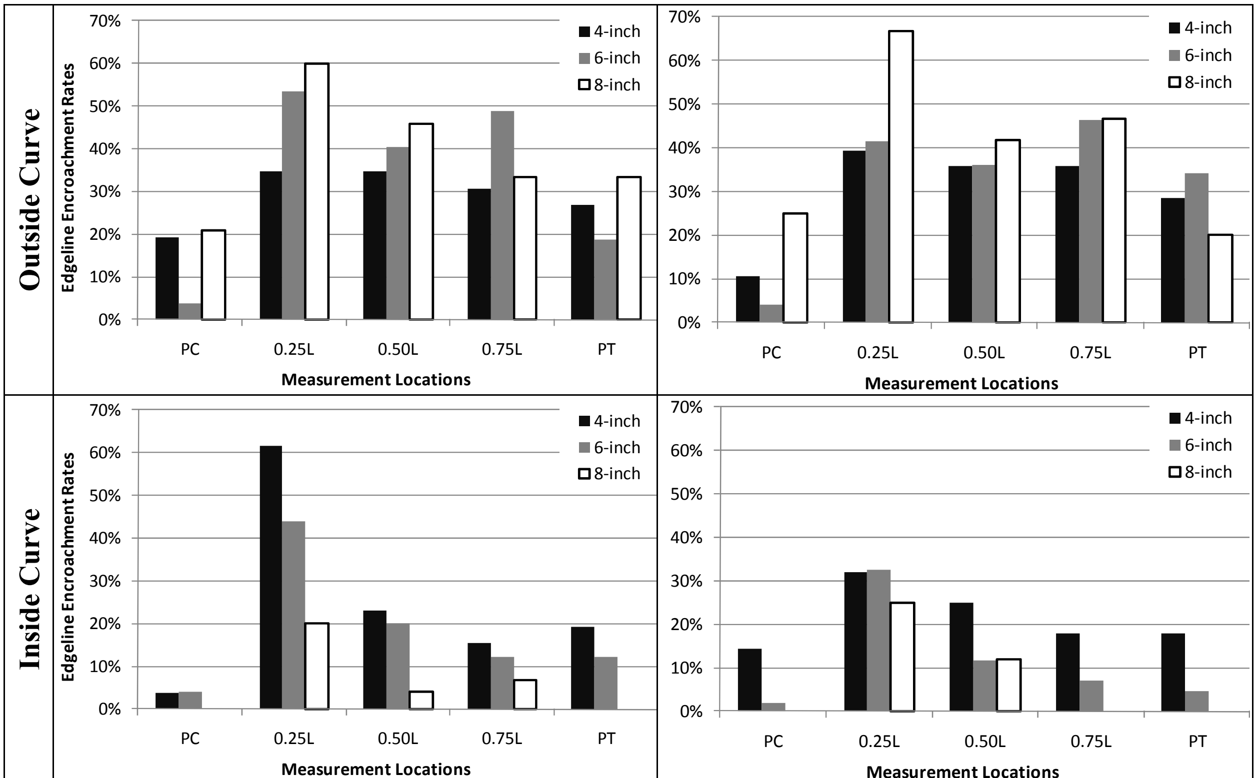


Figure 24. Encroachment for 200-Ft Radius, 90-Degree Curves.

In Figure 25, the potential impact of marking brightness on encroachments along horizontal curves was also investigated. Figure 25 does not show a significant impact from pavement marking brightness in the sharpest curves from the study, with a 200-ft radius and 90-degree deflection. The study participants did not appear to navigate the sharpest curves differently, whether the edge line pavement markings had half or normal brightness.



a) Normal Lighting Level b) Half Lighting Level

Figure 25. Encroachment for Sharp Curves with Respect to Brightness.

Eye Glance

Two aspects of eye-glance behavior were investigated. The first was glance duration, and the second was percent time conducting non-lane-keeping glances.

Glance duration, as shown Figure 26, appears to increase as marking width increases for both lane-keeping and non-lane-keeping glances. It is believed that an increase in the duration of NLKGs would suggest that the study participants feel more comfortable driving with the new treatment. It is questionable whether there is a significant difference between 4- and 6-inch-wide markings and 6- and 8-inch-wide markings, but the preliminary data analysis appears to support that drivers are more comfortable taking longer NLKGs with 8-inch-wide edge line pavement markings versus 4-inch-wide markings.

One other thing to note from Figure 26 is that it appears that study participants spent more time per glance along tangent segments than along curve segments. This was believed to be the result of the fact that tangent segments require less navigational adjustments than curve segments, and therefore study participants were afforded longer fixations. The majority of off-axis NLKGs were associated with the legibility task placed on the participants. Assuming that the minimum legibility index for the drivers was 30 ft per inch of letter height and knowing that the smallest legend was 7 inches, the researchers believed that all of the signs were read at 210 ft away or further. Given the course setup, this would mean that the participants would be able to read all of the signs with off-axis observation angles of less than 10 degrees. This would allow for all study participants to keep the downstream roadway alignment in their parafoveal view and not require them to use peripheral viewing to detect approaching roadway alignment changes.

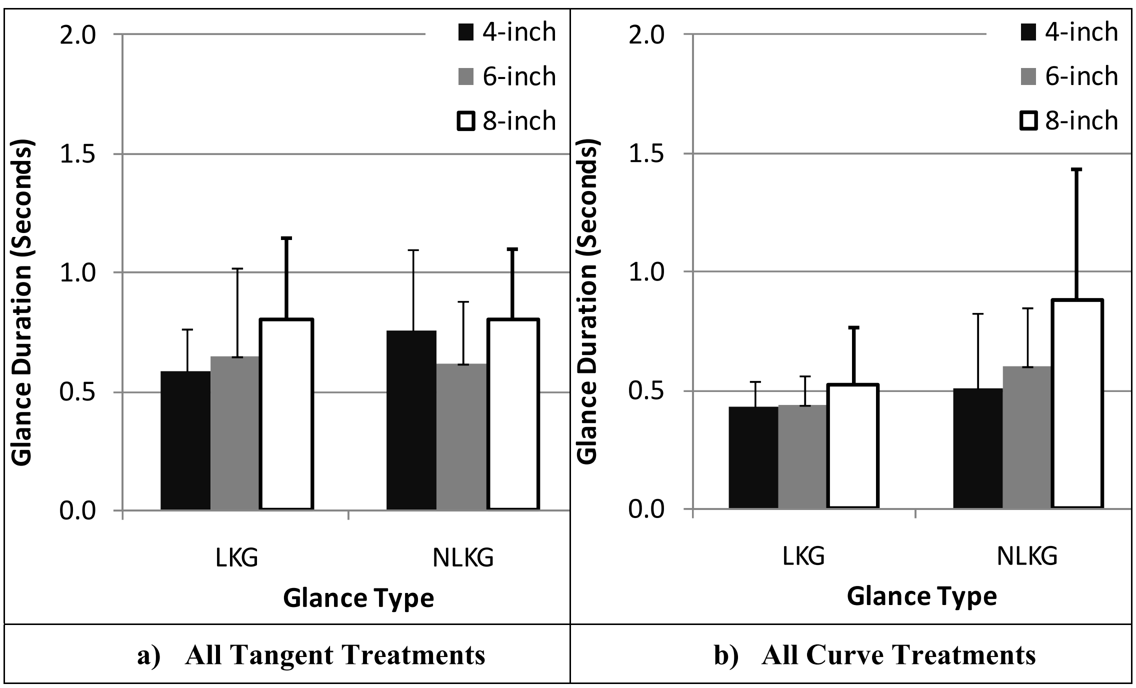
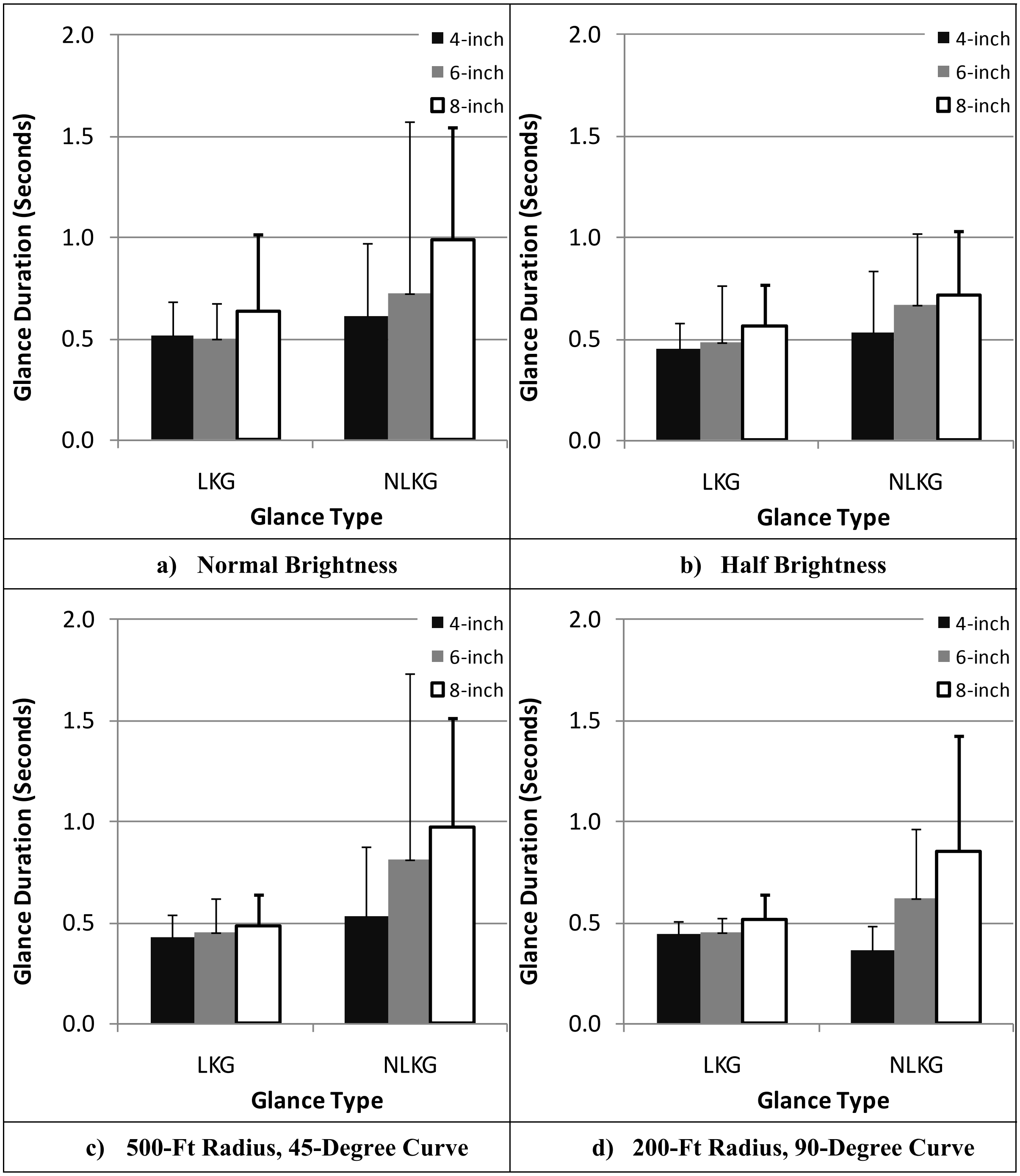


Figure 26. Glance Duration.

