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16. Abstract

This project was established to provide a means of conducting limited scope evaluations of numerous traffic control device issues. During the third year of the project, researchers completed assessments of three issues: a red border Speed Limit sign, sign and marking design for super high-speed roadways, and a comparison of retroreflectivity measurements made with portable and mobile retroreflectometers. The evaluation of the red border Speed Limit sign indicates that the red border treatment has a beneficial impact on reducing speeds at locations where the speed limit decreases. The researchers recommend using the red border to improve the conspicuity of Speed Limit signs at these locations. On super high-speed roadways, the researchers recommend that the legend on guide signs be a minimum of 22 inches and that an additional guide sign installation be provided in advance of the exit. Furthermore, sign sheeting for overhead signs on super high-speed roads should be limited to sheeting types that will provide adequate luminance. Pavement markings on these highways should be at least 6 inches wide. The researchers found that portable and mobile measurements are consistent with one another if both retroreflectometers are properly calibrated and operated. As part of the third-year activities, the researchers also evaluated lateral spacing for edge line rumble strips on two-lane highways, revised a set of guidelines for conducting a traffic signal warrant analysis, and are developing a handbook that will provide guidance on assessing and addressing the work zone impacts of significant projects.

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EVALUATION OF TRAFFIC CONTROL DEVICES: THIRD-YEAR ACTIVITIES

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DISCLAIMER

The contents of this report reflect the views of the authors, 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 the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names may appear herein solely because they are considered essential to the object of this report. This report does not constitute a standard, specification, or regulation. The engineer in charge was H. Gene Hawkins, Jr., P.E. #61509.

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CHAPTER 1: INTRODUCTION

INTRODUCTION

Traffic control devices provide one of the primary means of communicating vital information to road users. Traffic control devices notify road users of regulations and provide warning and guidance needed for the safe, uniform, and efficient operation of all elements of the traffic stream. There are three basic types of traffic control devices: signs, markings, and signals. These devices promote highway safety and efficiency by providing for orderly movement on streets and highways.

Traffic control devices have been a part of the roadway system almost since the beginning of automobile travel. Throughout that time, research has evaluated various aspects of the design, operation, placement, and maintenance of traffic control devices. Although there have been many different studies over the decades, recent improvements in materials, increases in demands and conflicts for drivers, higher operating speeds, and advances in technologies have created continuing needs for the evaluation of traffic control devices. Some of these research needs are significant and are addressed through stand-alone research studies at state and national levels. Other needs are smaller in scope (funding- or duration-wise) but not smaller in significance.

Unlike many other elements of the surface transportation system (like construction activities, structures, geometric alignment, and pavement structures), the service life of traffic control devices is relatively short (typically anywhere from 2 to 12 years). This shorter life increases the relative turnover of devices and presents increased opportunity for implementing research findings. The shorter life also creates the opportunity for incorporating material and technology improvements at more frequent intervals. Also, the capital cost of traffic control devices is usually less than that of these other elements. Research on traffic control devices can also be (but not always) less expensive than research on other infrastructure elements of the system because of the lower capital costs of the devices.

The traditional Texas Department of Transportation (TxDOT) research program planning cycle requires about a year to plan a research project and at least a year to conduct and report the results (often two or more years). With respect to traffic control devices, this type of program is best suited to addressing longer-range traffic control device issues where an implementation decision can wait two or more years for the research results.

In recent years, elected officials have also become more involved in passing ordinances and legislation that directly relate to traffic control devices. Examples include: creating the logo signing program, establishing signing guidelines for traffic generators such as shopping malls, and revising the *Manual on Uniform Traffic Control Devices* (MUTCD) to include specific signs. When these initiatives are initially proposed, TxDOT has a very limited time to respond to the concept. While the advantages and disadvantages of a specific initiative may be apparent, there may not be specific data upon which to base the response. Due to the limited available time, such data cannot be developed within the traditional research program planning cycle.

As a result of these factors (smaller scope, shorter service life, lower capital costs, and the typical research program planning cycle), some traffic control device research needs are not addressed in a traditional research program because they do not justify being addressed in a stand-alone project that addresses only one issue. This research project addresses these types of traffic control device research needs. This project is important because it provides TxDOT with the ability to:

- address important traffic control device issues that are not sufficiently large enough (either funding- or duration-wise) to justify research funding as a stand-alone project,
- respond to traffic control device research needs in a timely manner by modifying the research work plan at any time to add or delete activities (subject to standard contract modification procedures),
- effectively respond to legislative initiatives associated with traffic control devices,
- conduct traffic control device evaluations associated with a request for permission to experiment submitted to the Federal Highway Administration (FHWA) (see MUTCD section 1A.10),
- address numerous issues within the scope of a single project,
- address many research needs within each year of the project, and
- conduct preliminary evaluations of traffic control device performance issues to determine the need for a full-scale (or stand-alone) research effort.

FIRST-YEAR RESEARCH ACTIVITIES

During the first year of this research project, the research team undertook the research activities listed in Table 1-1. The first-year report describes the research efforts, results, and recommendations associated with these activities (*1*). Table 1-1 also presents brief descriptions of the results of the first-year efforts, along with the current implementation status.

Table 1-1. First-Year Activities.

Activity	Result	Status
Evaluate the effectiveness of dual logos.	Indicated that there is no evidence that the limited use of dual logos would be a problem.	TxDOT implemented dual logos with the logo signing contract that went into effect January 1, 2007.
Assess the impacts of rear-facing school speed limit beacons.	Found that rear-facing beacons improve compliance.	TxDOT incorporated rear-facing beacons in the 2006 Texas MUTCD.
Evaluate the impacts of improving Speed Limit sign conspicuity.	Found some indication that the red border improves compliance, but the data were not conclusive.	The effort was continued into the second and third years, and the results are described in each of those reports.
Crash-test a sign support structure.	The support structure failed the test.	The support structure was redesigned, and additional crash tests were conducted outside of this project. These crash tests were successful. FHWA has approved the redesign support, and it is being used in Texas.
Evaluate the benefits of retroreflective signal backplates.	There was no apparent benefit to using the retroreflective backplate at the study location.	FHWA issued an interim rule that allows the use of backplates under specific circumstances. Retroreflective backplates have been included in the 2006 Texas MUTCD.
Develop improved methods for locating no-passing zones.	Provided descriptions of multiple methods for determining the start and end of no-passing zones, but provided no testing of the accuracy of the methods.	A fourth-year activity will look at the feasibility of using global positioning system (GPS) data to establish no-passing zones.

SECOND-YEAR RESEARCH ACTIVITIES

During the second year of this research project, the research team undertook the research activities listed in Table 1-2. The second-year report describes the research efforts, results, and recommendations associated with these activities (*2*). Table 1-2 also presents brief descriptions of the results of the first-year efforts, along with the current implementation status.

Table 1-2. Second-Year Activities.

Activity	Result	Status
Evaluate the effectiveness of an extinguishable message Left Turn Yield sign.	Found the sign significantly reduced crashes and conflicts at the one location studied.	TxDOT will identify the benefits of the treatment in a letter to districts.
Evaluate the impacts of improving Speed Limit sign conspicuity.	There were significant long-term benefits to using the supplemental red border evaluated in the first year.	Evaluate the long-term benefits of the revised sign design in the third year.
Evaluate the benefits of dew-resistant retroreflective sheeting.	Dew-resistant sheeting reduces the formation of dew on the sign face and improves nighttime visibility of the sign.	TxDOT should conduct field testing of the prototype material to evaluate long-term performance.

THIRD-YEAR RESEARCH ACTIVITIES

During the third year of this research project, the research team undertook the following research activities:

- Evaluate the long-term impacts of improving Speed Limit sign conspicuity through a modified sign design (Chapter 2).
- Develop recommendations for sign and marking design for super high-speed roadways (Chapter 3).
- Compare and evaluate pavement marking retroreflectivity measurements made with portable and mobile retroreflectometers (Chapter 4).
- Update TxDOT Traffic Signal Warrant Guidelines (Chapter 5).
- Lateral Placement of Rumble Strips on Two-Lane Highways (Chapter 5).
- Begin development of the Work Zone Impacts Handbook (Chapter 5).

This report describes these activities in the chapters indicated in parenthesis. Chapter 6 provides an overall summary for the third year. Each of the chapters in this report has been prepared so that it can be distributed as a stand-alone document if desired.

REFERENCES

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2. Hawkins Jr., H.G., R. Garg, P.J. Carlson, and A.J. Holick. *Evaluation of Traffic Control Devices: Second Year Activities*. FHWA/TX-06/0-4701-2, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2005.

CHAPTER 2:
RED BORDER SPEED LIMIT SIGN

INTRODUCTION

Speed Limit signs play the important role of informing drivers of safe travel speeds along the nation's highways. Unfortunately, Speed Limit signs do not always achieve the desired effect resulting in vehicles traveling at unsafe speeds that can lead to fatal accidents. In 2004 the United States had 13,192 speed related fatalities which accounted for 30 percent of the nation's roadway fatalities. Additionally, in 2000 all speed related crashes accounted for a total cost of $40,390 million (*1*). This cost statistic leads to the conclusion that steps need to be taken to increase drivers' compliance with speed limits.

Researchers have several theories for why there is low compliance with speed limits. It is proposed that some drivers do not see, and therefore do not react to, posted Speed Limit signs. Alternatively, there is the philosophy of drivers not responding to Speed Limit signs because they do not see the need for a decrease in speed. An instance where the latter theory applies is on approaches to rural cities and towns. Drivers do not comply with the speed zones approaching these areas because the reduced speeds are well in advance of the communities and the importance of the speed zone is not accurately conveyed. The current research project addresses the lack of speed limit compliance at these rural locations and explores one possible solution.

This report outlines a third-year follow-up project which first began in 2004 to study the effects of adding a red border to Speed Limit signs to increase their conspicuity to drivers (*2, 3*). The desire was to see whether or not the red border would convey an increased sense of importance for Speed Limit signs and therefore result in slower speeds. The site locations for the research were at approaches to rural cities and towns where speed limits decrease from 70 mph to 55 mph.

Experimental Treatment

The philosophy of the researchers was that if drivers take more notice of Speed Limit signs and recognize an increased sense of importance due to sign modifications; then a higher degree of compliancy will be achieved. To accomplish this goal a red border was added to

Speed Limit signs to attract the attention of drivers. In the first year of the project rectangular red sheeting material that was 6 inches taller and 6 inches wider than the standard Speed Limit sign was placed behind the original signs. This design provided a 3 inch red border around the entire Speed Limit sign. In year two of the project a modified Speed Limit sign was devised. To create the modified Speed Limit sign the original black border was removed and replaced with a 1 inch red border along with the additional 3 inch red border added from the previous year's project. This design produced a Speed Limit sign with a red border totaling 4 inches. Examples of the standard Speed Limit sign, standard Speed Limit sign with red border, and modified red border Speed Limit sign are located in Figure 2-1.

a. Standard Speed Limit Sign (R2-1)

b. Standard Speed Limit Sign with Red Border

c. Modified Speed Limit Sign

Figure 2-1. Standard and Experimental Signs.

Project Objectives

The objective of the third-year follow-up project was to determine the long-term effect of the modified Speed Limit signs. Data were collected at three of the locations from the second-year project to determine whether or not the compliance of the Speed Limit signs had increased, decreased, or remained the same from when the modified signs had first been installed. The long-term data were collected 8 to 14 months after the end of Project 0-4701-2.

BACKGROUND INFORMATION

Over the years there have been several attempts to increase the compliance of speed limits. Report 0-4701-2 outlines many of these approaches. For example, the report discusses an attempt in Milwaukee to monitor the effect of overhead mounted Speed Limit signs. Also discussed was the United Kingdom's use of vehicle activated signs that respond to vehicles that are exceeding set speed limits (*3*). Additionally, the report from Project 0-4701-2 makes mention of the use of red borders on international speed limit signs (*2*). Figure 2-2 shows a few examples of these international Speed Limit signs. The Texas Transportation Institute conducted the first known experimental treatment within the United States of Speed Limit signs with red borders. This project explored the effect of the Speed Limit sign shown in Figure 2-1b. The results from this project were outlined in the 2003 research report entitled *Traffic Operational Impacts of Higher-Conspicuity Sign Materials* (*4*). This particular research project showed promising results and led to the current expanded research project and the new modified Speed Limit sign.

(a) International Speed Limit Sign	(b) International Speed Limit Sign with Alternative Coloring (Used in Sweden)	(c) Speed Limit Sign Used in France

Figure 2-2. International Speed Limit Sign (Speed Limit in km/h).

THIRD-YEAR PROJECT APPROACH

The purpose behind the third-year follow-up project was to evaluate the performance of the modified Speed Limit sign 8 to 14 months after initial installation. Researchers wanted to determine whether or not drivers' response to the modified signs had improved, remained the same, or decreased over time.

Long-Term Study Sites

Three of the original four sites from the second-year project were followed up on in this project. The three sites were:

- Site 1 – SH 7 eastbound (EB) traffic approaching Marlin,
- Site 2 – US 79 northbound (NB) traffic approaching Oakwood, and
- Site 3 – FM 39 northbound traffic approaching Normangee.

Site 1 – SH 7 Eastbound Traffic Approaching Marlin

State Highway 7 is a two-lane highway with shoulders on either side of the roadway where the speed limit approaching the modified 55 mph Speed Limit sign is 70 mph. The area surrounding the small town of Marlin is rural. The previous sign, before the modified Speed Limit sign was installed, was 24×30 inches with high intensity sheeting. The modified Speed Limit sign that was left up for the long-term study was made of high intensity sheeting.