In Figure 27, the researchers explored glance duration with respect to marking brightness, marking width, and curve geometry. It appears the impact of marking width far outweighed the impact of marking brightness, as shown in Figure 27a and Figure 27b, but the data do suggest that as marking brightness decreased, the study participants took shorter glances. Study participants glanced longer, regardless of the type of glance, as edge line pavement marking width increased. The impact of marking width on glance duration appears similar for both the sharpest curves in the study (200-ft radius and 90-degree deflection) and the least sharp curves (500-ft radius and 45-degree deflection) (see Figure 27c and Figure 27d). It should also be noted that it does appear that as the sharpness of a curve increases, NLKG durations decrease and LKG durations increase. If it were assumed that longer NLKGs were directly related to driver comfort and safety, this finding would support the use of wider edge line pavement markings.

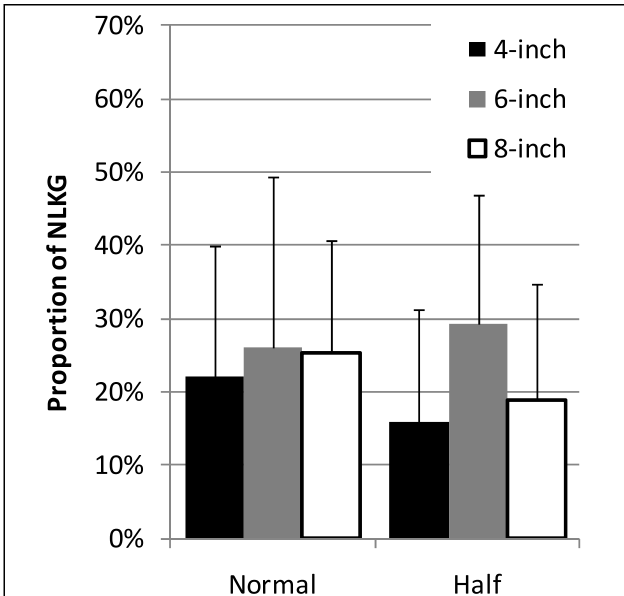


a) **Normal Brightness** b) **Half Brightness**

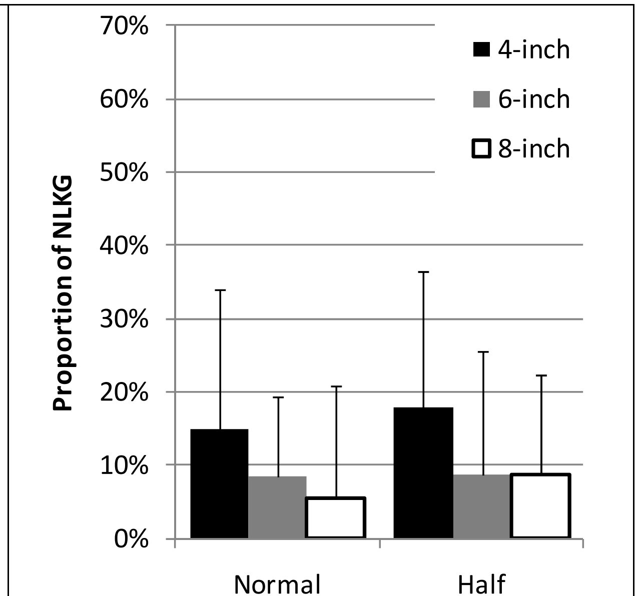
c) **500-Ft Radius, 45-Degree Curve** d) **200-Ft Radius, 90-Degree Curve**

Figure 27. Glance Duration versus Brightness, Marking Width, and Curve Geometry.

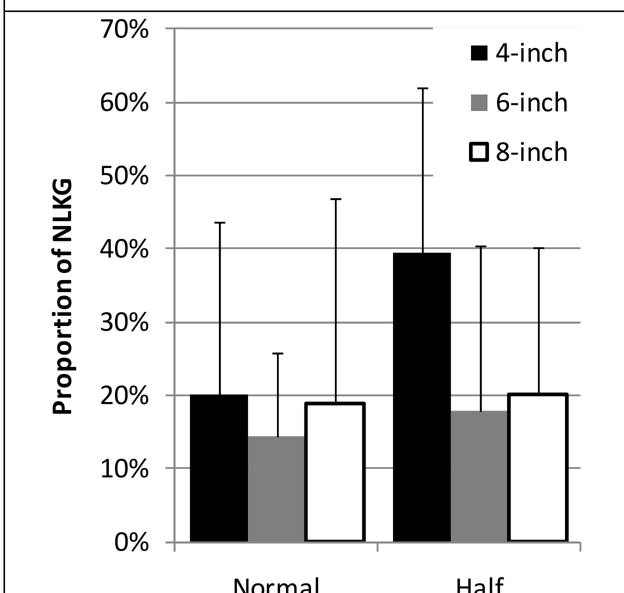
The researchers investigated the proportion of time spent on NLKGs with respect to marking width, brightness, and geometry. Figure 28 shows the proportion of time spent on NLKGs along all tangents. There does not appear to be an impact on NLKGs along tangents with respect to marking width.



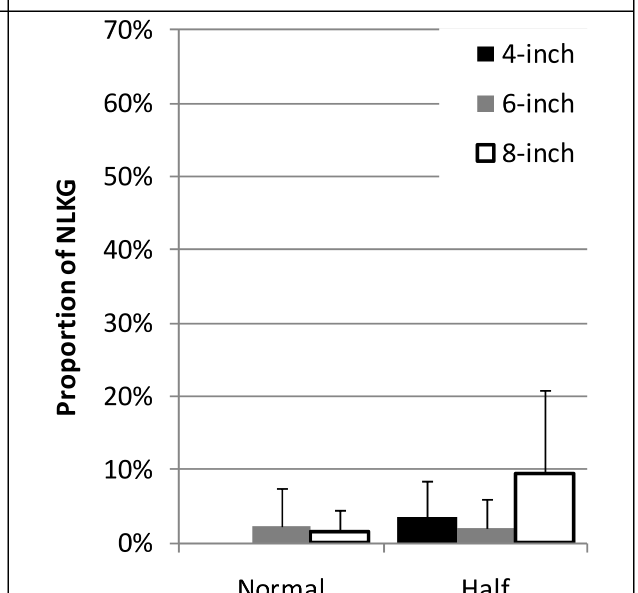
a) All Treatment Tangents



b) All Treatment Curves



c) 500-Ft Radius, 45-Degree Curve



d) 200-Ft Radius, 90-Degree Curve

Figure 28. General Alignment Comparison Using Proportion of NLKG.

Implications

The preliminary analysis provided several insights for the in-depth model analysis, and it appears to already suggest support for some initial considerations with regard to state-wide striping policies. The findings and their associated implications with respect to striping policies are as follows:

- Overall, speed appeared to decrease from phase I to phase II; however, as speed reduced even along the control curve and tangent, the preliminary analysis did not show that the speed reduction was a result of wider edge line pavement markings.
- The lateral placement data from the curves with the most severe geometry (200-ft radius and 90-degree deflection) show that participants drive closer to the centerline and thereby possibly decrease the likelihood of single-vehicle shoulder lane departures. This finding would appear to support wider edge line pavement markings in horizontal curves with severe geometry or possibly curves with a history of single-vehicle run-off-the-road crashes. However, the preliminary analysis does not appear to support changing from the standard state policy of 4-inch-wide edge line pavement markings.
- There were insufficient samples of encroachment collected along tangents sections to discuss preliminary implications. For horizontal curves, the preliminary results showed that encroachments decreased along the inside of horizontal curves. This implies that the use of wider edge line pavement markings along the inside of horizontal curves may have a positive impact on single-vehicle run-off-the-road crashes.
- For curves, both average LKG and NLKG duration appeared to increase with wider edge line pavement markings. At the same time, the proportion of NLKGs decreased with wider edge line pavement markings. The increase in NLKG duration combined with the decrease in percent time conducting NLKGs suggests that the participants felt more comfortable with wider edge line pavement markings. While it is questionable whether fewer but longer NLKGs in horizontal curves delineated with wider edge line pavement markings are beneficial, it leaves potential for drivers to spend more time focusing on curve navigation.
- For tangents, LKG and NLKG duration and the proportion of NLKGs appeared to increase with the installation of wider edge line pavement markings along tangent segments. These findings appear to support the earlier assumption that lane keeping along

tangent segments requires less visual attention than driving along horizontal curve segments. Again, whether an increase in longer NLKGs and the proportion of NLKGs would be beneficial to drivers is questionable, but if the assumption is that these increases are the result of improved driver comfort, this suggests that the use of wider edge line pavement markings may be beneficial along tangent segments.

- Marking brightness did not appear to impact eye-glance behavior.

MODEL ANALYSIS

In this section, the results of in-depth statistical analyses are reported. The researchers used the general findings of the observational analyses to design the testing used and summarized herein. Mixed model analyses were completed with respect to lateral position, speed, and encroachment data as the dependent variables.

Speed Model

As stated in the preliminary analysis, there appeared to be an overall speed reduction between the two phases of the study regardless of the change in the pavement marking width; hence, the first model explored was an analysis with respect to speed along the control curve.

The model results of the control curve are tabulated in Table 20. Speed was modeled in terms of phase, marking brightness, and direction of travel. This was the control curve, and so marking width was not changed between the two phases. Phase and direction were significant in this model at $\alpha = 0.05$. These results confirm the observational findings. No additional analysis was conducted with respect to speed as the dependent variable because any statistically significant findings with speed as the dependent variable would be confounded by the fact that, overall, speed changed regardless of changes in marking width between the two phases. However, the researchers decided to include speed as a covariate in the lateral position and encroachment analyses.

Table 20. Speed Model at 0.50L at Control Curve.

Summary of Fit

R-square	0.6745
Adjusted R-square	0.6648
Root Mean Square Error	2.0233
Mean of Response	30.4316
Observations (N)	105

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	30.0752	0.3403	25.08	88.37	**<0.0001**
Marking Brightness	−0.0470	0.2150	92.57	−0.22	0.8273
Direction	−2.1381	0.2035	80.73	−10.50	**<0.0001**
Phase	0.4703	0.2191	96.33	2.15	**0.0344**

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Marking Brightness	1	1	92.57	0.0479	0.8273
Direction	1	1	80.73	110.3511	**<0.0001**
Phase	1	1	96.33	4.6034	**0.0344**

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Lateral Position Model

Several different lateral position models were developed. Each model included speed as a covariate, and for the curves, each model was evaluated by direction because direction was found to be significant in curves, as shown in Table 21, which includes data from all curves except the control curve.

Table 21. Lateral Position Model at 0.50L Treatment Curves.

Summary of Fit

R-square	0.7078
Adjusted R-square	0.7054
Root Mean Square Error	11.5899
Mean of Response	39.4038
Observations (N)	738

Parameter Estimates[a,b]

Term Estimate		**Standard Error**	**Denominator DF**	**t Ratio**	**Probability > |t|**
Intercept	62.4544	5.6134	93.4	11.13	**<0.0001**
Phase	1.2440	0.4946	587.3	2.51	**0.0122**
Marking Brightness	−0.7374	0.4296	710.8	−1.72	0.0865
Direction	−17.0587	0.4747	728.0	−35.93	**<0.0001**
Curve Category (Easy)	0.4734	3.0401	4.3	0.16	0.8834
Curve Category (Hard)	−4.5719	3.3084	4.1	−1.38	0.2383
Speed at 0.50L	−0.9587	0.1777	226.9	−5.39	**<0.0001**

Fixed Effects Tests[a,b]

Source	**Number of Parameters**	**DF**	**Denominator DF**	**F Ratio**	**Probability > F**
Phase	1	1	587.3	6.3249	**0.0122**
Marking Brightness	1	1	710.8	2.9458	0.0865
Direction	1	1	728.0	1291.1580	**<0.0001**
Curve Category	2	2	4.137	1.0973	0.4147
Speed at 0.50L	1	1	226.9	29.0928	**<0.0001**

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Curves

First, the researchers investigated whether lateral position changed along the control curve to establish whether any statistically significant differences along the treatment curves could be attributed solely to changes associated with each treatment segment. The fixed effects tests for phase, marking brightness, and speed in Table 22, and Table 23 indicated that none of the parameters were statistically significant in modeling lateral position along the control curve in either direction.

Table 22. Lateral Position Model at 0.50L in Outside Lane of Control Curve.

Summary of Fit

R-square	0.5780
Adjusted R-square	0.5471
Root Mean Square Error	6.9235
Mean of Response	16.7556
Observations (N)	45

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	36.5086	16.3677	40.03	2.23	**0.0314**
Phase	1.3675	1.2212	32.09	1.12	0.2711
Marking Brightness	0.6648	1.1297	27.76	0.59	0.5609
Speed at 0.50L	−0.7096	0.5833	40.02	−1.22	0.2309

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Phase	1	1	32.09	1.2539	0.2711
Marking Brightness	1	1	27.76	0.3463	0.5609
Speed at 0.50L	1	1	40.02	1.4799	0.2309

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Since lateral position did not appear to be influenced by phase or marking brightness along the control curve, the researchers then modeled the remaining seven treatment curves by direction. The first models developed were aggregated models with all seven treatment curves. Table 24 and Table 25 show that marking brightness was statistically significant in the outside lane of the treatment curves but not significant for the inside lane. Marking width was not statistically significant. Using the models, the researchers calculated the estimated least square mean lateral placement in the middle of the curve (0.5L) with respect to normal and half brightness. In the outside lane of the curves, the estimated least square mean lateral placement of the study participants were 16.7 and 14.3 inches, respectively. While marking brightness was not statistically significant in the model for the inside of the treatment curves, the study participants did appear to also shift toward the centerline when the pavement markings were brighter by approximately 1.7 inches versus the outside lane shift of approximately 2.4 inches.

Table 23. Lateral Position Model at 0.50L in Inside Lane of Control Curve.

Summary of Fit

R-square	0.7731
Adjusted R-square	0.7609
Root Mean Square Error	7.4941
Mean of Response	42.2167
Observations (N)	60

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	69.5756	16.3677	40.03	2.23	**0.0314**
Phase	−1.2761	1.2212	32.09	1.12	0.2711
Marking Brightness	−1.0054	1.1297	27.76	0.59	0.5609
Speed at 0.50L	−0.8396	0.5833	40.02	−1.22	0.2309

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Phase	1	1	39.17	1.2887	0.2632
Marking Brightness	1	1	38.76	0.8115	0.3732
Speed at 0.50L	1	1	55.86	1.6670	0.2020

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

These models also included some additional independent variables: curve category, lateral position at PC, and speed at PC. At the time, the researchers were testing several different factors in their models to investigate the model sensitivity of various different potential independent variables, to ensure that the researchers would select the most representative models of all of the data.

Table 24. Lateral Position Model at 0.50L in Outside Lane of All Treatment Curves.

Summary of Fit

R-square	0.2970
Adjusted R-square	0.2789
Root Mean Square Error	7.6730
Mean of Response	16.025
Observations (N)	240

Parameter Estimates[a,b]

<table>
<tr><th>Term Estimate</th><th></th><th>Standard Error</th><th>Denominator DF</th><th>t Ratio</th><th>Probability > |t|</th></tr>
<tr><td>Intercept</td><td>−2.2807</td><td>6.8521</td><td>105.4</td><td>−0.33</td><td>0.7399</td></tr>
<tr><td>Marking Width</td><td>0.1537</td><td>0.6543</td><td>204.7</td><td>0.23</td><td>0.8145</td></tr>
<tr><td>Marking Brightness</td><td>−1.2140</td><td>0.5185</td><td>223.1</td><td>−2.34</td><td>0.0201</td></tr>
<tr><td>Curve Category (Easy)</td><td>−0.9523</td><td>1.3444</td><td>4.788</td><td>−0.71</td><td>0.5117</td></tr>
<tr><td>Curve Category (Hard)</td><td>4.3734</td><td>1.5005</td><td>5.134</td><td>2.91</td><td>0.0322</td></tr>
<tr><td>Lateral Position at PC</td><td>0.0919</td><td>0.0679</td><td>168.2</td><td>1.35</td><td>0.1778</td></tr>
<tr><td>Speed at PC</td><td>0.4589</td><td>0.2054</td><td>117.1</td><td>2.23</td><td>0.0273</td></tr>
</table>

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Marking Width	1	1	204.7	0.0552	0.8145
Marking Brightness	1	1	223.1	5.4811	**0.0201**
Curve Category	2	2	4.612	4.6611	0.0781
Lateral Position at PC	1	1	168.2	1.8310	0.1778
Speed at PC	1	1	117.1	4.9937	**0.0273**

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Table 25. Lateral Position Model at 0.50L in Inside Lane of All Treatment Curves.

Summary of Fit

R-square	0.5420
Adjusted R-square	0.5364
Root Mean Square Error	10.5765
Mean of Response	50.6707
Observations (N)	498

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	67.6723	7.3515	67.12	9.21	**<0.0001**
Marking Width	0.8775	0.5548	464.2	1.58	0.1144
Marking Brightness	−0.8576	0.4787	467.7	−1.79	0.0739
Curve Category (Easy)	−1.1241	4.5630	4.17	−0.25	0.8171
Curve Category (Hard)	−7.0269	4.9872	4.042	−1.41	0.2309
Lateral Position at PC	0.3422	0.0564	394.3	6.06	**<0.0001**
Speed at PC	−0.9264	0.2050	293.3	−4.52	**<0.0001**

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Marking Width	1	1	464.2	2.5020	0.1144
Marking Brightness	1	1	467.7	3.2089	0.0739
Curve Category	2	2	4.132	1.4733	0.3288
Lateral Position at PC	1	1	394.3	36.7460	**<0.0001**
Speed at PC	1	1	293.3	20.4314	**<0.0001**

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Since curve category was shown to be significant for the outside of the treatment curves, the researchers then modeled each curve individually. Table 26 and Table 27 show the lateral position models for the outside lanes of curves 2 and 6. These curves were considered to be the "hard" curves to navigate with respect to curve category. The researchers were testing the significance of marking brightness in the outside lanes of these two curves because it was found earlier in

Table 25 that the “hard” curve category and marking brightness were significant factors in the earlier model. The researchers calculated the estimated least square mean lateral placement in the middle of the curve (0.5L) with respect to normal and half brightness using the models shown in Table 26 and Table 27. The resulting values for normal and half brightness were 19.4 and 15.9 inches for curve 2, and 21.7 and 18.2 inches for curve 6, respectively. While the differences were not significant in these two models, these shifts in lateral position toward the centerline were larger than stated from the aggregate model by more than 1 inch, which the aggregate model of the outside lane showed marking brightness to be significant.