Site 2 – US 79 Northbound Traffic Approaching Oakwood

The Oakwood location consists of a two-lane roadway with shoulders in either direction with the speed limit approaching the modified 55 mph Speed Limit sign set at 70 mph. The area surrounding Oakwood is rural. The sign that was previously posted at the Oakwood site was 24×30 inches and consisted of engineering grade sheeting. For the long-term study a modified microprismatic Speed Limit sign was installed. Researchers compared the data collected during this project to data from the standard microprismatic Speed Limit sign tested during the second-year project.

Site 3 – FM 39 Northbound Traffic Approaching Normangee

As with the previous two sites the highway approaching Normangee has two lanes with shoulders on either side of the roadway. The speed limit approaching the modified 55 mph Speed Limit sign is 70 mph. The original sign was 24×30 inches and made of engineering grade sheeting. The long-term study was conducted on high intensity sheeting and was compared to the high intensity standard Speed Limit sign data from the second-year project.

TREATMENT FOR LONG-TERM STUDY

Below is a list of the Speed Limit signs and the abbreviations that are used to designate the signs in this project:

- standard Speed Limit sign with high intensity sheeting, HI_S;
- standard Speed Limit sign with microprismatic sheeting, MP_S;
- modified red border Speed Limit sign with high intensity sheeting, HI_R; and
- modified red border Speed Limit sign with microprismatic sheeting, MP_R.

DATA COLLECTION FOR LONG-TERM STUDY

The same data collection procedure used in the second-year project was copied for the third-year follow-up effort. Three measurement points were set up at each location, as seen in Figure 2-3. An overview of the measurement points is below.

- Point 1 was approximately one-half mile before the modified 55 mph Speed Limit sign. This is the control point. This distance was selected since it was well out of the sight distance of the Speed Limit sign. This allowed for the determination of the free flow speed of vehicles before the reduction in speed limit. It provided a good base point by which to measure the effectiveness of the modified Speed Limit sign.
- Point 2 was located approximately 250 ft before the modified Speed Limit sign. This is the legibility point. At this point the driver should have been able to easily read the Speed Limit sign.
- Point 3 was located approximately 500 ft downstream of the modified Speed Limit sign. This is the downstream point. At this point the driver should have responded to the reduction in speed and slowed down to the required speed limit.

Table 2-1 presents dates for the collection of the before, short-term, and long-term treatments. The first long-term after evaluation (LTA_1) is the first (or only for two sites) date for the long-term data collection. The second long-term after evaluation (LTA_2) is the second date for the Oakwood site.

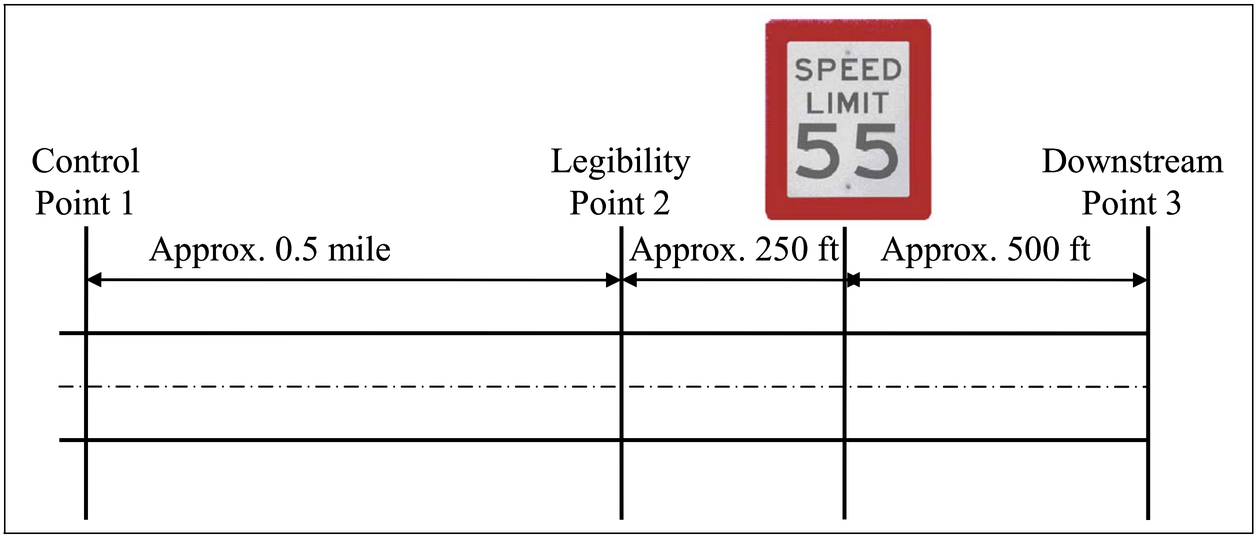

Figure 2-3. Data Collection Layout.

Table 2-1. Data Collection Dates (Month/Year).

Test Sites	Before Dates (B)	Short-Term After Dates (STA)	Long-Term After Dates (LTA_1 or LTA_2)*
SH 7 – Marlin	12/04	5/05	7/06
US 79 – Oakwood	5/05	6/05	2/06, 6/06
FM 39 – Normangee	5/05	6/05	2/06

Note: *LTA_1 represents the first or only date, LTA_2 represents the second date.

DATA REDUCTION

First, the data from each site were scanned and edited so that only vehicles that could be tracked through all three measurement points were used in the study. Next, the data were sorted to produce a free-flowing anomalous speed sample. Drivers that responded to vehicles in their proximity or that were turning needed to be extracted from the data since they would not reflect a true response to the modified signs. To accomplish this, vehicles exhibiting the following criteria were eliminated from the data:

- non-free-flowing vehicles (<6-second headway);
- motorcycles;
- vehicles with excessively slow speeds (e.g., speed 25 mph or more under the speed limit); and
- vehicles with excessively fast speeds (e.g., speeds greater than 95 mph).

DATA ANALYSIS

For the long-term analysis the data collected for the three sites were divided into daytime and nighttime categories. Daytime was classified as being from sunrise to sunset while nighttime was taken to be the time 30 minutes after sunset to 30 minutes before sunrise. This experimental setup called for the data to be analyzed for only 23 hours per day. For the long-term analysis all vehicle classifications were grouped together in the daytime and nighttime categories. There was no special treatment of passenger and heavy vehicles as conducted in previous projects. The mean speed, 85^{th} percentile speed, and percent of vehicles exceeding a specific speed threshold were the three Measures of Effectiveness (MOE) used for the long-term analysis.

Mean Speeds

The statistical software SPSS was used to calculate mean speeds and to test for statistical differences. The Generalized Linear Model Uni-variate was used to accomplish these tasks. If there were statistically significant differences in the variances according to Levene's Test then Tamhane's T2 test was used to compare the differences in means. If there were not statistically significant differences in the variances then Tukey's HSD test was used to compare means. The analysis of the means was computed separately for daytime and nighttime vehicles. In this analysis the different sign studies (i.e., before, short-term after, and long-term after) were used as independent variables while the vehicles' speeds were used as dependent variables.

85^{th} Percentile Speeds

Microsoft Excel aided in calculating the 85^{th} percentiles at the measurement points for each roadway during the daytime and nighttime. Many times the 85^{th} percentile is used to set the Speed Limit for roadways. It was hypothesized that, like the means, the difference in the 85^{th} percentiles would provide a good indicator of the effectiveness of the modified signs. However, no statistical analyses were applied to the 85^{th} percentiles to determine if the differences were statistically significant.

Percent Exceeding a Specified Speed Threshold

The percentage of vehicles exceeding specified speeds of 70, 65, 60, and 55 mph were calculated at each site's measurement points. Microsoft Excel was employed to run these calculations. Even though no additional statistical analyses were completed on these values they did provide some insightful trends. By comparing the increases and decreases in the differences of means and the percentage of vehicles exceeding specified speed limits, conclusions could be drawn concerning the effect the modified signs had on the upper extremities of the speed data. For example, if the average vehicle speed at a site saw a decrease along with a decrease in the percent of vehicles exceeding 70 mph then it could be inferred that the faster vehicles in the sample had decelerated due to the modified signs (*3*).

RESULTS FOR LONG-TERM STUDY

When analyzing the results collected from the research care must be taken to ensure that correct conclusions are drawn and that the scope of the statistical analyses is understood. The following paragraphs explain some of the assumptions that were made along with explanations and results gathered from the data.

First off, it must be noted that the mean speeds at the downstream point are affected by the mean speeds at the control point. For example, if the after condition mean speeds at the control point are statistically higher than those of the before conditions then it would be assumed that the after condition mean speeds at the downstream point would be higher than the before conditions. So, when examining the short-term and long-term treatments as shown in Table 2-2, Change in Mean Speeds, all but 5 of the 14 cases for the control point showed statistical differences. Since a majority of the mean speeds at the control point are not equal then direct comparisons cannot be made for the before and after conditions at the downstream point.

Therefore when looking at the results from the collected data there were several alternative trends that would indicate positive benefits of the modified Speed Limit sign. Changes in the mean speeds were calculated for short-term after and before conditions and for long-term after and before conditions at each of the measurement points. When examining the differences between before and after conditions for the control point (i.e., Long-term After - Before) and downstream point (i.e., Long-term After - Before) the following trends indicate positive effects:

- the reduction at the downstream point is greater than the reduction at the control point,
- an increase at the downstream point is less than the increase at the control point, and
- when there is a reduction at the downstream point and an increase at the control point.

In the long-term analysis the change in mean speeds and change in 85th percentile speeds provided 16 different scenarios among the three sites where these trends could be tested. Table 2-2 shows the change in mean speeds while Table 2-3 outlines the change in 85th percentile speeds. There were 8 of the 16 cases for the long-term treatments that showed positive benefits as described above. Seven of the eight cases that did not show positive benefits were made of microprismatic sheeting. The short-term analysis produced nine positive benefit cases out of a possible 12. In the short-term after treatment all three cases that did not show positive benefits included signs consisting of microprismatic sheeting. So, the long-term treatment follows a similar trend found in the second-year project concerning the effect of microprismatic sheeting in the modified red border Speed Limit sign.

Table 2-2. Change in Mean Speeds.

Location	Condition	Measure	STA-Before	LTA$_1$-Before	LTA$_2$-Before
US 79	Daytime	Control	-0.7*	-1.4*	-0.4
US 79	Daytime	Downstream	-0.8*	-0.2	0.7*
US 79	Nighttime	Control	-1.2*	-1.6*	-1.0*
US 79	Nighttime	Downstream	-1.1*	-0.7	-0.5
FM 39	Daytime	Control	0.2	-1.8*	-
FM 39	Daytime	Downstream	-3.8*	-3.1*	-
FM 39	Nighttime	Control	-0.7	-3.0*	-
FM 39	Nighttime	Downstream	-4.3*	-2.6*	-
SH 7	Daytime	Control	3.8*	0.01	-
SH 7	Daytime	Downstream	-1.7*	-0.3	-
SH 7	Nighttime	Control	3.8*	0.38	-
SH 7	Nighttime	Downstream	-0.6	-0.1	-

Notes: * The mean difference is significant at the 0.05 level.
There were two long-term after studies at the US 79 site.

Table 2-3. Change in 85th Percentile Speeds.

Location	Condition	Measure	STA	LTA_1	LTA_2
US 79	Daytime	Control	-1	-1.3	-0.8
US 79	Daytime	Downstream	-1	-0.7	0.2
US 79	Nighttime	Control	-2	-2.2	-1.2
US 79	Nighttime	Downstream	-1.1	-1.5	-0.7
FM 39	Daytime	Control	0	-2	-
FM 39	Daytime	Downstream	-4	-4.5	-
FM 39	Nighttime	Control	-1	-4.2	-
FM 39	Nighttime	Downstream	-4	-2.1	-
SH 7	Daytime	Control	4.6	0.5	-
SH 7	Daytime	Downstream	-1.7	0	-
SH 7	Nighttime	Control	4.7	0.9	-
SH 7	Nighttime	Downstream	0	-12.1	-

Notes: * The mean difference is significant at the 0.05 level.
There were two long-term after studies at the US 79 site.

Other indicators of the modified sign's effectiveness were the trends found in the percent of vehicles exceeding specified speed thresholds. In this area the three locations all exhibited different results. At SH 7 and FM 39 the data suggested positive effects from the modified signs; although, each did so in different ways. At SH 7 the percentage of vehicles exceeding the specified speeds of 70, 65, and 60 mph were anywhere from 20 to 50 percent over the before conditions at the legibility point (see Tables A-16 and A-18). However, at the downstream point, all of the values are equal to or less than those of the before conditions. This finding suggests that the vehicles exceeding the speed limit are slowing down when they encounter the modified Speed Limit sign. This trend holds for both the short-term and long-term treatments.

The data from FM 39 suggest the same end result as SH 7 but did so in an alternate way. The percentage of vehicles exceeding the threshold speeds at the downstream point are consistently 10 percent less than the before conditions (see Tables A-12 and A-14). The effect of the modified speed limit does decrease slightly over time but still achieves the desired result of influencing driver compliance.

As for US 79 it did not show the same results as SH 7 and FM 39. Over the course of the short-term and long-term treatment the percentage of vehicles exceeding threshold speeds did not drastically change. This result was not surprising, even though there really is not an explanation for it, considering the results the microprismatic sheeting has produced. Tables A-7 through A-18 in the Appendix contain the data for the Percent Exceeding Results.