Table 26. Lateral Position Model at 0.50L in Outside Lane of Treatment Curve 2 (200-Ft Radius, 90 Degrees).

Summary of Fit

R-square	0.7078
Adjusted R-square	0.7054
Root Mean Square Error	11.5899
Mean of Response	39.4038
Observations (N)	738

Parameter Estimates[a,b]

Term Estimate		**Standard Error**	**Denominator DF**	**t Ratio**	**Probability > $\lvert t \rvert$**
Intercept	−30.2002	15.5055	9.171	−1.95	0.0827
Marking Width	2.3578	2.7429	13.74	0.86	0.4048
Marking Brightness	−1.7638	2.3303	16.37	−0.76	0.4599
Speed at PC	1.3338	0.5057	10.2	2.64	**0.0245**
Lateral Position at PC	0.3232	0.3113	16.56	1.04	0.3142

Fixed Effects Tests[a,b]

Source	**Number of Parameters**	**DF**	**Denominator DF**	**F Ratio**	**Probability > F**
Marking Width	1	1	13.74	0.7389	0.4048
Marking Brightness	1	1	16.37	0.5729	0.4599
Speed at PC	1	1	10.2	6.9564	**0.0245**
Lateral Position at PC	1	1	16.56	1.0775	0.3142

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Table 27. Lateral Position Model at 0.50L in Outside Lane of Treatment Curve 6 (200-Ft Radius, 90 Degrees).

Summary of Fit

R-square	0.5892
Adjusted R-square	0.5207
Root Mean Square Error	6.3326
Mean of Response	19
Observations (N)	29

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	−0.3503	14.1122	13.27	−0.02	0.9806
Marking Width	−2.1471	1.4915	18.72	−1.44	0.1665
Marking Brightness	−1.7730	1.5520	23.84	−1.14	0.2647
Speed at PC	0.8552	0.4663	13.15	1.83	0.0894
Lateral Position at PC	−0.2340	0.1313	16.81	−1.78	0.0928

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Marking Width	1	1	18.72	2.0725	0.1665
Marking Brightness	1	1	23.84	1.3050	0.2647
Speed at PC	1	1	13.15	3.3642	0.0894
Lateral Position at PC	1	1	16.81	3.1763	0.0928

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Tangents

As with the curve models, the researchers first investigated whether lateral position changed along the control tangent (tangent 9) to establish whether any statistically significant differences along the treatment tangents could be attributed solely to changes associated with each treatment segment. The fixed effects tests for phase and marking brightness in Table 28 indicated that none of the parameters were statistically significant in modeling lateral position along the control tangent.

Table 28. Mean Lateral Position along Control Tangent (Tangent 9).

Summary of Fit

R-square	0.7078
Adjusted R-square	0.7054
Root Mean Square Error	11.5899
Mean of Response	39.4038
Observations (N)	738

Parameter Estimates[a,b]

Term	Estimate	Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	28.7248	1.0093	26.62	28.46	**<0.0001**
Phase	0.7400	0.4214	180.2	1.76	0.0808
Marking Brightness	0.2441	0.4116	175.7	0.59	0.5539

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Phase	1	1	180.2	3.0834	0.0808
Marking Brightness	1	1	175.7	0.3518	0.5539

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

The researchers then analyzed the tangents that had gradual lane shifts. Tangents 2 and 3 were paired together with 6-inch-wide edge lines in phase I and 8-inch-wide edge lines in phase II. Tangents 5 and 6 were paired together with 4-inch-wide edge lines in phase I and 6-inch-wide edge lines in phase II. The model for tangents 2 and 3 are in Table 29, and the model for tangents 5 and 6 are in Table 30. In both models, the study participants shifted away from the edge line as edge line pavement marking width increased. Using the models presented in Table 29 and Table 30, the researchers calculated the estimated mean lateral shift away from the edge line to be 3.4 and 2.6 inches for the models, respectively. Marking brightness was not significant in either model.

Table 29. Mean Lateral Position Model along Shifting Tangents 2 and 3.

Summary of Fit

R-square	0.7078
Adjusted R-square	0.7054
Root Mean Square Error	11.5899
Mean of Response	39.4038
Observations (N)	738

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > |t|
Intercept	16.5714	6.2593	325.3	2.65	**0.0085**
Marking Width	1.6592	0.4133	323.8	4.01	**<0.0001**
Marking Brightness	0.2584	0.3393	306.4	0.76	0.4469
Mean Speed	0.4734	0.1682	331.7	2.81	**0.0052**

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Marking Width	1	1	323.8	16.1156	**<0.0001**
Marking Brightness	1	1	306.4	0.5801	0.4469
Mean Speed	1	1	331.7	7.9216	**0.0052**

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Table 30. Mean Lateral Position Model along Shifting Tangents 5 and 6.

Summary of Fit

R-square	0.5828
Adjusted R-square	0.5790
Root Mean Square Error	5.2571
Mean of Response	30.4107
Observations (N)	336

Parameter Estimates[a,b]

Term Estimate		Standard Error	Denominator DF	t Ratio	Probability > $\lvert t \rvert$
Intercept	38.0397	6.3607	143.1	5.98	**<0.0001**
Marking Width	1.2934	0.3624	321.5	3.57	**0.0004**
Marking Brightness	−0.1348	0.2869	304.9	−0.47	0.6389
Mean Speed	−0.2252	0.1726	330.9	−1.30	0.1929

Fixed Effects Tests[a,b]

Source	Number of Parameters	DF	Denominator DF	F Ratio	Probability > F
Marking Width	1	1	321.5	12.7377	**0.0004**
Marking Brightness	1	1	304.9	0.2206	0.6389
Mean Speed	1	1	330.9	1.7024	0.1929

[a] DF stands for degrees of freedom.
[b] Statistically significant values at $\alpha = 0.05$ are shown in **bold**.

Encroachment Model

The encroachment data were categorical in nature, and so generalized estimating equation (GEE) modeling was used for the analysis. The quantity of encroachments with respect to each study curve and direction are tabulated in Table 31. The frequency of encroachments was small, especially for the inside curve direction, and so the analyses were completed using aggregated models for the treatment curves.

Table 31. Encroachment Data with Respect to Sample Size.

Curve	Direction	Phase I		Phase II	
		Sample Size	Encroachments	Sample Size	Encroachments
1*	Outside	27	2	29	5
	Inside	30	0	30	0
2	Outside	54	20	30	10
	Inside	53	1	28	0
3	Outside	54	16	30	6
	Inside	51	1	30	0
4	Outside	54	31	30	22
	Inside	54	2	29	1
5	Outside	54	8	30	6
	Inside	54	0	30	0
6	Outside	53	19	30	10
	Inside	50	7	28	1
7	Outside	54	31	30	19
	Inside	54	9	30	0
8	Outside	54	31	30	4
	Inside	54	20	29	7

*Indicates that curve 1 was the control curve.

The aggregate models with respect to encroachments associated with curves 2 through curve 8 are shown in Table 32 and Table 33. Along the centerline in the outside lane of curves 2 through curve 8, neither marking width nor brightness was statistically significant. However, in the inside lane of curve 2 through 8, there does appear to be a potential impact from the marking width on inside edge line encroachment. The resulting statistic was almost significant with $\alpha = 0.05$, so the researchers added curve category into the model to investigate further.

Table 32. Encroachment Model at 0.5L in the Outside Lane for All Treatment Curves.

Analysis of GEE Parameter Estimates
Empirical Standard Error Estimates[a,b]

Parameter Estimate		Standard Error	95% Confidence Limits		Z Pr	>|Z|
Intercept	1.3292	0.9425	−0.518	3.1764	1.41	0.1584
Initial Marking Width (Phase 1)	0.3716	0.288	−0.1928	0.936	1.29	0.1968
Wider Marking (Phase 2)	0	0	0	0		
Normal Marking Brightness	0.0513	0.1523	−0.2471	0.3498	0.34	0.7362
Half Marking Brightness	0	0	0	0		
Speed at 0.5L	−0.0709	0.0336	−0.1367	−0.005	−2.11	**0.0349**

[a] PR stands for probability.
[b] Statistically significant values at α = 0.05 are shown in **bold**.

Table 33. Encroachment Model at 0.5L in the Inside Lane for All Treatment Curves.

Analysis of GEE Parameter Estimates
Empirical Standard Error Estimates[a,b]

Parameter Estimate		Standard Error	95% Confidence Limits		Z Pr	>|Z|
Intercept	−1.5346	1.2534	−3.9912	0.922	−1.22	0.2208
Initial Marking Width (Phase 1)	1.1408	0.6117	−0.0581	2.3397	1.86	0.0622
Wider Marking (Phase 2)	0	0	0	0		
Normal Marking Brightness	−0.4361	0.2488	−0.9237	0.0516	−1.75	0.0797
Half Marking Brightness	0	0	0	0		
Speed at 0.5L	−0.051	0.0337	−0.1171	0.0152	−1.51	0.131

Contrast Estimate Results[a,b,c]

Label Estimate		Standard Error	Alpha	Confidence Limits		Chi-Square	Pr>Chi-Square
Wider Markings	−1.1408	0.6117	0.05	−2.3397	0.0581	3.48	0.0622
Exp (Wider Markings)	0.3196	0.1955	0.05	0.0964	1.0598		
High Brightness	−0.4361	0.2488	0.05	−0.9237	0.0516	3.07	0.0797
Exp (High Brightness)	0.6466	0.1609	0.05	0.397	1.053		

[a] PR stands for probability.
[b] Statistically significant values at α = 0.05 are shown in **bold**.
[c] Exp(parameter) stands for the odds ratio associated with that parameter.

Table 34 is the aggregate model of encroachment along the inside lane of curves 2 through 8 with respect to marking width, marking brightness, curve category, and curve speed. It was found that when curve category was included in the model, marking width became statistically significant. The odds ratio with respect to a marking width of 0.4071 suggests that study participants in the inside lane were approximately 59 percent less likely to encroach on the wider inside edge line in phase II versus the narrower edge lines in phase I.