One last frame of reference for the effectiveness of the modified signs is Table 2-4. A positive result in Table 2-4 indicates a deceleration from the control point to the downstream point. As can be seen, the change in mean speeds from the control point to the downstream point at each site leveled off over the long-term treatment.

Table 2-4. Change in Mean Speeds from Control to Downstream.

Location	Condition	Before	Short-Term After	Long-Term After$_1$	Long-Term After$_2$
US 79	Daytime	8.2	8.3	7.0	7.1
US 79	Nighttime	7.0	6.9	6.2	6.5
FM 39	Daytime	6.0	10.1	7.2	-
FM 39	Nighttime	6.3	9.9	5.8	-
SH 7	Daytime	5.3	10.8	5.6	-
SH 7	Nighttime	6.2	10.6	6.7	-

FINDINGS AND RECOMMENDATIONS

Overall, the modified red border Speed Limit signs did show some positive results in the research project. However, the decreases in mean speeds at the downstream point were small. The only place where the mean speed showed an impressive decrease for this project was at the downstream on FM 39. But, at this site the mean speed at the control point was an equal amount below the before mean speed which reduces the magnitude of improvement. Additionally, even though the effects of the modified signs were beneficial in the long-term treatment they did decrease from the short-term treatment. This finding suggests that drivers were becoming accustomed to the modified signs. These results are contrary to what was found in portions of the second-year project. In the second-year project the long-term analysis of the standard red border Speed Limit sign (Figure 2-1b) showed increased benefits from the signs over time.

As for the modified red border Speed Limit signs, one good benefit was seen in the percent of vehicles exceeding specified speed thresholds. As mentioned in the results, the data imply that the number of vehicles speeding decreased due to the modified sign. But, this treatment did not decrease the mean speeds by a significant amount. Additionally, for an unknown reason, the high intensity sheeting consistently out-performed the microprismatic sheeting.

In closing, the modified red border Speed Limit sign did not show a large magnitude of increase in speed limit compliance. However, the third-year results, when combined with those of the first and second year, show overall benefits. Therefore, the researchers recommend that a red border be included in the MUTCD as an option for improving conspicuity of the Speed Limit sign. If the red border is used with the Speed Limit sign, the researchers recommend that it be the standard Speed Limit sign with an added red border (Figure 2-1b) as opposed to the modified red border Speed Limit sign (Figure 2-1c). The standard Speed Limit sign with red border showed better results and is easier to implement in the field. The researchers did not find any evidence that the type of sheeting used on the sign impacted nighttime driver compliance with the sign.

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CHAPTER 3:
SIGN AND MARKING DESIGN FOR SUPER HIGH-SPEED ROADWAYS

INTRODUCTION

The proposed Trans-Texas Corridor (TTC) presents new challenges for road designers because of its unique design parameters. A significant feature of the TTC is the expectation that the posted speed limits may be in the 80 to 90 mph range. This increase in speed will decrease the amount of time drivers will have to read and respond to signs and pavement markings along the roadway. To evaluate whether motorists would be provided with adequate signs and markings, researchers performed a limited evaluation of the legibility and visibility impacts of higher speeds on sign and marking design. The evaluation evaluated the legibility impacts of speed on sign reading and response to determine the appropriate letter height for freeway guide signs, as well as visibility issues associated with pavement markings to determine the appropriate pavement marking width for lane lines and edge lines.

SELECTION OF DESIGN PARAMETERS

Typically, the effectiveness of a sign and a pavement marking depends on visibility, legibility, driver needs, speed, and type of vehicle. Due to the variance in needs of driver population using the highway, it is important to include all of the design parameters. For this project, the following design parameters were selected.

- Design speed – 90 mph
- Roadway Geometry – tangent section with two 12 ft lanes and 0 percent grade
- Type of vehicle – passenger vehicle
- Type of sign – overhead guide sign, height of center of sign taken to be 20 ft above the driver eye height
- Maximum sign width – 24 ft
- Amount of information on sign – Varies
- Legibility index for signs – 30 ft/in, 40 ft/in, and 50 ft/in
- Type of marking – long line (lane line and edge line)

OVERHEAD GUIDE SIGNS ANALYSIS

The research identified two controlling parameters for choosing an appropriate letter height for overhead guide signs on the TTC, sign width and legibility height. The sign width parameter determines the maximum letter height that can be accommodated within a sign of a set width. In comparison, the legibility height determines the minimum letter height that is needed to provide the appropriate legibility distance. Each of these parameters is addressed separately.

Sign Width

One of the limiting factors associated with an overhead guide sign is the sign width. The width of an overhead guide sign is dependent on the length of the words on the sign, which is a function of the word(s) and the letter height. The longest word typically found on an overhead guide sign is the destination (which is usually the name of a city), so this activity focused on determining sign width and lettering height based on names of Texas cities. After defining the average destination length, the maximum letter height was calculated for a given sign width.

Average Word Length for Texas City Names

The number of characters for a city name is important in sign design because more characters require more sign width. The analysis is based on establishing a standard letter height for all overhead guide signs on the TTC to maintain uniformity. The researchers used several methods to identify the length of word that should fit within the maximum sign width.

In the first method, the researchers developed a list of Texas cities with a population over 50,000 using data from the 2000 census and counted the number of letters in each city name, including counting the blank as a character for city names that consisted of two words (*1*). Researchers then calculated the average, mode, median, minimum, and maximum city name lengths. These data represent the cities that are most likely to be shown as a destination in a freeway guide sign on the TTC. These same data were then used to calculate a weighted average city name length, where the sum of the length times population was divided by the sum of the population. Then the researchers generated a list of Texas cities with a population over 5,000 and calculated the same statistics. Finally, researchers calculated the length of city name for those cities that are official control cities for the Interstate Highway System (Abilene, Amarillo, Austin, Beaumont, Corpus Christi, Dallas, El Paso, Fort Worth, Galveston, Houston, Laredo, Lubbock, San Antonio, Texarkana, Van Horn, Waco, and Wichita Falls) (*2*). Results for these analyses are shown in Table 3-1. From this list, it is simple to see that only cities that have eight or more characters should be considered in the analysis. Table 3-2 is a list of the cities with a population over 50,000 with eight or more characters in the city name, since only larger cities would typically be listed as a destination in a freeway guide sign.

Table 3-1. Statistical Results for Length of Texas City Names (Characters).

Parameter	City Population > 50,000	City Population > 5,000	Interstate Control Cities
Number of Cities	48	345	17
Average Length (no. of characters)	8.7	8.8	8.2
Weighted Average Length	8.1	8.3	7.9
Mode	7	8	7
Median	8	8	8
Longest Name	20	23	14
Shortest Name	4	4	4
85^{th} percentile length	11	12	11

Table 3-2. Cities over 50,000 Population with Eight or More Characters in the City Name.

City Name	Number of Characters in City Name	City Name	Number of Characters in City Name
North Richland Hills	20	Lewisville	10
College Station	15	Sugar Land	10
Corpus Christi*	14	Round Rock	10
Grand Prairie	13	Arlington	9
Wichita Falls*	13	Harlingen	9
The Woodlands	13	Galveston*	9
Flower Mound	12	Amarillo*	8
San Antonio*	11	Pasadena	8
Brownsville	11	Mesquite	8
Port Arthur	11	Beaumont*	8
Fort Worth*	10	Longview	8
Carrollton	10	Victoria	8
Richardson	10	McKinney	8
San Angelo	10	Missouri City	8

Note: * indicates an Interstate Highway control city.

After considering the statistical analysis for length of city names, the city of San Antonio was chosen as the city to evaluate for these guidelines. San Antonio was selected as the design basis as it is an existing Interstate Highway control city and it has the same number of characters as the 85th percentile value for cities over 50,000 population and the 85th percentile character length for the control cities. Although there are names longer than San Antonio, it provides a reasonable benchmark to use in this project.

Computation of Sign Widths

The first step to deciding which letter height provides adequate legibility is to figure out the maximum letter size allowable for a two-lane overhead guide sign. Larger letters require more spacing between letters and wider side clearances. As these distances increase the sign width required also increases. For the analysis, the researchers assumed a maximum practical sign width of 24 ft, which represents a sign that spreads over two lanes. Therefore, by defining which letter heights will require a sign less than 24 ft, the researchers can then look at the variables they are able to control such as units of information and the design legibility index to find the best combination for adequate legibility.

For this project the researchers chose the city of "San Antonio" to place on the overhead guide sign. The font chosen was Clearview alphabet 5W which has a height/width ratio of 1:0.773 and a stroke width-to-height ratio of 1:5.1. Using this font, the sign width was computed by using the known side clearances and letter widths that the *Manual on Uniform Traffic Control Devices* (MUTCD) website provides (*3*). The word spacing, border spacing, and border widths also add to the overall width of a sign. The spacing between the two words and the border spacing are equal to the uppercase letter height. The actual border width is assumed to be 2 inches because the overall area of the sign will be greater than 60 square ft (*4*). Using the information provided, Table 3-3 was constructed to illustrate the total sign width required for various letter heights. It is important to note that these widths are an approximation. For exact sign width computation SignCAD should be used. The table shows that the maximum letter height for "San Antonio" is 22 inches because the sign width associated with it is less than 24 ft.

Table 3-3. Sign Widths Required for Variable Letter Heights Using "San Antonio."

Letter Height (in)	Sign Width (ft)
16	17.3
17	18.3
18	19.4
19	20.4
20	21.5
21	22.6
22	23.6
23	24.7
24	25.7
25	26.8
26	27.9

Legibility Height

The legibility height determines the minimum allowable letter height for a word so that a driver is able to read the sign before the vehicle reaches the cutoff point where the sign can no longer be read. To calculate the legibility height, the distance at which the driver must begin reading the sign is first computed. This required reading distance consists of the cutoff point plus the reading distance. The legibility height is computed by dividing the required reading distance by the legibility index for an average driver. The legibility index defines the distance at which a person can read a letter with a height of 1 inch.

The evaluation of determining an appropriate reading time for computing the required reading distance will first be discussed followed by the computation of the legibility height.

Evaluation of Reading Time

The reading time is the amount of time needed by the average driver to read an entire sign. An overhead guide sign can have several panels that constitute one sign. During this reading time the driver will typically shift his or her eyes back and forth from the road to the sign, reading only parts of the sign at a time. Researchers have attempted to model this reading behavior and have generated models that can predict reading time based on the number of information units and number of sign panels.

The earliest and most commonly used model was developed by Mitchell and Forbes in which the reading time was the number of familiar words divided by three plus one second (5). This model was modified by Odelscalchi et al. to include the minimum time of 2 seconds for a sign to be read (6). The final equation used is shown as Equation 3-1 where n is the number of units of information and T_r is reading time and will be referred to as Method 1. A unit of information can be a word, a number, or a symbol.

$$T_r = 2 + n/3 \qquad \text{Equation (3-1)}$$

Table 3-4 lists the number of information units and corresponding reading times for the method described above.

Table 3-4. Method 1: Reading Times.

Number of Information Units	Reading Times (Seconds)
2	2.67
3	3.00
4	3.33
5	3.67
6	4.00
7	4.33
8	4.67
9	5.00
10	5.33
11	5.67
12	6.00

A second method (referred to as Method 2), proposed by Messer and McNees (7), uses a graph to find the required reading time. In the second method, the graph gives the time needed for reading the guide signs and does not account for the driving task. To compute the required reading time, Messer and McNees proposed the reading time should be divided by a factor of 0.56 to account for the time needed for the driving task, which is similar to how the first method adds two seconds. Table 3-5 is the summary of adjusted reading times proposed by Messer and McNees (7). The legibility distance (LD) and letter height calculated by using these two methods are detailed in the next section.

Table 3-5. Method 2: Reading Times

Number of Information Units	Reading Times (seconds)			
	2 Panels	3 Panels	4 Panels	5 Panels
8	5.20	5.30	5.50	5.50
9	5.30	5.40	5.60	5.80
10	5.39	5.54	5.71	5.98
11	5.45	5.63	6.04	6.25
12	5.53	5.71	6.18	6.43

Analysis of Required Letter Heights for Legibility

The first step in calculating the legibility height (LH) is to determine the required reading time. The inputs for the required reading time are amount of information and number of sign panels. Method 1 uses only the amount of information, whereas Method 2 incorporates both the amount of information and number of sign panels. Both methods will be analyzed to aid in the researchers' recommendations. The required reading time is multiplied by the vehicle speed to compute the distance traveled while reading. Next the distance at which the driver can no longer view the sign because the driver's view is cut off from the top of the windshield is found. The distance traveled while reading is added to the cutoff distance to give the required legibility distance. The legibility height, also referred to as the required letter height, is then calculated by dividing the legibility distance by the legibility index of a typical driver. This process of computing the legibility is shown below.

1) reading time, T_r;
2) traveling distance $X = 1.47 * V * T_r$ (ft), V is speed in mph and T_r is time in seconds;
3) lost legibility distance due to cutoff vertical angle of 7.5 degrees (6) = 150 ft (assuming center of sign is 20 ft above the driver eye height);
4) legibility distance required LD = X +150 (ft); and
5) required letter height LH = LD / Legibility Index.

The steps listed above are used to calculate the required letter heights by changing the amount of information, number of sign panels, and legibility index (LI). The units of information are varied from 2 to 12 units because these amounts can be found in freeway conditions. The legibility indexes used are 30, 40, and 50 ft/in. These values were chosen because they are common design criteria. Table 3-6 presents the required letter heights for different combinations of information units and legibility indexes for the first method.

Table 3-6. Method 1: Required Letter Heights for a 90 mph Freeway.

Number of Information Units	Letter Heights for Specific Legibility (in)		
	30 ft/in	40 ft/in	50 ft/in
2	16.8	12.6	10.1
3	18.2	13.7	10.9
4	19.7	14.8	11.8
5	21.2	15.9	12.7
6	22.6	17.0	13.6
7	24.1	18.1	14.5
8	25.6	19.2	15.3
9	27.1	20.3	16.2
10	28.5	21.4	17.1
11	30.0	22.5	18.0
12	31.5	23.6	18.9

For the second method the same lost legibility, traveling, and legibility distance equations are used along with the required letter height equation to compute the values for letter heights presented in Table 3-7. These values are dependent upon the adjusted reading times that were formulated from the times presented in Table 3-5.

Table 3-7. Method 2: Required Letter Heights for a 90 mph Freeway

Number of Information Units	2 Panels with LI (ft/in) of:			3 Panels with LI (ft/in) of:			4 Panels with LI (ft/in) of:		
	30	40	50	30	40	50	30	40	50
8	27.9	20.9	16.8	28.4	21.3	17.0	29.3	21.9	17.6
9	28.4	21.3	17.0	28.8	21.6	17.3	29.7	22.3	17.8
10	28.8	21.6	17.3	29.4	22.1	17.7	30.2	22.6	18.1
11	29.0	21.8	17.4	29.8	22.4	17.9	31.6	23.7	19.0
12	29.4	22.0	17.6	30.2	22.6	18.1	32.3	24.2	19.4

Assuming each sign panel is the width of two lanes, overhead signs will consist of only one panel for this project although it is possible in the future for parts of the TTC to have four lanes. Therefore, the researchers chose to only look at two panels for Method 2.

Analysis of Sign Luminance for Letter Heights

The final step in the letter height analysis process was an evaluation of the luminance needed to meet driver legibility needs. Previous research on minimum retroreflectivity levels for overhead guide signs identified the minimum sign luminance associated with various accommodation levels and legibility indices *(8)*. Table 3-8 indicates that 85 percent of older drivers would be accommodated at a legibility index of 40 ft/in if the sign legend luminance is at least 11.7 cd/m^2.

Table 3-8. Threshold Luminance Values by Accommodation Level (cd/m^2).

Older Driver Accommodation Level (percent)	Legibility Index (ft/in)		
	20	30	40
75	0.5	1.9	5.7
85	0.8	3.8	11.7
95	1.6	11.7	19.2
98	1.7	16.5	31.5

Note: Based on white Series E(Modified) 16/12-inch uppercase/lowercase words on a green background.

The researchers evaluated the luminance provided in an overhead guide sign by using the ERGO program produced by Avery-Dennison to calculate sign luminance for several types of sign sheeting. The critical distance for evaluation is 880 ft (22 inch letter × 40 ft/in legibility index). The analysis indicated that an overhead freeway guide sign centered over two lanes with a sign centroid located 24 ft above the road surface would provide adequate luminance for a light truck or truck or sport utility vehicle (SUV) type of vehicle if the sign is fabricated from one of the sign sheeting types indicated below. Table 3-9 indicates the sign luminance provided by various microprismatic sheeting types as a function of the sign centroid height, the letter height, and the legibility index. The data in the table indicate that, as long as the sign centroid is 26 ft or lower, the three sheeting types in the table will provide adequate luminance for the sign to be read at the legibility distance by an older driver in a light truck or SUV. The luminance values would be lower for a large commercial vehicle due to the larger observation angle.

Table 3-9. Sign Luminance Provided by Microprismatic Sheeting Types.

Sign Centroid Height (ft)	Legibility Distance (ft)	Luminance Provided at Legibility Distance (cd/m^2)			
		3M DG[3]	3M LDP	3M VIP	AD T-7500
22	880	13.1	14.6	7.1	13.2
24	880	12.2	13.6	6.7	12.3
26	880	12.2	13.3	6.6	12.1
28	880	11.2	12.5	6.2	11.4

Luminance values are based on a legibility distance of 880 ft (22 in letter × 40 ft/in legibility index).

Letter Height Recommendations

The recommendation for the letter height of an overhead guide sign is based on both the sign width and legibility height analyses. The sign width analysis showed that the maximum letter height for the word “San Antonio” is 22 inches. Therefore, the recommended letter height cannot be more than 22 inches.

The legibility height analysis is used to determine the minimum letter height required for overhead guide signs. The first step in this analysis is to choose which legibility index the overhead guide signs should be designed for. Historically signs have been designed using a

50 ft/in legibility index but the MUTCD now recommends using a 40 ft/in index, and suggests that 33 ft/in can be beneficial. Based on the guidance in the MUTCD, the researchers strove to make recommendations that meet the 40 ft/in legibility index.

Using a 40 ft/in legibility index with Method 1, a letter height of 22 inches would satisfy legibility requirements for 10 units of information or less. Using Method 2 with a 40 ft/in legibility index, a letter height of 22 inches would satisfy legibility requirements for 12 units of information using two panel signs. Based on these findings, the researchers recommend a minimum uppercase letter height of 22 inches for destination names on overhead guide signs and further recommend that the total amount of information on overhead guide sign installations (total of all panels at a location) be limited to 10 to 12 units of information. In addition, the researchers recommend that the type of sign sheeting used on overhead guide signs be one of the following: 3M DG^3, 3M LDP, or Avery-Dennison T-7500.

Table 3-6 shows that increasing the amount of information by one unit typically causes a 1 inch increase in letter height to maintain legibility. Also, a 1 inch increase in letter height causes approximately a 1 ft increase in sign width for the word "San Antonio." Therefore, the amount of information on a guide sign is the key limiting factor for maintaining the legibility of longer names for destinations. Therefore, it is also recommended to use more redundancy of signs. This redundancy will allow the use of fewer units of information per sign so that a driver can read the sign.

The overall size should also be a consideration for the overhead guide signs on the TTC. These overhead guide signs may be much larger and higher off the ground due to minimum overhead clearance requirements. This will make the center of the guide signs higher than usual which will cause larger wind forces to act on the increased surface areas. Due to the overall larger sign size (width and height), special supporting structures might be needed. If sign centroids are located higher than 26 ft above the road surface, the external sign lighting may be required to provide the level of luminance needed to meet driver legibility needs.

PAVEMENT MARKINGS

In Texas, 4 inches is the normal width of pavement marking used to delineate roadway lanes. This width allows drivers to detect the pavement markings and safely drive within each lane. The goal of this analysis is to determine if wider pavement markings are needed for the TTC and, if so, how much wider they should be.

Two different analyses are used to determine the required pavement marking width for the TTC. The first analysis looks at the geometry of pavement markings currently in use on Texas highways for daytime conditions and will be referred to as the Geometric Analysis. It assumes the current pavement width of 4 inches is adequate for 50 mph and 70 mph and applies the same viewing geometry for 90 mph. The other analysis evaluates the retroreflective properties of a pavement marking at nighttime and will be referred to as Retroreflectivity Analysis. Researchers used a software program to calculate a preview time of a pavement marking given its width and other design conditions and then compare it to the minimum preview time for adequate visibility. The results and discussion for each analysis follow.

Geometric Analysis

A key concept in evaluating the effectiveness of pavement markings is the preview time. Preview time is the amount of time that passes from when the driver can visually detect a pavement marker until the car reaches the same location. The preview time is a guideline that ensures the driver has enough time to see a pavement marker and react. Table 3-10 gives the preview distances corresponding to preview times of 2 to 3 seconds and at speeds of 50, 70, and 90 mph. Given a preview time and the road speed, the preview distance, distance from the driver to the pavement marker, is calculated. It is assumed the design speed of the TTC is 90 mph.

Table 3-10. Preview Distance (ft) for Varying Speeds.

Preview Time (s)	Speed (mph)		
	50	70	90
2.00	147.0	205.8	264.6
2.25	165.4	231.5	297.7
2.50	183.8	257.3	330.8
2.75	202.1	283.0	363.8
3.00	220.5	308.7	396.9

Using the preview distance and the width of the pavement marker as the base and height of a right triangle, the angle representative of the pavement marker's width to the driver is calculated. Assuming this angle is the angle needed to provide an adequate preview time, the required pavement marker width for a speed of 90 mph can be found. Table 3-11 provides a summary of these calculations.

Table 3-11. Required Pavement Marker Width for 90 mph.

Preview Time (s)	50 mph Angle (rad)	70 mph Angle (rad)	Width (in) of 90 mph marking needed to equal preview time associated with indicated speed	
			50 mph	70 mph
2.00	0.0023	0.0016	7.2	5.1
2.25	0.0020	0.0014	7.2	5.1
2.50	0.0018	0.0013	7.2	5.1
2.75	0.0016	0.0012	7.2	5.1
3.00	0.0015	0.0011	7.2	5.1

Retroreflectivity Analysis

The retroreflectivity analysis was used to determine the necessary pavement marking width to provide visibility at night. Different design parameters were chosen along with varying pavement marking widths to determine the amount of preview time that is provided to a driver. A computer program developed by COST 331, a management committee comprised of 15 European countries, was used to calculate the preview time with a given set of conditions (*9*). A short literature review was conducted to determine the preview time needed for drivers on the TTC. It was determined a preview time of 2.0 seconds for pavement markings is recommended for drivers when pavement markings are used in conjunction with raised pavement markings (RPMs) (*10*). The preview time of 2.0 seconds will be used for this project to determine an adequate pavement marking width. It is important to note that without RPMs, the recommended preview distance increases to 3.65 seconds (*10*).

Selection of Parameters

The first step in the retroreflectivity analysis is to identify and choose values for the parameters of the preview time calculation. Table 3-12 provides the design parameters and their chosen values. The researchers used common practice as well as engineering knowledge and experience to determine the appropriate value for each parameter.

Table 3-12. Parameters for Retroreflectivity Analysis.

Parameter	Value
Driver Age	60 and 70 years old
Speed	90 mph
Glare	0.02 cd/m^2
Vehicle	Passenger car
Curvature of Road	No horizontal or vertical curvature
Headlamp illumination	Low beam
Headlamp intensity factor	100%
Pavement surface retroreflectivity	5, 10, and 15 mcd/m^2/lx
Pavement marking retroreflectivity	100 mcd/m^2/lx
Diffuse illumination (roadway lighting)	Off
Pavement marking type	Continuous line
Pavement marking position	Right of the vehicle
Pavement marking width	4 and 6 inches

An older driver age was chosen because drivers' ability to see at night diminishes with age, and pavement markings should be designed for older drivers to include the entire driving population. The glare parameter accounts for the affects of vehicles' headlamps from oncoming traffic (9). The road curvature is flat and straight because it is understood the TTC will follow an alignment to allow for high-speed passenger rail which will result in a relatively flat and straight alignment. A headlamp intensity factor of 100 percent is for clean headlamps in good-working condition, and this value decreases for dirty or older headlamps (9). [AUTHOR: Should this be ref. 11?] The values for retroreflectivity of the pavement surface are those typically found in Texas based on the researchers' experience. Roads made of darker materials, such as asphalt, usually have lower values, and roads made of lighter materials, such as concrete, usually have higher values. The value for pavement marking retroreflectivity, 100 millicandelas per square meter per lux (mcd/m^2/lx), is a commonly accepted minimum value for a pavement marking before it is typically replaced. The researchers chose to design the pavement marking width for a continuous line located on the right of the vehicle. It was decided not to design based on a broken line because the broken lines will have RPMs to assist with visibility. Because pavement markings have less retroreflectivity when located to the right of a vehicle, the researchers chose this orientation so both left and right pavement marking orientation would be adequate.

Design Vehicle

An important topic of discussion is the design vehicle of the COST 331 software versus the vehicles that will use the TTC. The COST 331 software is based on the average dimensions for a European car. These dimensions are not the same for the average car found in the United States. Table 3-13 presents the average vehicle dimensions for European cars, as determined by COST 331, and the average vehicle dimensions for U.S. cars, as determined by a project conducted by the Texas Transportation Institute.

Table 3-13. Average Vehicle Dimensions (Inches).

Measurement	European Average (9)	U.S. Average (*11*)
Headlamp Height	25.6	29.5
Headlamp Separation	47.2	48.3
Driver Eye Height	47.2	50.5
Driver Eye Lateral Offset	7.9	14.5

The comparison between the average European and U.S. vehicle shows that vehicles in the U.S. have headlamps higher from the pavement surface, further apart, and further away from the driver's eyes. By having larger dimensions, the entrance and observation angles of the average U.S. vehicle will be larger than the average European vehicle. Larger entrance and observation angles will usually decrease the amount of retroreflectivity of a pavement marking, thus decreasing its visibility to the driver. The result of this observation is the preview time calculated by the COST 331 software will be slightly higher than the actual preview time provided to U.S. drivers. The amount of this difference would require complex optical calculations and is out of the scope of this project.

Retroreflectivity Analysis Results

Using the COST 331 software and the parameter values shown in Table 3-12, the preview times were calculated for varying driver ages and pavement surface retroreflectivity as shown in Table 3-14. These two parameters were varied to understand the sensitivity of each factor.

Table 3-14. Results of COST 331 Calculated Preview Times.