Table 34. Encroachment Model at 0.5L in the Inside Lane for All Treatment Curves with Curve Category.

Analysis of GEE Parameter Estimates
Empirical Standard Error Estimates[a,b]

Parameter Estimate		Standard Error	95% Confidence Limits		Z Pr	>|Z|
Intercept	−4.1685	1.1413	−6.4055	−1.9316	−3.65	**0.0003**
Initial Marking Width (Phase 1)	0.8986	0.3254	0.2609	1.5363	2.76	**0.0057**
Wider Marking (Phase 2)	0	0	0	0		
Normal Marking Brightness	−0.4046	0.2478	−0.8902	0.081	−1.63	0.1025
Half Marking Brightness	0	0	0	0		
Hard Curve	−1.0884	0.8291	−2.7134	0.5367	−1.31	0.1893
Easy Curve	−1.5783	0.9479	−3.4361	0.2794	−1.67	0.0959
Moderate Curve	0	0	0	0		
Speed at 0.5L	0.0769	0.0264	0.025	0.1287	2.91	**0.0037**

Contrast Estimate Results[a,b,c]

Label Estimate		Standard Error	Alpha	Confidence Limits		Chi-Square	Pr>Chi-Square
Wider Markings	−0.8986	0.3254	0.05	−1.5363	−0.2609	7.63	**0.0057**
Exp (Wider Markings)	0.4071	0.1325	0.05	0.2152	0.7703		
High Brightness	−0.4046	0.2478	0.05	−0.8902	0.081	2.67	0.1025
Exp (High Brightness)	0.6672	0.1653	0.05	0.4106	1.0844		

[a] PR stands for probability.
[b] Statistically significant values at α = 0.05 are shown in **bold**.
[c] Exp(parameter) stands for the odds ratio associated with that parameter.

CHAPTER 7
SUMMARY AND RECOMMENDATIONS

This report documents a study conducted by the Texas Transportation Institute for the Texas Department of Transportation to investigate potential benefits of wider and/or brighter edge line markings. TTI was already conducting field study research with respect to crashes and macroscopic traffic analyses in horizontal curves of wider edge line markings, and so it was decided that a complimentary human factors analysis would better enable the research team to assess other potential benefits of wider edge line pavement markings. Since a human factors study generally allows for greater controls during the data collection, the researchers also included an assessment of pavement marking brightness. In this report, the researchers documented the following:

- At the completion of this study, the majority of states were installing wider pavement markings either on a regular or experimental basis to investigate the potential benefit of wider pavement markings.
- The crash data analysis supports the use of wider edge line pavement markings to improve safety along rural roadways.
- Study participants encroached less along the edge line in the inside lane of horizontal curves as marking width increased.
- Study participants shifted away from the edge lines in the outside lane of horizontal curves as marking brightness increased.
- Study participants shifted away from edge lines as edge line marking width increased along tangents with small shifts in alignment.

These findings and their implications with respect to TxDOT policy on the use of wider and/or brighter pavement markings are tabulated in Table 35.

Table 35. Summary of MOEs with Respect to Findings.

Topic Finding		Implication
Wider Pavement Marking Usage	• The majority of states are using and/or experimenting with wider markings, and this appears to be an increasing trend with respect to the 2001 study conducted by Gates and Hawkins (*1*).	This has little direct impact on TxDOT pavement marking practices, but it does suggest that there is support within the majority of states that the installation of wider pavement markings is an acceptable practice.
Safety Study	• Crash data collected over approximately a six-year period from over 2,000 centerline miles of rural highway from two different states support the finding that crashes are reduced after the installation of wider edge line pavement markings.	While the data were not collected in Texas, the researchers believe this at least supports the use of wider edge line pavement markings in field safety evaluations along rural two-lane highways in Texas.
Speed	• Speed decreased overall from phase I to phase II, regardless of changes in pavement marking width or brightness.	Speed was used as a covariate in the analysis, and therefore, no implications can be made.
Lateral Placement	• As edge line marking width increased along lightly shifting tangents, vehicle lateral placement shifted away from the edge lines. • As edge line marking brightness increased, vehicle lateral placement shifted away from the edge lines in the outside lane of horizontal curves.	With respect to marking width, this finding would support the use of wider edge line markings along tangent segments with a high rate of ROR crashes. As for marking brightness, brighter edge line markings along horizontal curves may reduce ROR crashes.
Encroachment	• As edge line marking width increased along the inside lane of horizontal curves, the likelihood of edge line encroachment decreased by almost 60 percent.	This supports the use of wider edge line pavement markings along horizontal curves since they may reduce ROR crashes.
Eye Glance	• Pavement marking brightness did not appear to impact eye-glance behavior. • As edge line pavement marking width increased, LKG and NLKG durations increased, while the total percentage of NLKGs decreased.	This suggests that wider edge line pavement markings provide a more comfortable driving environment for drivers and provide more time for drivers to focus on critical driving tasks, which could be used to support the use of wider edge line pavement markings along rural highways.

RECOMMENDATIONS

Based on the above findings, the researchers recommend that TxDOT consider the use of wider edge line pavement markings for two-lane highways. The latest safety analyses support their positive effect on safety. In addition, the surrogate operational studies showed that the traditional surrogate measure of safety such as lateral placement and edge line encroachments support the positive safety findings in that drivers tend to position themselves slightly closer to the centerline and experience fewer edge line encroachments. The eye tracking data also support the recommendation in that drivers appear to have more opportunity to focus on critical driving tasks when wider edge lines are used.

It is important to note that the recommendation is not thoroughly supported for all state highway types. The studies, and therefore the recommendation, were primarily focused on two-lane highways. In addition, the retrospective safety analysis was based on crash and roadway data from states other than Texas. Therefore, the researchers recommend that TxDOT consider an experimental approach across at least two comparable districts but preferably across two pairs of comparable districts. The purpose of this experimental approach would be to conduct additional before-after crash analyses specific to Texas. While a before-after crash analysis could be conducted across all roadway types, the researchers recommend that the farm-to-market system be included at a minimum. A district, or a pair of districts, would install wider edge lines on their newly seal coated highways, and the other district(s) would install standard width edge lines markings along their newly seal coated highways. After two years, Empirical Bayes statistical analyses could be conducted to determine the safety impacts of the wider edge line pavement markings in Texas.

Although the researchers studied different levels of pavement marking retroreflectivity, there were no significant discoveries and therefore this report does not include pavement marking minimum retroreflectivity recommendations. The edge line pavement markings used in the human factors portion of the study documented in this report were approximately 200 mcd/m^2/lx, and the researchers created an additional headlight setting that approximated 100 mcd/m^2/lx. The pavement marking brightness levels used in this study only showed a statistically significant impact on lateral placement in the outside lane of horizontal curves. The pavement marking brightness levels used in this study did not change encroachment or driver eye glance patterns.

Previous safety research has been conducted with respect to the potential safety impact of retroreflectivity, but it has been limited to evaluating the safety impact along roadway segments with retroreflectivity values at or above 200 mcd/m2/lx (*29*). Some early findings suggest that safety becomes correlated with retroreflectivity at or below 200 mcd/m^2/lx (*31, 32*). The researchers from these two studies are continuing their work and are both attempting to investigate the safety impact of retroreflectivity values as low as 100 mcd/m^2/lx. As of now, there is no clear link between pavement marking retroreflectivity and safety.

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APPENDIX: WIDER PAVEMENT MARKINGS SURVEY

SURVEY INSTRUMENT FOR U.S. WIDER PAVEMENT MARKINGS SURVEY

Hello:
You are invited to participate in our survey on the usage of wider longitudinal pavement markings, i.e., pavement markings located as edge, center, or skip/lane lines that are wider than the standard 4-inch pavement marking. Through this survey, we are contacting each state and are asking them to answer some questions about wider longitudinal pavement markings. It will take less than 15 minutes to complete the survey. The goal of this survey is to obtain information and identify potential data sources related to wider longitudinal pavement markings. This information will be used in combination with crash data in an attempt to identify any safety benefits associated with the usage of wider pavement markings. Please answer all of the questions to the best of your knowledge. Your participation in this study is greatly appreciated. If you are not the appropriate person in your state to answer the questions, please forward the e-mail to the appropriate individual. If you have questions at any time about the survey or the procedures, you may contact Adam Pike at 979-862-4591 or by email at a-pike@tamu.edu. Please complete the survey within 30 days. Thank you very much for your time. Please start the survey by clicking on the Continue button below.

Has your state implemented wider longitudinal pavement markings, i.e., pavement markings located as edge, center, or skip/lane lines that are wider than the standard 4-inch pavement marking? Implementation refers to any usage of wider lines at either the local, district, or state level.

1. Yes
2. No

What wider line width does your state use? Select all that apply.

1. 5 inch
2. 6 inch
3. 8 inch
4. Other ________________________________

Why have wider longitudinal pavement markings been implemented? Select all that apply.

1. Experimental
2. Spot treatments (e.g., severe curves, bridge approaches, etc.)
3. High crash areas
4. State trend
5. Recommendations from other states
6. Research results
7. Other ________________________________

When were the first wider longitudinal pavement markings installed on your state's roadways?

1. Within the past year
2. Between 1 and 2 years ago
3. Between 2 and 3 years ago
4. Greater than 3 years ago
5. Comments

When were the majority of the wider longitudinal pavement markings installed on your roadways?

1. Within the past year
2. Between 1 and 2 years ago
3. Between 2 and 3 years ago
4. Greater than 3 years ago
5. Comments

Approximately how many miles of road do you believe your state has striped with each of the following wider pavement marking widths?

5-inch-wide longitudinal pavement markings

6-inch-wide longitudinal pavement markings

8-inch-wide longitudinal pavement markings

Other width longitudinal pavement markings

Do records exist that indicate the location where wider longitudinal pavement markings have been implemented?

1. Yes
2. No
3. Uncertain (please add comments)

Do records exist that indicate the location where standard 4-inch-wide longitudinal pavement markings have been implemented?

1. Yes
2. No
3. Uncertain (please add comments)

If records exist for either of the two previous questions, where can they be found? Select all that apply.

1. Online database
2. Request DOT electronic files
3. Request DOT paper files
4. Request DOT maps of roadway characteristics
5. Visit to state or local DOTs to search their files
6. No records exist
7. Other ____________________________________

Do records exist that indicate any of the following in regards to the areas where wider longitudinal pavement markings have been applied? Select all that apply.

1. Location, beginning and end (e.g., mile markers, roads, etc.)
2. Date of application (preferably the month)
3. Road type/class
4. Number of miles installed
5. Line type installed (e.g., edge, lane/skip, center)
6. AADT
7. Speed limit
8. Number of lanes
9. Median type and width if applicable
10. Lane width
11. Shoulder width
12. Pavement edge drop-offs
13. Curve and tangent locations
14. Terrain type
15. Other ____________________________________

At sites where pavement marking width is known, do AADT records exist for:

	Yes	No
Several years before the application date?	❑	❑
A time after the application date?	❑	❑
The percent of heavy vehicles?	❑	❑
The percent of nighttime driving?	❑	❑

If records exist for either of the two previous questions, where can they be found? Select all that apply.
1. Online database
2. Request DOT electronic files
3. Request DOT paper files
4. Request DOT maps of roadway characteristics
5. Visit to state or local DOTs to search their files
6. No records exist
7. Other ___________________________________

How often are AADT values updated for roads that have 6-inch-wide markings on them?
1. At least once a year
2. Once every 2 years
3. Once every 3 years
4. Once every 5 years
5. Once every 10 years

Do records exist that indicate areas and dates of work zones on your roadways?
1. Yes
2. No

Do records exist that indicate areas of improvements made to roadways before being striped with wider markings and after being striped with wider markings? Select any improvements below that are maintained in a database.
1. Installation of chevrons or additional roadside delineators
2. Installation of advance curve warning signs
3. Installation of retroreflective raised pavement markers
4. Installation of rumble strips
5. New surface treatments, i.e., overlay, chip seal/seal coat, or a new road surface
6. Speed limit changes
7. Roadway expansion
8. Other ___________________________________

If records exist for either of the two previous questions, where can they be found? Select all that apply.
1. Online database
2. Request DOT electronic files
3. Request DOT paper files
4. Request DOT maps of roadway characteristics
5. Visit to state or local DOTs to search their files
6. No records exist
7. Other ___________________________________

	Yes	No	NA
Has your state received any public feedback or comments on wider longitudinal pavement markings?	❑	❑	❑
Has the public shown a favorable response to currently installed wider longitudinal pavement markings?	❑	❑	❑
Has the public requested wider longitudinal pavement markings be installed or increased usage of wider longitudinal pavement markings?	❑	❑	❑

Please add any additional comments below.

Does your state plan on installing wider longitudinal pavement markings in the future?

1. Yes
2. No

Please add the reasoning behind your answer to the previous question in the box below.

This is the last page of the survey. Please fill in the contact information and answer the last few questions. Thank you for taking the time to complete our survey.

Name:

Title:

State:

E-mail Address:

Phone Number:

Do you have any additional comments or suggestions related to our research efforts?

Would it be OK if we contact you again if we have any further questions?

1. Yes
2. No

Would you like us to transmit our findings to you when the final report has been published?

1. Yes
2. No

AGENCY RESPONSES TO WIDER PAVEMENT MARKING SURVEY

Below are the full agency responses to the online survey administered by the Texas Transportation Institute from November 2006 through February 2007. Only the state DOTs that responded to the survey are listed below. An “N” denotes states that responded that wider longitudinal pavement markings are not used in their state.

Arizona DOT
Arkansas DOT
California DOT (N)
Hawaii DOT (N)
Illinois DOT
Indiana DOT
Iowa DOT
Kansas DOT
Kentucky DOT
Louisiana DOT (N)
Maine DOT
Maryland DOT
Massachusetts DOT
Michigan DOT
Mississippi DOT
Nevada DOT
New Hampshire DOT
New York DOT
North Dakota DOT (N)
Oregon DOT (N)
Pennsylvania DOT
South Carolina DOT
South Dakota DOT
Tennessee DOT
Texas DOT
Washington DOT (N)
West Virginia DOT
Wisconsin DOT (N)
Wyoming DOT

Of the respondents, 76 percent indicated that wider markings were used in their state.

	Arizona DOT	Arkansas DOT
Are wider markings used?	Yes	Yes
Typical width	6 inches/8 inches	6 inches
Basis for implementation	State trend	Spot treatments (at narrow bridges)
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Between 2 and 3 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	5,500 miles of 6 inch/ 30 miles of 8 inch	50 miles
Are records of locations with wider markings kept?	No	No
Are records of locations with 4-inch markings kept?	No	No
If records exist for either of the two previous questions, where can they be found?	No records exist	No records exist
Details of records with regards to locations with wider markings	No records exist	No records exist
What AADT records exist for sites where pavement marking width is known?	Several years before; a time after application date; percent heavy vehicles	No records exist
If records exist for either of the two previous questions, where can they be found?	Online databases	No records exist
How often are AADT values updated for roads that have 6-inch-wide markings?	At least once a year	No records exist
Are records kept for areas and dates of work zones on your roadways?	Yes	No
Details of records of improvements made to roadways before and after being striped with wider marking	No records exist	No records exist
If records exist for either of the two previous questions, where can they be found?	Request DOT electronic files	No records exist
Any public feedback on wider longitudinal pavement markings?	Yes	No
Has the public shown a favorable response to currently installed wider markings?	Yes	NA
Has the public requested wider markings be installed or increased usage of wider markings?	No	No
Future wider marking installation planned?	Yes	Yes
Please add the reasoning behind your answer to the previous question	Attainment of higher target value of wider markings may result in a slightly lower maintenance requirement	Install wider 6-inch edge lines 1,500 feet in advance of narrow bridges
Additional comments	NR	NR

NR—no response; NA—not applicable.

	California DOT	Hawaii DOT
Are wider markings used?	No	No
Typical width	NA	NA
Basis for implementation	NA	NA
When were first wider markings installed?	NA	NA
When were majority of wider markings installed?	NA	NA
Approximate number of miles of roadway with wider markings	NA	NA
Are records of locations with wider markings kept?	NA	NA
Are records of locations with 4-inch markings kept?	Uncertain (consult maintenance)	NR
If records exist for either of the two previous questions, where can they be found?	Other	NR
Details of records with regards to locations with wider markings	NA	NA
What AADT records exist for sites where pavement marking width is known?	NR	NR
If records exist for either of the two previous questions, where can they be found?	NR	NR
How often are AADT values updated for roads that have 6-inch-wide markings?	NA	NA
Are records kept for areas and dates of work zones on your roadways?	No	NR
Details of records of improvements made to roadways before and after being striped with wider markings	No records exist	NR
If records exist for either of the two previous questions, where can they be found?	No records exist	NR
Any public feedback on wider longitudinal pavement markings?	NA	No
Has the public shown favorable response to currently installed wider markings?	NA	NA
Has the public requested wider markings be installed or increased usage of wider markings?	NA	No
Future wider marking installation planned?	No	No
Please add the reasoning behind your answer to the previous question	No current plan for wider lines exists	Not warranted until studies show safety benefits
Additional comments	NR	NR

NR—no response; NA—not applicable.

	Illinois DOT	Indiana DOT
Are wider markings used?	Yes	Yes
Typical width	5 inches/6 inches	5 inches
Basis for implementation	High crash areas; state trend	Other—wider lines on interstates
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	6,000 miles of 5 inch; 5,000 miles of 6 inch	1,200 miles
Are records of locations with wider markings kept?	Yes	No
Are records of locations with 4-inch markings kept?	Yes	No
If records exist for either of the two previous questions, where can they be found?	On-site visit	No records exist
Details of records with regards to locations with wider markings	Location; date of application; number of miles installed	Other—all lane miles
What AADT records exist for sites where pavement marking width is known?	Several years before application date; a time after application date; percent heavy vehicles	Percent heavy vehicles; Percent night traffic
If records exist for either of the two previous questions, where can they be found?	On-site visit	Other—interstate traffic count stations
How often are AADT values updated for roads that have 6-inch-wide markings?	Once every 3 years	NR
Are records kept for areas and dates of work zones on your roadways?	No	No
Details of records of improvements made to roadways before and after being striped with wider markings	NR	NR
If records exist for either of the two previous questions, where can they be found?	NR	NR
Any public feedback on wider longitudinal pavement markings?	No	No
Has the public shown favorable response to currently installed wider markings?	No	No
Has the public requested wider markings be installed or increased usage of wider markings?	No	No
Future wider marking installation planned?	Yes	Yes
Please add the reasoning behind your answer to the previous question	NR	To continue placing 5-inch lane lines on interstate
Additional comments	NR	DOT practice to mark all lane lines on interstate with 5-inch lines and use 4-inch lines for edge lines

NR—no response; NA—not applicable.

	Iowa DOT	**Kansas DOT**
Are wider markings used?	Yes	Yes
Typical width	6 inches	6 inches
Basis for implementation	Experimental	State trend; recommendation from other states; research results
When were first wider markings installed?	Within the past year	Greater than 3 years ago
When were majority of wider markings installed?	Within the past year	Between 1 and 2 years ago
Approximate number of miles of roadway with wider markings	10 miles	1,000 miles of 6 inch
Are records of locations with wider markings kept?	NR	Currently developing database for this information
Are records of locations with 4-inch markings kept?	NR	Currently developing database for this information
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT electronic files, Request DOT maps
Details of records with regards to locations with wider markings	NR	Location; date of application; road type/class; number of miles installed; line type installed; AADT; speed limit; lane width
What AADT records exist for sites where pavement marking width is known?	NR	Several years before application date; a time after application date; percent heavy vehicles; percent night traffic
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT electronic files; request DOT maps
How often are AADT values updated for roads that have 6-inch-wide markings?	NR	At least once a year
Are records kept for areas and dates of work zones on your roadways?	NR	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	NR	Installation of chevrons or additional roadside delineators, advance curve warning signs, retroreflective raised pavement markings, rumble strips; new surface treatment; speed limit changes
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT electronic files; request DOT paper files; request DOT maps; on-site visit
Any public feedback on wider longitudinal pavement markings?	No	Yes
Has the public shown favorable response to currently installed wider markings?	NA	Yes
Has the public requested wider markings be installed or increased usage of wider markings?	NA	No
Future wider marking installation planned?	No (not yet)	Yes
Please add the reasoning behind your answer to the previous question	Future implementation dependent on feedback on test	Safety benefit to motorist to help prevent lane departure crashes

	sections	
Additional comments	Iowa State University to evaluate and collect feedback on recent test sections	Lead state on lane departure crashes; currently collecting data on this information

NR—no response; NA—not applicable.