Pavement Marking Width (inches)	Pavement Surface Retroreflectivity (mcd/m^2/lx)	Driver Age	Preview Time (sec)
4	5	60	2.1
		70	1.9
	10	60	2.0
		70	1.9
	15	60	2.0
		70	1.8
6	5	60	2.2
		70	2.0
	10	60	2.2
		70	2.0
	15	60	2.1
		70	1.9

Although only pavement marking widths of 4 inches and 6 inches are shown, researchers investigated other widths. The analysis determined 5 inches did not show a significant improvement over 4 inches, and widths larger than 6 inches were over-designing the needed visibility. The results show that the 4 inch pavement marking provides the minimum preview time of 2.0 seconds for drivers less than 60 but not for drivers older than 60. The 6 inch pavement marking provides the minimum preview time for drivers up to 70 years old except for pavement surfaces with a retroreflectivity of 15 mcd/m^2/lx.

Marking Width Recommendations

For the geometric analysis, assuming a 4 inch wide pavement marker is adequate for vehicle speeds of 50 mph, the pavement markings on the TTC should be over 7 inches wide to provide the same visual standards. On the other hand, assuming a 4 inch wide pavement marking is adequate for vehicle speeds of 70 mph, the required pavement marking width is only 5 inches wide. The researchers determined that the width of 4 inches is acceptable for both 50 mph and 70 mph. Therefore, based on the geometric analysis, the recommended pavement marking width is 6 inches because it is a compromise between the 50 mph and 70 mph findings.

The retroreflectivity analysis shows that the 4 inch pavement marking is marginally adequate for drivers up to 60 years old. The preview time of the 4 inch pavement marking is

2.0 seconds, the minimum recommended preview time, when the pavement surface retroreflectivity is both 10 and 15 mcd/m^2/lx. As previously discussed, the actual preview time will be slightly less than those calculated by the COST 331 software. Therefore, the preview times of the 4 inch pavement marking are slightly less than the calculated 2.0 seconds which means it provides inadequate preview time for drivers. The 6 inch pavement marking has higher values of preview time and will provide the necessary preview time for drivers up to 70 years old. Both the geometric and retroreflectivity analysis lead the researchers to recommend the use of 6 inch wide pavement markings for the TTC.

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CHAPTER 4:
PORTABLE AND MOBILE RETROREFLECTOMETER MEASUREMENT COMPARISONS

INTRODUCTION

Pavement markings are used to provide drivers with information as well as safety. Pavement markings are especially important during nighttime driving to delineate the edges of lanes on roadways. Drivers are able to "see" the pavement markings because the light from the headlamps is reflected back to the vehicle by the pavement markings. This process of reflecting light back to its source is called retroreflectivity. The level of retroreflectivity for a given pavement marking is one of the key factors that determine its visibility to a driver at night. Historically retroreflectivity has been measured with portable units that require technicians to stand on the roadway and acquire measurements. New mobile measuring technology is now being used that allows technicians to measure retroreflectivity from a vehicle traveling at highway speeds, which increases safety and efficiency.

While mobile retroreflectometers have several advantages over the portable units, there are concerns over the accuracy of the mobile systems. Retroreflectivity measurements greatly depend on the entrance and observation angles of the instrument. With portable units these angles are typically kept constant for each measurement because the instrument takes static measurements. The mobile units' angles have more opportunity to be inconsistent because the vehicle is moving and the instruments' relative position to the roadway surface is subject to bumps in the road and the vehicle's suspension.

This activity evaluated whether a mobile retroreflectometer and portable retroreflectometer provide consistent results. Researchers performed a statistical analysis to determine if the mean retroreflectivity given by each type of retroreflectometer is significantly different.

OBJECTIVE

The overall goal of this project was to compare the difference between portable and mobile retroreflective measuring instruments. To compare the retroreflectometers, different road segments were chosen within or near Brazos County, Texas. Researchers measured marking retroreflectivity on each road segment with both the portable and mobile retroreflectometers.

Road segments were chosen to represent a variety of pavement surfaces and marking retroreflectivity levels. A statistical analysis was then done to determine if the difference between the mean retroreflectivity values was statistically significant.

RESEARCH APPROACH

The efforts associated with this research activity included creating a data collection method, choosing data collection sites, and choosing retroreflectometers. The data collection method defined the required number of data points and the distance between each data point. The frequency and distance between points determined the required length of road segment for each site. After this step was completed, the researchers were able to choose sites that provided adequate distance.

Data Collection Methodology

This research utilized data from two different efforts – the experimental design created for this activity and data previously collected two months before this activity. The experiment conducted by the researchers in this activity will be referred to as the 'conducted study' and the data that are being used from a prior study will be referred to as the 'previous study.' The conducted study methodology was used on Sites 1 through 5 and the previous data collection methodology was used on Site 6.

Conducted Study

Before collecting data, the researchers had to determine the number of retroreflective measurements needed for each instrument to conduct a statistical comparison. Equation 4-1 was used to find the amount of data required for each retroreflectometer to provide 95 percent confidence that the difference between the true mean of each retroreflectometer is equal to or less than a specific value denoted by Δ. The value for the standard deviation, σ, was chosen as 40 because it is the approximate average value of the standard deviation for both the portable and mobile retroreflectometers based on previous data collection.

$$n = 2*(t_{\alpha/2} * \sigma / \Delta)^2 \quad \text{(Equation 4-1)}$$

Using Equation 4-1 the number of readings required for varying difference in means is shown in Table 4-1. The table shows that more data are needed when the difference in true means decreases and the precision increases.

Table 4-1. Required Data of Each Instrument for Various Levels of Precision.

Difference in True Means	Number of Data Points Needed
25	23
20	34
15	57
10	126
5	494

The researchers decided to use a difference in means of 15 $mcd/m^2/lx$ between portable and mobile sampling for two reasons. First, this value gives a reasonable number of required portable measurements of 57. Higher precision calls for more portable readings which increase the safety risks of data collection. Second, for most pavement markings, a difference of 15 $mcd/m^2/lx$ will still allow the percent difference to be less than 10 percent of the measured retroreflectivity, which is considered acceptable.

The other statistical constraint was the number of readings required for the mobile retroreflectometer to produce repeatable results. By reviewing the literature, the researchers determined that a minimum of 150 readings are needed for the mobile retroreflectometer's average value to be within a 10 percent tolerance for repeated tests (*1*).

Based on the confidence interval and repeatability concerns, the length of road segment needed for analysis was determined to be 1000 ft. This distance allowed for more than 150 data values for the mobile retroreflectometer. For each road segment the mobile retroreflectometer made two runs and an average value was used for analysis.

The portable sampling method closely followed ASTM D6359 guidelines whereby three 100 ft zones were established within the 1000 ft segment with a zone at the beginning, middle, and end (*2*). Within each zone 20 measurements were taken which produced 60 total portable measurements for the pavement marking segment, which are shown in Figure 4-1.

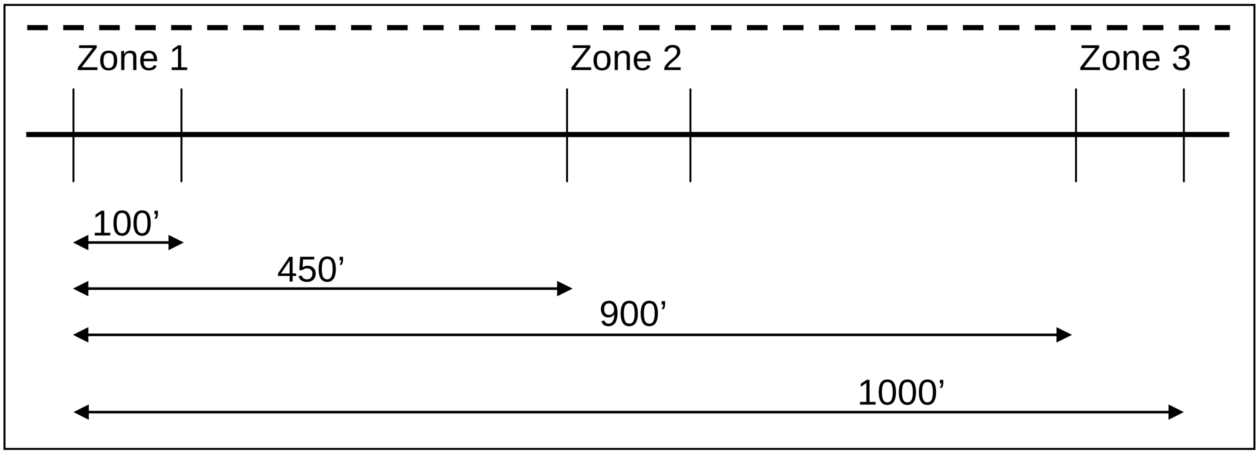


Figure 4-1. Data Collection Layout for Conducted Study.

The portable and mobile data collection were conducted over a two-day period at each site to ensure the retroreflectivity of the pavement markings did not change due to environment conditions. For example, it is possible for the retroreflectivity of a pavement marking to change if it rains because the water can wash away materials deposited on the pavement marking. The researchers found no evidence of rain or other environmental changes over the two-day period that would change the retroreflectivity of the pavement markings.

Previous Study

At this site, the length of road segment was 500 ft for each comparison. Within each segment 38 equidistant portable measurements were taken. The mobile retroreflectometer was driven once over each segment. The average amount of mobile measurements for each segment was 100. Both the portable and mobile retroreflectometer measurements were taken the same day.

Site Descriptions

Once the required road segment length was determined to be 1000 ft, the researchers identified sites within a reasonable driving distance from Texas A&M University. In choosing sites, the researchers wanted a variety of pavement materials and levels of retroreflectivity. This variety allowed the researchers to identify trends or shortcomings when comparing the retroreflectometers. The three main pavement surfaces identified as most common to Texas are concrete, hot mix asphalt (HMA), and chip seal.

Site 1 – FM 46

The first site is located on FM 46 about one mile north of Franklin, Texas. The road is a two-lane rural highway and the pavement type is HMA. The white edge line for the northbound (NB) and southbound (SB) lanes was measured, which gave a total of two pavement marking segments. The retroreflectivity was about 275 mcd/m^2/lx for one line and 340 mcd/m^2/lx for the other. Figure 4-2 presents a photo of the site and Figure 4-3 presents close-up photos of each pavement marking.

Figure 4-2. Site 1 – FM 46, North of Franklin.

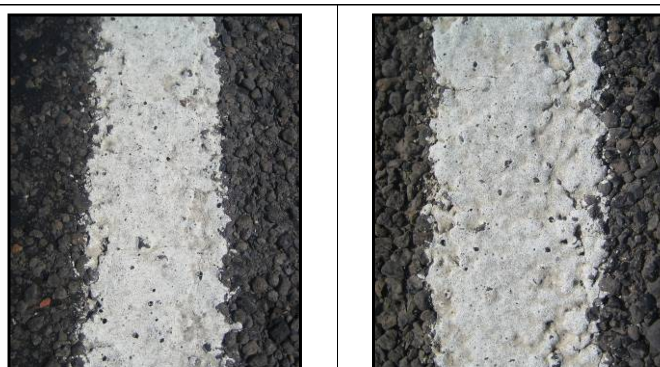
a. NB Pavement Marking b. SB Pavement Marking

Figure 4-3. Site 1 Pavement Markings.

Site 2 – FM 39

Site 2 is located on FM 39 just north of its intersection with US 190/SH 21 (near North Zulch). The road is a two-lane rural highway and the pavement type is chip seal. Researchers measured retroreflectivity of both the northbound and southbound white edge lines. The pavement markings looked to be fairly new and the retroreflectivity levels were about 250 and 300 mcd/m^2/lx for the two lines. Figure 4-4 presents a photo of the site and Figure 4-5 presents close-up photos of each pavement marking.

Figure 4-4. Site 2 – FM 39, North of US 190/SH 21 Intersection.



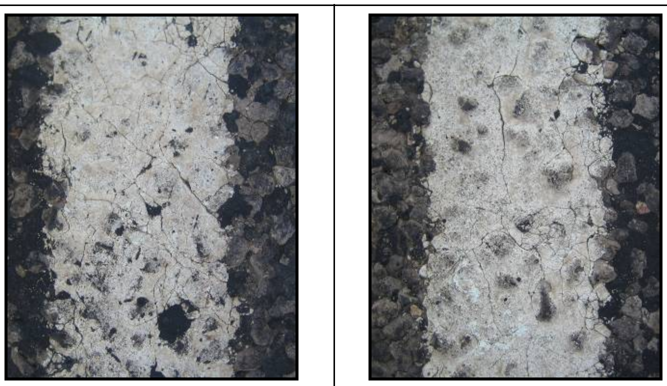
a. NB Pavement Marking | b. SB Pavement Marking

Figure 4-5. Site 2 Pavement Markings.

Site 3 – FM 50

Site 3 is on FM 50 about three miles north of the intersection with FM 60 near College Station. The road is a two-lane rural highway and the pavement type is chip seal. Again, the researchers measured the retroreflectivity of each white edge line. The pavement markings looked old and worn, and the retroreflectivity levels were about 100 mcd/m^2/lx for one line and 160 mcd/m^2/lx for the other. Figure 4-6 presents a photo of the site and Figure 4-7 presents close-up photos of each pavement marking.

Figure 4-6. Site 3 – FM 50, North of FM 50/FM 60 Intersection.



a. NB Pavement Marking	b. SB Pavement Marking

Figure 4-7. Site 3 Pavement Markings.