	Kentucky DOT	Louisiana DOT
Are wider markings used?	Yes	No
Typical width	6 inches, other—12 inches	NA
Basis for implementation	Experimental; state trend; recommendations from other states; other—perceived safety and convenience benefits	NA
When were first wider markings installed?	Greater than 3 years ago	NA
When were majority of wider markings installed?	Greater than 3 years ago	NA
Approximate number of miles of roadway with wider markings	1,500+ centerline miles of 6 inch	NA
Are records of locations with wider markings kept?	Yes	NA
Are records of locations with 4-inch markings kept?	Yes	NR
If records exist for either of the two previous questions, where can they be found?	NR	NA
Details of records with regards to locations with wider markings	Location; road type/class; number of miles installed; line type installed; AADT; speed limit; number of lanes; median type and width; lane/shoulder width	NR
What AADT records exist for sites where pavement marking width is known?	Several years before application date; a time after application date; percent heavy vehicles; percent night traffic	NR
If records exist for either of the two previous questions, where can they be found?	Request DOT electronic files	NR
How often are AADT values updated for roads that have 6-inch-wide markings?	At least once a year	NA
Are records kept for areas and dates of work zones on your roadways?	No	NR
Details of records of improvements made to roadways before and after being striped with wider markings	No records exist	NA
If records exist for either of the two previous questions, where can they be found?	No records exist	NA
Any public feedback on wider longitudinal pavement markings?	Yes	NA
Has the public shown favorable response to currently installed wider markings?	Yes	NA
Has the public requested wider markings be installed or increased usage of wider markings?	Yes	NA
Future wider marking installation planned?	Yes	No
Please add the reasoning behind your answer to the previous question	Current state policy unlikely to change in the near future	Significant reasons needed to justify additional cost of installing wider markings

Additional comments	12-inch-wide lines used in place of double wide lines; wide markings on all fully controlled access highways and a very few other roads	Higher priority on use of raised pavement markers to supplement centerline markings

NR—no response; NA—not applicable.

Maine	**DOT**	**Maryland DOT**
Are wider markings used?	Yes	Yes
Typical width	8 inches	5 inches; other—10 inches/18 inches
Basis for implementation	Experimental; high crash areas	Experimental; spot treatments; high crash areas; state trend
When were first wider markings installed?	Between 1 and 2 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Between 1 and 2 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	7 miles for both edge line and centerlines	5,000+ miles
Are records of locations with wider markings kept?	No	Yes
Are records of locations with 4-inch markings kept?	Yes	No
If records exist for either of the two previous questions, where can they be found?	Request DOT paper files; request DOT maps; on-site visit	Request DOT paper files; request DOT maps; on-site visit
Details of records with regards to locations with wider markings	No records exist	Location; date of application; road type/class; number of miles installed; line type installed; AADT; speed limit; number of lanes; median type/width; lane/shoulder width; curve and tangent locations
What AADT records exist for sites where pavement marking width is known?	Several years before application date; a time after application date; percent heavy vehicles; percent night traffic	Several years before application date; a time after application date; percent heavy vehicles; percent night traffic
If records exist for either of the two previous questions, where can they be found?	Request DOT maps; on-site visit	Request DOT electronic files; request DOT paper files; request DOT maps; on-site visit
How often are AADT values updated for roads that have 6-inch-wide markings?	No records exist/NR	At least once a year
Are records kept for areas and dates of work zones on your roadways?	No	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	No records exist	Installation of chevrons or additional roadside delineators, advance curve warning signs, retroreflective pavement markings, rumble strips; new surface treatments; speed limit changes; roadway expansion
If records exist for either of the two previous questions, where can they be found?	No records exist	Request DOT electronic files; request DOT paper files; request DOT maps; on-site visit
Any public feedback on wider longitudinal pavement markings?	No	Yes
Has the public shown favorable response to currently installed wider markings?	NA	Yes
Has the public requested wider markings be installed or increased usage of wider markings?	No	Yes

Future wider marking installation planned?	No (not yet)	Yes
Please add the reasoning behind your answer to the previous question	Testing underway—no determination as to the effectiveness of treatment	Safety
Additional comments	Truck drivers indicated they liked the wider lines for the fact that they could speed with increased visibility of edge line; DOT is trying to slow speeds down by the appearance of a narrow road as well as increased visibility of large animals such as a moose due to contrast with wider markings	NR

NR—no response; NA—not applicable.

	Massachusetts DOT	Michigan DOT
Are wider markings used?	Yes	Yes
Typical width	6 inches	6 inches
Basis for implementation	High crash areas; state trend; research results; other—as part of highway safety plan	Recommendations from other states
When were first wider markings installed?	Greater than 3 years ago	Between 1 and 2 years ago
When were majority of wider markings installed?	Greater than 3 years ago	Between 1 and 2 years ago
Approximate number of miles of roadway with wider markings	2,200 miles, 9,500 lane miles of state highway	10,000 miles
Are records of locations with wider markings kept?	Uncertain—used on all roads	Yes
Are records of locations with 4-inch markings kept?	Uncertain—do not use 4-inch-wide markings	Yes
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT paper files
Details of records with regards to locations with wider markings	NR	Location; road type/class; number of miles installed; line type installed; AADT; speed limit; number of lanes; median type and width; lane width
What AADT records exist for sites where pavement marking width is known?	NR	Several years before application date; a time after application date; percent heavy vehicles
If records exist for either of the two previous questions, where can they be found?	NR	Online database
How often are AADT values updated for roads that have 6-inch-wide markings?	NR	Once every 2 years
Are records kept for areas and dates of work zones on your roadways?	No	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	Installation of retroreflective raised pavement markings and installation of rumble strips	NR
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT paper files
Any public feedback on wider longitudinal pavement markings?	Yes	Yes
Has the public shown favorable response to currently installed wider markings?	Yes	Yes
Has the public requested wider markings be installed or increased usage of wider markings?	No (6 inch currently used on all roads)	No
Future wider marking installation planned?	Yes	Yes
Please add the reasoning behind your answer to the previous question	DOT policy dictates use of 6-inch longitudinal markers on all roads	All edge lines to be 6 inches (restricted to edge lines only)
Additional comments	Yes	NR

NR—no response; NA—not applicable.

	Mississippi DOT	New Hampshire DOT
Are wider markings used?	Yes	Yes
Typical width	6 inches	6 inches
Basis for implementation	State trend; recommendations from other state	High crash areas
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Between 2 and 3 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	2,000-3,000 miles	500 miles
Are records of locations with wider markings kept?	No	Yes
Are records of locations with 4 inch markings kept?	No	Yes
If records exist for either of the two previous questions, where can they be found?	No records exist	Request DOT electronic files; request DOT paper files
Details of records with regards to locations with wider markings	No records exist	Location; date of application; road type/class; number of miles installed; line type installed; speed limit
What AADT records exist for sites where pavement marking width is known?	Several years before application date; a time after application date; percent heavy vehicles	Several years before application date; a time after application date
If records exist for either of the two previous questions, where can they be found?	Online database; request DOT electronic files	Request DOT electronic files; request DOT paper files
How often are AADT values updated for roads that have 6-inch-wide markings?	Once every 3 years	NR
Are records kept for areas and dates of work zones on your roadways?	Yes	No
Details of records of improvements made to roadways before and after being striped with wider markings	NR	Installation of chevrons or additional roadside delineators, advance curve warning signs, retroreflective pavement markings, rumble strips; new surface treatments; speed limit changes; roadway expansion
If records exist for either of the two previous questions, where can they be found?	No records exist	Request DOT electronic files; request DOT paper files
Any public feedback on wider pavement markings?	Yes	No
Has the public shown favorable response to currently installed wider markings?	Yes	No
Has the public requested wider markings be installed or increased usage of wider markings?	Yes	No
Future wider marking installation planned?	Yes	Yes

Please add the reasoning behind your answer to the previous question	DOT decision to use wider markings on all new construction and maintenance projects	New bypasses, highway speed roadways striped with 6-inch edge lines and medians; we also maintain all current 6-inch markings on a yearly basis
Additional comments	NR	NR

NR—no response; NA—not applicable.

	Nevada DOT	**New York DOT**
Are wider markings used?	Yes	Yes
Typical width	8 inches	6 inches
Basis for implementation	Recommendations from other states	Spot treatments; state trend; recommendations from other states; research results; other—to aid older drivers
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	600 miles (1,200 for both directions)	1,000 miles
Are records of locations with wider markings kept?	Uncertain—all interstate routes	Uncertain—records of markings exist; however, width may not be known
Are records of locations with 4-inch markings kept?	Uncertain—all other routes in state	Yes
If records exist for either of the two previous questions, where can they be found?	Other—total miles available upon request	Request DOT paper files; request DOT maps; on-site visit
Details of records with regards to locations with wider markings	No records exist	Location; date of application; road type/class; number of miles installed; line type installed; AADT; speed limit; number of lanes; median type and width; lane/shoulder width
What AADT records exist for sites where pavement marking width is known?	No records exist	Several years before application date; a time after application date; percent heavy vehicles
If records exist for either of the two previous questions, where can they be found?	No records exist	Request DOT electronic files; request DOT paper files; request DOT maps; on-site visit
How often are AADT values updated for roads that have 6-inch-wide markings?	NR	NR
Are records kept for areas and dates of work zones on your roadways?	No	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	NR	Installation of chevrons or additional roadside delineators, advance curve warning signs, retroreflective pavement markings, rumble strips; new surface treatments; speed limit changes; other—usually found in separate records
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT electronic files; request DOT paper files; request DOT maps; on-site visit
Any public feedback on wider longitudinal pavement markings?	Yes	Yes
Has the public shown favorable response to currently installed wider markings?	Yes	Yes

Has the public requested wider markings be installed or increased usage of wider markings?	NA/No	Yes
Future wider marking installation planned?	Yes	Yes
Please add the reasoning behind your answer to the previous question	Positive feedback on 8-inch lines used on the freeway	Used primarily at spot locations and as another option
Additional comments	NR	Nighttime visibility seemed to improve, while older drivers tended to like the wider markings; also more helpful in inclement weather

NR—no response; NA—not applicable.