Site 4 – 5th Street

Site 4 is the entrance road into the Texas A&M University Riverside Campus. The road has two lanes with a HMA pavement surface. The two solid yellow lines of the centerlines were measured the westbound (WB) direction. Counting each line in the marking as separate lines provided two pavement marking segments. The pavement markings appeared to be worn and they also were paint markings, whereas markings at all other sites were thermoplastic. The retroreflectivity values were about 50 mcd/m^2/lx for each line. Figure 4-8 presents a photo of the site and Figure 4-9 presents close-up photos of each pavement marking.

Figure 4-8. Site 4 – 5th Street, Entrance to Texas A&M Riverside Campus.

a. Left Pavement Marking | b. Right Pavement Marking

Figure 4-9. Site 4 Pavement Markings.

Site 5 – SH 21

State Highway 21 was measured on the westbound bridges over the Little Brazos River and Brazos River and on the eastbound (EB) bridge over the Brazos River. The highway is a four-lane divided facility in the area that was measured, and the pavement type is concrete. The researchers were able to collect data on both the white right edge line and yellow left edge line for all three bridges which totaled six pavement marking segments. The pavement markings were considerably thicker compared to markings at the other sites, due to multiple levels of restriping. The height of the pavement markings from the surface of the concrete was as high as half an inch. In some cases the pavement marking had a uniform height, but quite often the pavement marking was broken or chipped. In areas where the second pavement marking has not chipped or broken the pavement marking appears to be new. Retroreflectivity levels of the white markings ranged from 175 to 400 mcd/m^2/lx, while retroreflectivity of the yellow lines ranged from 160 to 260 mcd/m^2/lx. Every pavement marking segment had some areas with chipped or broken pavement markings which likely lowered the average retroreflectivity and increased the standard deviation. All three bridges are similar in structure, pavement material, and pavement markings so only the photographs from the bride over the Little Brazos River are shown in Figures 4-10 and 4-11. In addition to the top view photo, Figure 4-11 also includes a side view photo to illustrate the height of the marking material at this site.

Site 6 – SH 40

Site 6 is the newly built SH 40 which is located between SH 6 and Wellborn Road in College Station. The road is a four-lane divided highway. For each traveled direction, two pavement segments were measured and on each segment both the yellow left edge line and white right edge line were measured, totaling eight pavement segments. Due to faulty data provided by the mobile retroreflectometer, only six pavement segments were used for analysis. The pavement markings on this facility were new, with retroreflectivity levels from about 200 to 300 mcd/m^2/lx for both the white and yellow lines. Figures 4-12 through 4-14 present photos of the site and markings.

Figure 4-10. Site 5 – SH 21, Bridge over Little Brazos River.

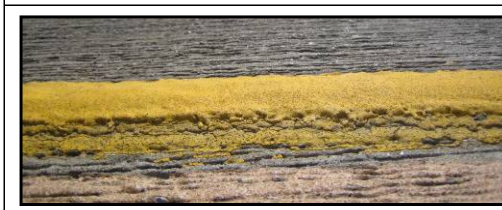
 a. Left Edge Line Pavement Marking (top view)	 b. Right Edge Line Pavement Marking (top view)
 c. Left Edge Line Pavement Marking (profile view)	 d. Right Edge Line Pavement Marking (profile view)

Figure 4-11. Site 5 Pavement Markings.

Figure 4-12. Site 6 – SH 40, between SH 6 and Wellborn Road.

a. Left Edge Line Pavement Marking

b. Right Edge Line Pavement Marking

Figure 4-13. Site 6 WB Pavement Markings.

a. Left Edge Line Pavement Marking

b. Right Edge Line Pavement Marking

Figure 4-14. Site 6 EB Pavement Markings.

Retroreflectometers

The two types of retroreflectometers available are portable and mobile. Portable units are carried or rolled by the operator to a pavement marking and placed on the marking to obtain a reading. Mobile units are mounted to the side of a vehicle and readings are obtained as the vehicle drives adjacent to pavement markings. The portable unit used in this comparison is the MX 30, and the mobile unit is the Laserlux as indicated in Figure 4-15. The MX 30 uses the European Committee of Normalization (CEN) geometry with an entrance angle of 88.76° and an observation angle of 1.05°. The Laserlux uses slightly different geometry with an entrance angle of 88.5° and an observation angle of 1.0°. A previous study found the difference between the two geometries produced results that differed by less than 5 percent. It also observed that the CEN geometry was generally slightly lower than the Laserlux geometry although the Laserlux values were higher in a significant number of cases (*1*). This study allows the researchers to assume the geometries will produce similar results and will not affect the statistical comparison.

a) MX 30 Retroreflectometer

b) Laserlux Mobile Retroreflectometer System

Figure 4-15. Portable and Mobile Retroreflectometers.

DATA ANALYSIS

The data collected by the portable retroreflectometer were written by hand on-site and later transferred into Microsoft Excel for data reduction. The data collected by the mobile retroreflectometer were automatically transferred into an Excel file by the on-board computer that runs the system. From each data set the number of samples, mean, and standard deviation was found because these three parameters were needed in the statistical analysis. A statistical analysis was then performed for each pavement marking section to evaluate whether the average retroreflectivity readings from the portable and mobile retroreflectometers were significantly different. This section describes in detail the procedures for the data reduction and statistical analysis.

Data Reduction

The portable and mobile retroreflectometers each had their own method of data reduction because the raw data for each are reported differently. For the portable data the retroreflectivity value is given for each measurement.

The mobile data are more complicated because the output for each sample is actually a set of points with a mean and average standard deviation. The system cannot output the value for every single retroreflectivity reading. For example, if the total number of points measured is 150, the output may report the data as 15 samples with 10 measured values within each sample. For each of the 15 samples a mean and standard deviation are reported. Also the number of readings within each sample does not remain constant although they are close in value. Therefore, special care was taken to ensure the weighted mean and weighted standard deviation were calculated for a pavement marking section because of the difference in readings per reported sample.

Portable Data Reduction Method

The portable data reduction used simple statistical formulas to find the number of samples, mean, and standard deviation. The number of samples for each pavement marking section was 60 as set by the design of the experiment. The mean was found by using the Microsoft Excel formula for the mean and the standard deviation was calculated in the same way.

Mobile Data Reduction Method

The first parameter calculated was the number of readings, which is also referred to as the number of samples for the statistical analysis. To find this value the number of readings for each reported sample was summed to equal the total number of samples.

Next, the weighted mean was calculated. The first step was to multiply the number of readings and average retroreflectivity for each reported sample to give a sum of all the retroreflectivity readings for a reported sample. All the sums for the reported samples were then summed and divided by the total number of samples, the first calculated parameter, to give a weighted mean. Table 4-2 depicts this process for calculating the weighted mean.

Table 4-2. Calculating Mobile Weighted Mean for Retroreflectivity.

Reported Values				Calculated Sum
Sample	**Number of Readings**	**Average Retroreflectivity**	**Std Dev**	
1	19	227.32	16.89	4319.08
2	21	214.37	14.01	4501.77
3	20	230.91	15.42	4618.2
4	21	232.41	18.97	4880.61
5	22	217.99	34.34	4795.78
6	21	218.9	32.93	4596.9
7	20	245.78	17.98	4915.6
8	21	232.7	17.46	4886.7
9	20	240.99	16.58	4819.8
10	21	247.62	15.91	5200.02
Total =	206			47534.46
Mean = 47534.46 / 206 = **230.7498**				

The weighted standard deviation was calculated last. The first step was to square the standard deviation and multiply by the number of readings, minus one for each sample. These values given by each sample were then summed. The weighted standard deviation was calculated by taking the square root of the sum divided by the total number of readings, the first calculated parameter, minus the number of reported samples. Table 4-3 shows this process of calculating the weighted standard deviation.

Table 4-3. Calculating Mobile Weighted Standard Deviation for Retroreflectivity.

Reported				Calculated	
Sample	**No. of Readings (n)**	**Average Retroreflectivity**	**Std Dev**	**Variance (Std Dev)^2**	**(n-1)*Variance**
1	19	227.32	16.89	285.2721	5134.8978
2	21	214.37	14.01	196.2801	3925.602
3	20	230.91	15.42	237.7764	4517.7516
4	21	232.41	18.97	359.8609	7197.218
5	22	217.99	34.34	1179.2356	24763.9476
6	21	218.90	32.93	1084.3849	21687.698
7	20	245.78	17.98	323.2804	6142.3276
8	21	232.70	17.46	304.8516	6097.032
9	20	240.99	16.58	274.8964	5223.0316
10	21	247.62	15.91	253.1281	5062.562
Total	206				89752.0682
	Std Dev =	$\sqrt{89752.0682/(206-10)} = 21.3990$			

Statistical Analysis

Once the sample size, mean, and standard deviation were found for both the portable and mobile retroreflectometers for one pavement marking segment, the statistical analysis was ready to be performed. Student's T-test was used to evaluate whether the difference in true means given by each type of retroreflectometer was statistically significant.

The null hypothesis (H_0) was the difference in means between the portable and mobile retroreflectometers was equal to zero, which infers that the means are equal. The alternative hypothesis (H_1) was the difference in true means was not equal to zero, which infers that the means are not equal. Because the alternative hypothesis was that the means are not equal, a two-tailed test was used. Alpha was chosen as 0.05 to give a 5 percent chance of falsely rejecting H_0 when in fact it is true.

RESULTS

The results of the data reduction and statistical analysis are shown in Table 4-4.

Table 4-4. Retroreflectometers Results and Comparisons.

Test Site	Direction	Pavement Type	Color	Avg Retro		Std Deviation		Retro % Diff	p-value
				Mobile	Portable	Mobile	Portable		
FM 46 (Site 1)	NB	HMA	White	252	305	27	30	17%	0.052
	SB	HMA	White	320	365	27	33	12%	0.108
FM 39 (Site 2)	NB	Chip Seal	White	232	262	23	16	11%	0.181
	SB	Chip Seal	White	273	317	26	33	14%	0.104
FM 50 (Site 3)	NB	Chip Seal	White	141	182	18	46	23%	0.090
	SB	Chip Seal	White	103	90	17	30	13%	0.521
5th Street (Site 4)	NB Left	HMA	Yellow	-	34	-	6	-	-
	NB Right	HMA	Yellow	40	46	10	10	13%	0.216
SH 21 (Site5)	WB1	Concrete	White	306	390	139	77	22%	0.511
	WB1	Concrete	Yellow	208	260	38	57	20%	0.215
	WB2	Concrete	White	312	400	86	74	22%	0.290
	WB2	Concrete	Yellow	198	253	21	28	22%	0.017*
	EB1	Concrete	White	173	274	150	73	37%	0.441
	EB1	Concrete	Yellow	161	210	126	36	23%	0.661
SH 40 (Site 6)	EB1	Chip Seal	White	255	240	53	50	6%	0.772
	EB1	Chip Seal	Yellow	214	214	31	47	0%	0.996
	EB2	Chip Seal	White	309	293	47	33	5%	0.734
	WB1	Chip Seal	Yellow	229	293	32	33	22%	0.051
	WB2	Chip Seal	White	195	214	33	30	9%	0.549
	WB2	Chip Seal	Yellow	233	277	49	42	16%	0.355

All retroreflective values are in units of mcd/m^2/lx.
(*) denotes a statistically significant difference in average mean values

DISCUSSION

Based upon the results shown in Table 4-4, three important areas are discussed.

Measuring Low Retroreflectivity

The first noticeable detail in the table is that a mobile retroreflectivity mean is not given for the left pavement marking for Site 4, 5th Street. The value is not given because the mobile retroreflectometer was unable to read the retroreflectivity of the pavement marking. The retroreflectivity was so low that the system could not distinguish the pavement marking from the pavement surface. Originally the retroreflectivity for all pavement markings at Sites 3 and 4 were unable to be read by the mobile retroreflectometer. At that time the portable unit found the average retroreflectivity of all four of these pavement markings to be less than 100 mcd/m^2/lx. The software of the mobile retroreflectometer was analyzed by the technicians and re-tooled so that it could read the pavement markings with low retroreflectivity. On the second data collection attempt for Sites 3 and 4, the average retroreflectivity increased to be higher than 100 mcd/m^2/lx for the northbound approach to Site 3 while the other three pavement markings remained below it. The re-tooling worked somewhat because the southbound approach of Site 3 and right side of the line for Site 4 were able to be read. Additional research of the mobile retroreflectometer is needed to determine how and if it can read extremely low retroreflectivity values as those of the left side of Site 4.

Consistency

A noticeable trend in Table 4-4 is that the portable values tend to be larger than the mobile values. Of all the portable and mobile values collected by the researchers, Sites 1 through 5, 12 out of the 13 pavement marking segments have portable values greater than the mobile values. For Sites 1 through 4 the differences between portable and mobile means are closely related because they fall within differences of 11 to 17 percent with one exception. Also, the differences between portable and mobile means for Site 5 are closely related because five out of the six pavement marking segments fall within 20 to 23 percent. The increase in difference for Site 5 is due to the broken and chipped pavement markings that have a higher standard deviation. These trends lead the researchers to believe that this test procedure allowed both the portable and mobile instruments to produce consistent results because the portable values were consistently a similar percentage higher than the mobile values. By altering the calibration of the two instruments, the researchers believe it would be possible to decrease the percent difference between the portable and mobile retroreflectometers.

Statistical Comparisons

The p-value in the table was calculated by using Student's t-test to compare significance of the difference in means for the two retroreflectometers. The null hypothesis was the true mean of the mobile and portable retroreflectometer are equal with alpha being 0.05. Therefore, to reject that the average portable and mobile readings are equal, the p-value must be less than

0.05. Only 1 of the 19 comparisons had a p-value less than 0.05, which means the other 18 comparisons are not significantly different. Therefore, an overwhelming majority of comparisons prove that the portable and mobile retroreflectometers produce equal means.