	North Dakota DOT	Oregon DOT	Pennsylvania DOT
Are wider markings used?	No	No	Yes
Typical width	NA	NA	6 inches
Basis for implementation	NA	NA	Experimental; spot treatments
When were first wider markings installed?	NA	NA	Greater than 3 years ago
When were majority of wider markings installed?	NA	NA	Between 1 and 2 years ago
Approximate number of miles of roadway with wider markings	NA	NA	1,500 miles
Are records of locations with wider markings kept?	NA	NA	Yes
Are records of locations with 4-inch markings kept?	NR	NR	Yes
If records exist for either of the two previous questions, where can they be found?	NR	NR	Comment—skips are 6 inches, and edge lines are 4 inches on expressways
Details of records with regards to locations with wider markings	NA	NA	Road type/class
What AADT records exist for sites where pavement marking width is known?	NR	NR	A time after application date; percent heavy vehicles
If records exist for either of the two previous questions, where can they be found?	NR	NR	No records exist
How often are AADT values updated for roads that have 6-inch-wide markings?	NA	NA	At least once a year
Are records kept for areas and dates of work zones on your roadways?	NR	NR	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	NA	NA	NR
If records exist for either of the two previous questions, where can they be found?	NR	NR	No records exist
Any public feedback on wider pavement markings?	NA	NA	No
Has the public shown favorable response to currently installed wider markings?	NA	NA	No
Has the public requested wider markings be installed or increased usage of wider markings?	No	No	No
Future wider marking installation planned?	No	No	Yes
Please add the reasoning behind your answer to the previous question	NR	NR	6-inch-wide skip line is standard in Pennsylvania
Additional comments	NR	NR	NR

NR—no response; NA—not applicable.

	South Carolina DOT	South Dakota DOT
Are wider markings used?	Yes	Yes
Typical width	6 inches	6 inches
Basis for implementation	Other—use on interstate routes	Spot treatments
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Greater than 3 years ago	Between 2 and 3 years ago
Approximate number of miles of roadway with wider markings	840 miles	1,500 miles
Are records of locations with wider markings kept?	Yes	Comment—not in one easy location
Are records of locations with 4-inch markings kept?	Comment—all state roads have 4-inch markings	No
If records exist for either of the two previous questions, where can they be found?	Other—entire interstate system has been striped with 6-inch lines at various times over the last 10 years	On-site visit
Details of records with regards to locations with wider markings	Comment—all information exists but not easily obtained	NR
What AADT records exist for sites where pavement marking width is known?	Several years before application date; a time after application date; percent heavy vehicles	NR
If records exist for either of the two previous questions, where can they be found?	On-site visit	No records exist
How often are AADT values updated for roads that have 6-inch-wide markings?	At least once a year	NR
Are records kept for areas and dates of work zones on your roadways?	No	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	NR	Installation of chevrons or additional roadside delineators and advance warning signs; new surface treatments; speed limit changes
If records exist for either of the two previous questions, where can they be found?	No records exist	On-site visit
Any public feedback on wider pavement markings?	Yes	Yes
Has the public shown favorable response to currently installed wider markings?	Yes	Yes
Has the public requested wider markings be installed or increased usage of wider markings?	No	No
Future wider marking installation planned?	Yes	Yes
Please add the reasoning behind your answer to the previous question	6-inch-wide lines to be used on all interstate routes	For locations with narrow shoulders and where vehicles leaving the road may not be able to recover, more guidance desired

Additional comments	NR	Plans to incorporate records into geographical information system (GIS) database; public desires higher quality markings not specific on width or brightness

NR—no response; NA—not applicable.

Tennessee	DOT	Texas DOT
Are wider markings used?	Yes	Yes
Typical width	6 inches	6 inches
Basis for implementation	Other—higher visibility on interstate highways	Experimental
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	500 miles	500 miles
Are records of locations with wider markings kept?	Yes. Comment: standard for most interstate highways and resurfacing plans would generally have it listed as an item number	Yes
Are records of locations with 4-inch markings kept?	Yes. Comment: same as above	Yes
If records exist for either of the two previous questions, where can they be found?	Other (comment)—difficult task to look up plans for all interstates	NR
Details of records with regards to locations with wider markings	Comment: if log miles are known, some of the record details could be accessed electronically	NR
What AADT records exist for sites where pavement marking width is known?	Several years before application date; a time after application date; percent heavy vehicles	NR
If records exist for either of the two previous questions, where can they be found?	Online database	NR
How often are AADT values updated for roads that have 6-inch-wide markings?	At least once a year	NR
Are records kept for areas and dates of work zones on your roadways?	No	NR
Details of records of improvements made to roadways before and after being striped with wider markings	No records exist	NR
If records exist for either of the two previous questions, where can they be found?	No records exist	NR
Any public feedback on wider pavement markings?	Yes	No
Has the public shown favorable response to currently installed wider markings?	Yes	No
Has the public requested wider markings be installed or increased usage of wider markings?	No	No
Future wider marking installation planned?	Yes	No (not yet)
Please add the reasoning behind your answer to the previous question	We have used wider lines for several years; we feel the visible impact is beneficial to the public	Several districts within state currently testing wider markings
Additional comments	NR	NR

NR—no response; NA—not applicable.

	Washington DOT	West Virginia DOT
Are wider markings used?	No	Yes
Typical width	NA	6 inches/8 inches
Basis for implementation	NA	Experimental; state trend
When were first wider markings installed?	NA	Within the past year
When were majority of wider markings installed?	NA	Within the past year
Approximate number of miles of roadway with wider markings	NA	15 miles of 6 inch; 88 miles of 8 inch (West Virginia Turnpike utilized wider markings 4 years ago)
Are records of locations with wider markings kept?	NA	Yes
Are records of locations with 4-inch markings kept?	NR	Yes. Comment: Entire state currently using 4 inch except for the Turnpike and the approximately 15 miles of 6-inch line placed this year
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT maps; on-site visit
Details of records with regards to locations with wider markings	NA	Location; date of application; road type/class; number of miles installed; line type installed; AADT; speed limit; number of lanes; median type and width; lane/shoulder width; curve and tangent locations; terrain type
What AADT records exist for sites where pavement marking width is known?	NR	Several years before application date; a time after application date; percent heavy vehicles; percent night traffic
If records exist for either of the two previous questions, where can they be found?	NR	On-site visit
How often are AADT values updated for roads that have 6-inch-wide markings?	NA	Once every 2 years
Are records kept for areas and dates of work zones on your roadways?	NR	Yes
Details of records of improvements made to roadways before and after being striped with wider markings	NA	Installation of chevrons/additional roadside delineators, advance curve warning signs, retroreflective pavement markings and rumble strips; new surface treatments; roadway expansion
If records exist for either of the two previous questions, where can they be found?	NR	On-site visit
Any public feedback on wider pavement markings?	NA	Yes
Has the public shown favorable response to currently installed wider markings?	NA	Yes
Has the public requested wider markings be installed or increased usage of wider markings?	No	Yes
Future wider marking installation planned?	No	Yes
Please add the reasoning behind your answer to the previous question	Budget limitations; desire to improve current 4-inch striping first	Future deployment planned statewide on all expressways and interstate routes beginning in 2007; markings will utilize wet reflective properties that will meet ASTM 2176 and 2177

Additional comments	NR	6-inch markings to be used for all long lines on all interstates and four-lane expressways beginning next year

NR—no response; NA—not applicable.

Wi	sconsin DOT	Wyoming DOT
Are wider markings used?	No. Comment: Several years ago but none currently	Yes
Typical width	6 inches	8 inches
Basis for implementation	Experimental	Other—policy decision made years ago
When were first wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
When were majority of wider markings installed?	Greater than 3 years ago	Greater than 3 years ago
Approximate number of miles of roadway with wider markings	20 miles	5-10 miles
Are records of locations with wider markings kept?	NR	No
Are records of locations with 4-inch markings kept?	Yes	Yes. Comment: All of our lines, with the exception noted above, are 4-inch lines
If records exist for either of the two previous questions, where can they be found?	Request DOT electronic files; request DOT paper files	No records exist
Details of records with regards to locations with wider markings	NR	No records exist
What AADT records exist for sites where pavement marking width is known?	NR	Several years before application date; a time after application date; percent heavy vehicles
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT paper files
How often are AADT values updated for roads that have 6-inch-wide markings?	NR	At least once a year
Are records kept for areas and dates of work zones on your roadways?	NR	No
Details of records of improvements made to roadways before and after being striped with wider markings	NR	New surface treatments; roadway expansion
If records exist for either of the two previous questions, where can they be found?	NR	Request DOT electronic files
Any public feedback on wider pavement markings?	NR	No
Has the public shown favorable response to currently installed wider markings?	NR	No
Has the public requested wider markings be installed or increased usage of wider markings?	NR	No
Future wider marking installation planned?	No	No
Please add the reasoning behind your answer to the previous question	Currently focusing on installing more wet-reflective materials for lane lines on freeways and expressways	No current need due to relatively low traffic volumes
Additional comments	Installation was 15 years ago; roadway has since been reconstructed/repaved	Practice started years ago, now maintain lines annually

NR—no response; NA—not applicable.