Referring back to the experiment setup, the sample sizes were chosen to be 95 percent confident that the difference in true means was less than 15 mcd/m^2/lx. This confidence infers that 95 percent, or 19 out of 20, of the comparisons should produce means within 15 mcd/m^2/lx of each other using this experimental method. The results show that 12 out of 13 comparisons set up by the researchers had equal means. Therefore, the results closely match the confidence of the experimental setup which indicates this experimental method produced valid results. Although the results from Site 6 cannot be included in validating the hypothesis because they were not based on the researchers' experimental setup, it is notable that every comparison found the difference in means to not be significant.

One caveat to make note of is that the differences between portable and mobile mean retroreflectivity values are seemingly large in some cases, yet their difference is not significant. For example at Site 5, EB1, the difference in means is 101 yet it is not significant. The reason it is not significant is because the standard deviation is quite large at 150 and 73 for the mobile and portable retroreflectometers, respectively. The large standard deviation was not caused by the instruments, but by the pavement marking and pavement surface. The pavement marking was not uniform because it was broken and chipped in several places. Therefore it is unreasonable to determine the performance of a mobile retroreflectometer by having a set value or percent that it must be within compared to a portable unit. The performance must be measured within the context of whether a pavement marking is uniform. Newer pavement markings should have lower standard deviations and the difference in means between portable and mobile retroreflectometers should be small. The allowable difference in means will increase as the pavement marking increases with age and becomes non-uniform due to deterioration.

FINDINGS

Based on the results of this activity, the researchers offer the following findings regarding mobile and portable retroreflectivity measurement:

- Both the portable and mobile retroreflectometers produced repeatable results. The accuracy of the mobile retroreflectometer largely depends on the calibration of the instrument. Operators of the mobile retroreflectometer should use careful consideration when calibrating the instrument. Also, more research is needed to determine the exact affects of calibration on accuracy.
- The mobile retroreflectometer cannot read pavement markings with low retroreflectivity as easily as the portable unit. Pavement markings with low retroreflectivity could pose a problem to inexperienced users of the mobile retroreflectometer.
- Using a minimum of 60 portable and 150 mobile measurements, the true averages of the portable and mobile retroreflectometers were within 15 mcd/m^2/lx with 95 percent confidence. The researchers believe the mobile retroreflectometer can consistently measure average retroreflectivity within 15 mcd/m^2/lx of the true mean, assuming the portable unit measures the true mean.
- It is the researchers' belief that the mobile retroreflectometer produces accurate results when correctly calibrated and operated.

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CHAPTER 5: ADDITIONAL WORK ACTIVITIES

INTRODUCTION

There were several third-year activities that are different from the first- and second-year activities in that the results cannot be described as a chapter in the annual research report. In some cases, these activities resulted in a separate product that does not fit into the confines of a chapter report. In other cases, they represent work activities that represented a distinct effort on the part of the research team, but which did not produce reportable results. There were three of these activities in the third year and they addressed the following topics: traffic signal warrant analysis, lateral placement of rumble strips on two-lane highways, and impacts of work zones.

TRAFFIC SIGNAL WARRANT ANALYSIS GUIDELINES

In September 1998, the Texas Transportation Institute (TTI) developed, as part of a Texas Department of Transportation (TxDOT)-sponsored research project, a document containing guidelines for conducting a traffic signal warrant analysis (*1*). This document described the traffic signal warrants contained in the 1980 Texas *Manual on Uniform Traffic Control Devices* (MUTCD) and provided guidelines on how to conduct a traffic signal warrant analysis. This document was very useful and TxDOT named it as one of its top research innovations that year. Five years after this document was published, TxDOT published the 2003 Texas MUTCD. This manual was followed in the past year by the 2006 Texas MUTCD. The traffic signal warrants in the 2006 Texas MUTCD are based on those in the national MUTCD and are significantly different from those of the 1980 Texas MUTCD. The differences between the signal warrants in the 1980 Texas MUTCD and the current 2006 Texas MUTCD are significant enough that the 1998 signal warrant guide is difficult to use. Therefore, in the third year of this project, TTI researchers developed an updated version of the guidelines for conducting a traffic signal warrant analysis. These guidelines are based on the signal warrants in the 2006 Texas MUTCD. The guideline document was produced as a product of this research and is available as a separate document (*2*).

LATERAL PLACEMENT OF RUMBLE STRIPS ON TWO-LANE HIGHWAYS

Rumble strips are typically grooves that are placed on the edge of the paved roadway to alert drivers when they are leaving a traffic lane. Between September 2003 and February 2005, TTI conducted research Project 0-4472 for TxDOT. That research project tested various applications of rumble strips, focusing upon the operational aspects of in-lane, transverse rumble strips and centerline rumble strips. Operational aspects of edge line rumble strips were also tested. Based on these efforts and input by TxDOT, the researchers then developed initial application guidelines for rumble strips.

The lateral placement of edge line rumble strips on two-lane roadways is one aspect of rumble strips that was not addressed in the previous TTI rumble strip research effort. Therefore, TxDOT requested that TTI look at this issue as one of the activities in the current research project (Project 0-4701). In the 0-4701 effort, TTI researchers examined the state-of-the-practice with respect to the installation of continuous shoulder rumble strips on two-lane roadways, as well as the key issues that need to be considered in order to determine the optimal lateral offset of shoulder rumble strips on two-lane roadways. A review of previous research shows a lack of information with respect to several of the key issues. A sensitivity analysis was conducted to determine the effect of vehicle speed, departure angle, driver reaction time, shoulder width, and shoulder rumble strips lateral offset on the remaining shoulder width available for drivers to correct their errant vehicle trajectory. Based on these findings, researchers developed potential interim recommendations with respect to the lateral offset of shoulder rumble strips.

In July 2006, TTI researchers presented the results of their efforts and the potential interim guidelines to a group of TxDOT personnel with expertise and/or interest in rumble strip applications. The researchers and TxDOT personnel discussed the potential guidelines and the potential changes that might result from the findings of a new research project , which began in September 2006 (Project 0-5571). The consensus of the group was that more information is needed to develop definitive guidelines and such information would best be gathered and analyzed as part of a dedicated research project. A primary focus of Project 0-5571, which started in the fall, will be to develop guidelines for lateral placement of rumble strips on two-lane highways. Accordingly, the potential guidelines developed from the Project 0-4701 efforts are not reported and will not be implemented.

WORK ZONE IMPACTS HANDBOOK

In September 2004, the Federal Highway Administration (FHWA) published a final rule establishing new procedures related to assessing the safety and mobility impacts of work zones on the traveling public. The rule applies to all state and local governments who receive federal-aid funding for highway projects. The rule requires work zone impacts to be identified and addressed as part of a transportation management plan that begins at project development and proceeds through construction, including an after implementation review and assessment element. The transportation management plan for a given project is expected to address temporary traffic control, transportation operations, and public information aspects for the project. The overall goal of the rule is to improve work zone safety and mobility by creating a mechanism to establish good policy and practices that consider the broader safety and mobility impacts of work zones. The compliance deadline for the new rule is October 12, 2007.

Overall, implementing the new rule is both a challenge and an opportunity. As written, the work zone assessment process is a multifaceted procedure that must identify impacts, address those limitations, examine resources and costs, perform periodic evaluations, and address implementation and training needs. To assist TxDOT in implementing the work zone impacts rule, researchers are developing a *Work Zone Impacts Handbook* that will provide the information needed to understand and implement the rule at the project level. The handbook will provide detail and explanation on all the components of the rule, identify relevant TxDOT policies, and contain an index of strategies that are applicable to work zone impact mitigation. The overall goal of the *Work Zone Impacts Handbook* is to provide the guidance and knowledge for TxDOT personnel to create the transportation management plans required by the rule. The handbook is intended to be an explanatory reference, not an encyclopedia of all work zone knowledge.

During the third year of this project, the research team identified the critical elements to include in the handbook, prepared a detailed outline and began to develop the material for each chapter. This effort will continue into the fourth year of the project, during which researchers will meet with TxDOT staff on a regular basis to review the handbook content and further refine the guidance provided by the handbook.

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CHAPTER 6:
SUMMARY AND RECOMMENDATIONS

As described in Chapter 1, this research project was funded to address numerous, small-scale research efforts related to traffic control devices. In the third year of the project, three major evaluations were completed and are described in individual chapters of this report. Project activities also included three additional activities that are described in a single chapter.

SUMMARY OF FINDINGS

The three major evaluations considered various aspects related to the operational impacts of traffic control device improvements. The following sections provide a brief description of the key issues and types of assessments associated with each of the activities.

Red Border Speed Limit Sign

In this evaluation, the researchers installed two types of red borders on Speed Limit signs where the speed limit decreased at the approach to an urban area. One treatment consisted of a 3 inch red border added to a standard Speed Limit sign (standard sign with red border). In the other treatment, the standard Speed Limit sign was modified by removing the black border, increasing the overall sign size by 6 inches in each direction, and providing a 4 inch red border around the sign (modified red border sign). The short-term impacts of the standard sign with the red border were evaluated in the first year, the long-term impacts of the standard sign with a red border and the short-term impacts of the modified red border sign were evaluated in the second year, and the long-term impacts of the modified red border sign were evaluated in the third year.

The results of the evaluations over the three years indicated that the standard sign with a red border had beneficial long-term impacts that were greater than those of the modified red border sign. The average reductions in the mean speed and 85th percentile speed by the standard sign with red border were 4.5 and 4.7 mph, respectively. The modified sign with red border had an average decrease of 1.5 mph for the 85th percentile speed and a 0.1 mph average increase in the mean speed, which was determined to be insignificant. Both sign treatments reduced the number of speeding vehicles and, as mentioned before, the standard sign with red border out-performed the modified sign with red border. At the downstream point, the average reduction from the before conditions in the percent of vehicles exceeding 55 mph was 20.5 percent for the standard sign with red border, while the modified sign with red border had only a 3.5 percent decrease.

Sign and Marking Design for Super High-Speed Roadways

One of the features of an expanded toll road system in Texas that may help to attract travelers to the toll roads is the ability to legally travel with higher speed limits. The Texas Department of Transportation (TxDOT) is also implementing 80 mph speed limits on some sections of I-10 and I-20 in specific counties identified by legislation. Providing the ability for vehicles to legally travel at 80 or 90 mph creates situations for which existing traffic control devices may not have been specifically designed. As part of this project, researchers performed limited evaluations of sign and marking performance issues to determine if the design of guide signs or pavement markings needed to be changed to accommodate the needs of faster traffic.

The researchers found that the use of guide signs with larger letters presents a practical limitation that places a limit on the maximum height of letters, due to the fact that the length of a guide sign with letters larger than 22 inches is wider than the ability of the facility to accommodate the sign. The limitation on the size of guide signs indicates that redundancy of the message is the best way to address the demands of high-speed information processing of guide signs. In addition, the researchers recommend that the type of sign sheeting used on overhead guide signs be one of the following: 3M DG^3, 3M LDP, or Avery-Dennison T-7500.

The evaluation of pavement marking design focused upon size factors and preview time. Based on the analyses, the researchers recommend a minimum width of 6 inches for all pavement markings on roads with speed limits of 80 mph or higher.

Portable and Mobile Retroreflectometer Measurement Comparisons

The ability to measure pavement marking retroreflectivity is becoming increasingly important, particularly with the expectation that the Federal Highway Administration (FHWA) will propose minimum levels of pavement marking retroreflectivity in the near future. Mobile retroreflectometers provide the ability to make retroreflectivity measurements of a large quantity of pavement markings. However, there have been some concerns about the ability of mobile retroreflectometers to produce retroreflectivity values that are consistent with those produced by a portable retroreflectometer. In this activity, researchers made retroreflectivity measurements for pavement markings on a variety of pavement surfaces with both portable and mobile retroreflectometers. The evaluation findings indicate that a mobile retroreflectometer, which properly calibrated and operated, can produce retroreflectivity values that are not statistically significantly different from those produced by a portable retroreflectometer. However, the actual differences in retroreflectivity levels may range from 0 to 25 percent. Due to the large standard deviations associated with some of these measurements, such large differences are not statistically different.

IMPLEMENTATION RECOMMENDATIONS

The implementation status of the individual activities is described in the following sections.

Red Border Speed Limit Sign

Based on the findings from the three years of evaluations, the researchers recommend that a red border be considered as a conspicuity treatment for Speed Limit signs at locations where the speed limit is decreasing. The recommended red border treatment is to add a red border to the standard Speed Limit sign. This border should be 3 inches for the standard sized Speed Limit sign (24×30 inches) and the width of the border should be increased for larger signs. It is further recommended that a microprismatic material be used for the red border to improve recognition of the treatment in nighttime conditions. However, the use of a microprismatic material should not be required, as the second year evaluation results found benefits to the red border even with a beaded Type III red border. Once experience is gained with the widespread use of a red border with Speed Limit signs at locations where the speed limit is decreasing, consideration should be given to the use of the red border with all Speed Limit signs.

Speed Limit signs convey an important safety message, perhaps second in significance to the Stop, Yield, and Do Not Enter signs. A distinguishing feature for all of these signs is the use of red in the sign. For these signs and in most traffic sign applications, red indicates stop or a prohibitory message. However, in the greater context of warning concepts, red also is used to indicate danger. It is in this concept of indicating danger that a red border around a Speed Limit sign makes sense. Failure to obey a speed limit creates a potentially hazardous condition and may place the driver and vehicle occupants in danger. It is important that the Speed Limit sign have a greater level of conspicuity than regulatory signs. The use of red with the Speed Limit sign provides this higher level of conspicuity and, as the results show, causes drivers to notice the sign and improves compliance with the speed limit. An added benefit of putting a red border around the speed limit sign is that it makes the sign more consistent with the standard speed limit sign design used in most countries in Europe and many other countries of the world (as illustrated in Figure 2-2a). This design should improve recognition of the speed message among international tourists as well, although such recognition was not a part of this research evaluation.

Sign and Marking Design for Super High-Speed Roadways

Based on the analysis conducted for this project, the researchers recommend that TxDOT use larger letters for signs on roads with 80 mph and higher speed limits. A letter height of 22 inches is recommended for all guide sign destination legends. In addition, the researchers recommend that an additional installation of the guide sign be provided in advance of the exit and that the retroreflective sheeting used on overhead freeway guide signs be 3M DG^3, 3M LDP, or Avery-Dennison T-7500. Pavement markings on these roads should have a minimum width of 6 inches.

Portable and Mobile Retroreflectometer Measurement Comparisons

Based on the research findings, mobile retroreflectometers should be permitted to make retroreflectivity measurements of pavement markings and be expected to provide results that are comparable to those measured with a portable retroreflectometer. The Texas Transportation Institute (TTI) Mobile Retroreflectometer Certification Program provides a means of evaluating the ability of a mobile retroreflectometer to make accurate retroreflectivity measurements.

APPENDIX:
LONG-TERM RED BORDER SPEED LIMIT SIGN RESULTS

The tables (A-1 through A-18) in this appendix present the results of the short-term and long-term analysis of the impacts of the modified red border Speed Limit sign. The researchers collected data at three sites.

The following terms are used in the tables in this appendix:

MOE	Measure-of-effectiveness
B	Before
STA	Short-term after
LTA_1	Long-term after, first data collection effort
LTA_2	Long-term after, second data collection effort
MP_S	Microprismatic sheeting, standard design
MP_R	Microprismatic sheeting, red-border design
HI_S	High intensity sheeting, standard design
HI_R	High intensity sheeting, red-border design

Table A-1. Daytime Results for US 79, All Vehicles.

Location	MOE: Speed (mph)	B (MP_S)	STA (MP_R)	LTA_1 (MP_R)	LTA_2 (MP_R)	STA-B	LTA_1-B	LTA_2-B
	Date (mo/yr)	5/05	6/05	2/06	6/06			
	Sample Size	1302	2893	2226	3596			
Control Point 1	Mean	69.2	68.5	67.8	68.8	-0.7*	-1.4*	-0.4
	85^{th} Percentile	74.0	73.0	72.7	73.2	-1.0	-1.3	-0.8
	Std. Dev.	6.79	4.97	5.19	4.84			
Control Point 2	Mean	65.5	65.3	65.4	66.1	-0.2	-0.1	0.6*
	85^{th} Percentile	71.0	71.0	70.8	71.8	0.0	-0.2	0.8
	Std. Dev.	5.83	5.74	5.51	5.61			
Control Point 3	Mean	61.0	60.2	60.8	61.7	-0.8*	-0.2	0.7*
	85^{th} Percentile	68.0	67.0	67.3	68.2	-1.0	-0.7	0.2
	Std. Dev.	6.19	6.03	6.09	6.20			

* The mean difference is significant at the 0.05 level.

Table A-2. Nighttime Results for US 79, All Vehicles.

Location	MOE: Speed (mph)	B (MP_S)	STA (MP_R)	LTA_1 (MP_R)	LTA_2 (MP_R)	STA-B	LTA_1-B	LTA_2-B
	Date	5/05	6/05	2/06	6/06			
	Sample Size	401	789	1150	672			
Control Point 1	Mean	68.1	66.9	66.5	67.1	-1.2*	-1.6*	-1.0*
	85^{th} Percentile	73.0	71.0	70.8	71.8	-2.0	-2.2	-1.2
	Std. Dev.	5.66	4.91	5.06	5.22			
Control Point 2	Mean	65.7	64.8	64.2	64.8	-0.9*	-1.5*	-0.9
	85^{th} Percentile	71.0	70.0	69.5	70.4	-1.0	-1.5	-0.6
	Std. Dev.	6.09	5.84	5.37	5.88			
Control Point 3	Mean	61.1	60.0	60.4	60.6	-1.1*	-0.7	-0.5
	85^{th} Percentile	68.0	67.0	66.5	67.3	-1.0	-1.5	-0.7
	Std. Dev.	6.91	6.42	5.97	6.50			

* The mean difference is significant at the 0.05 level.

Table A-3. Daytime Results for FM 39, All Vehicles.

Location	MOE: Speed (mph)	B (HI_s)	STA (HI_R)	LTA (HI_R)	STA-B	LTA-B
	Date	5/05	6/05	2/06		
	Sample Size	1572	1263	1363		
Control Point 1	Mean	69.5	69.7	67.7	0.2	-1.8*
	85th Percentile	75.2	75.2	73.2	0.0	-2.0
	Std. Dev.	6.42	5.93	6.09		
Control Point 2	Mean	62.6	59.5	62.1	-3.1*	-0.5
	85th Percentile	69.0	66.0	69.35	-3.0	0.9
	Std. Dev.	6.49	5.95	6.88		
Control Point 3	Mean	63.5	59.7	60.4	-3.8*	-3.1*
	85th Percentile	71.0	67.0	66.5	-4.0	-4.5
	Std. Dev.	6.92	6.48	6.36		

* The mean difference is significant at the 0.05 level.

Table A-4. Nighttime Results for FM 39, All Vehicles.

Location	MOE: Speed (mph)	B (HI_s)	STA (HI_R)	LTA (HI_R)	STA-B	LTA-B
	Date	5/05	6/05	2/06		
	Sample Size	337	268	465		
Control Point 1	Mean	68.3	67.6	65.3	-0.7	-3.0*
	85th Percentile	75.0	74.0	70.8	-1.0	-3.2
	Std. Dev.	5.81	6.21	6.11		
Control Point 2	Mean	61.2	57.9	61.2	-3.3	0.0
	85th Percentile	67.0	64.0	66.9	-3.0	-0.1
	Std. Dev.	6.27	5.66	5.97		
Control Point 3	Mean	62.1	57.8	59.5	-4.3*	-2.6*
	85th Percentile	69.0	65.0	66.9	-4.0	-2.1
	Std. Dev.	6.75	6.23	6.56		

* The mean difference is significant at the 0.05 level.

Table A-5. Daytime Results for SH 7, All Vehicles.

Location	MOE: Speed (mph)	B (HI_s)	STA (HI_R)	LTA (HI_R)	STA-B	LTA-B
	Date	12/04	5/05	7/06		
	Sample Size	4653	2030	2774		
Control Point 1	Mean	67.0	70.8	67.0	3.8*	0.0
	85th Percentile	72.2	76.8	72.7	4.6	-4.1
	Std. Dev.	5.77	6.53	5.93		
Control Point 2	Mean	64.7	72.5	73.8	7.8*	9.1*
	85th Percentile	70.8	80.2	81.4	9.4	10.6
	Std. Dev.	6.12	7.23	7.16		
Control Point 3	Mean	61.7	60.0	61.4	-1.7*	-0.3
	85th Percentile	69.0	67.3	69.0	-1.7	0.0
	Std. Dev.	6.69	6.69	6.84		

* The mean difference is significant at the 0.05 level.

Table A-6. Nighttime Results for SH 7, All Vehicles.

Location	MOE: Speed (mph)	B (HI_s)	STA (HI_R)	LTA (HI_R)	STA-B	LTA-B
	Date	12/04	5/05	7/06		
	Sample Size	2275	471	392		
Control Point 1	Mean	64.7	68.5	65.1	3.8*	0.4
	85th Percentile	69.5	74.2	70.4	4.7	0.9
	Std. Dev.	5.76	7.43	6.31		
Control Point 2	Mean	61.5	69.6	70.3	8.1*	8.8*
	85th Percentile	67.3	77.4	78.5	10.1	11.2
	Std. Dev.	6.40	8.42	7.42		
Control Point 3	Mean	58.5	57.9	58.4	-0.6	-0.1
	85th Percentile	65.3	65.3	53.2	0.0	-12.1
	Std. Dev.	6.72	7.68	6.51		

* The mean difference is significant at the 0.05 level.

Table A-7. Daytime Percent Exceeding Results for US 79, All Vehicles.

Location	Percent Exceeding 70 mph			
	B (MP_S)	STA (MP_R)	LTA_1 (MP_R)	LTA_2 (MP_R)
Control Point 1	42.8	37.8	32.3	39.2
Control Point 2	20.7	19.4	18.7	23.9
Control Point 3	7.6	5.6	7.2	9.1
Location	**Percent Exceeding 60 mph**			
	B (MP_S)	STA (MP_R)	LTA_1 (MP_R)	LTA_2 (MP_R)
Control Point 1	95.2	95.0	93.1	95.8
Control Point 2	83.3	82.1	83.5	85.5
Control Point 3	54.1	48.0	52.1	58.0
Location	**Percent Exceeding 55 mph**			
	B (MP_S)	STA (MP_R)	LTA_1 (MP_R)	LTA_2 (MP_R)
Control Point 1	99.1	99.5	98.6	99.1
Control Point 2	96.3	96.4	96.8	97.1
Control Point 3	83.3	79.1	83.7	87.0

Table A-8. Change in Daytime Percent Exceeding Results for US 79, All Vehicles.

Location	Δ Percent Exceeding 70 mph		
	STA-B	LTA_1-B	LTA_2-B
Control Point 1	-5.0	-10.5	-3.6
Control Point 2	-1.3	-2.0	3.2
Control Point 3	-2.0	-0.4	1.5
Location	**Δ Percent Exceeding 60 mph**		
	STA-B	**LTA_1-B**	**LTA_2-STA**
Control Point 1	-0.2	-2.1	0.6
Control Point 2	-1.2	0.2	2.2
Control Point 3	-6.1	-2.0	3.9
Location	**Δ Percent Exceeding 55 mph**		
	STA-B	**LTA_1-B**	**LTA_2-STA**
Control Point 1	0.4	-0.5	0.0
Control Point 2	0.1	0.5	0.8
Control Point 3	-4.2	0.4	3.7

Table A-9. Nighttime Percent Exceeding Results for US 79, All Vehicles.

Location	Percent Exceeding 65 mph			
	B (MP_S)	STA (MP_R)	LTA_1 (MP_R)	LTA_2 (MP_R)
Control Point 1	71.3	63.4	62.3	65.5
Control Point 2	53.6	48.9	42.9	48.4
Control Point 3	28.4	20	21.4	25.0
Location	**Percent Exceeding: 60 mph**			
	B (MP_S)	**STA (MP_R)**	**LTA_1 (MP_R)**	**LTA_2 (MP_R)**
Control Point 1	95.0	92.1	91.8	91.7
Control Point 2	83.5	78.8	79.8	80.2
Control Point 3	52.1	46.4	48.7	50.6
Location	**Percent Exceeding: 55 mph**			
	B (MP_S)	**STA (MP_R)**	**LTA_1 (MP_R)**	**LTA_2 (MP_R)**
Control Point 1	99.5	99.1	98.7	98.8
Control Point 2	96.5	95.2	95.2	95.4
Control Point 3	83.5	77.7	81.9	81.4

Table A-10. Change in Nighttime Percent Exceeding Results for US 79, All Vehicles.

Location	Δ Percent Exceeding 65 mph		
	STA-B	LTA_1-B	LTA_2-B
Control Point 1	-7.9	-9.0	-5.8
Control Point 2	-4.7	-10.7	-5.2
Control Point 3	-8.4	-7.0	-3.4
Location	**Δ Percent Exceeding 60 mph**		
	STA-B	**LTA_1-B**	**LTA_2-B**
Control Point 1	-2.9	-3.2	-3.3
Control Point 2	-4.7	-3.7	-3.3
Control Point 3	-5.7	-3.4	-1.5
Location	**Δ Percent Exceeding 55 mph**		
	STA-B	**LTA_1-B**	**LTA_2-B**
Control Point 1	-0.4	-0.8	-0.7
Control Point 2	-1.3	-1.3	-1.1
Control Point 3	-5.8	-1.6	-2.1

Table A-11. Daytime Percent Exceeding Results for FM 39, All Vehicles.

Location	Percent Exceeding 70 mph		
	B (HI_s)	STA (HI_R)	LTA (HI_R)
Control Point 1	48.6	49.5	33.7
Control Point 2	13.3	4.3	12.1
Control Point 3	17.6	7.2	7.6
Location	**Percent Exceeding 60 mph**		
	B (HI_s)	**STA (HI_R)**	**LTA (HI_R)**
Control Point 1	92.9	93.8	90.2
Control Point 2	63.1	44.3	61.0
Control Point 3	67.0	42.6	50.0
Location	**Percent Exceeding 55 mph**		
	B (HI_s)	**STA (HI_R)**	**LTA (HI_R)**
Control Point 1	98.0	98.6	97.4
Control Point 2	89.2	76.9	84.7
Control Point 3	90.8	74.7	80.4

Table A-12. Change in Daytime Percent Exceeding Results for FM 39, All Vehicles.

Location	Change in Percent Exceeding:					
	70 mph		60 mph		55 mph	
	STA-B	LTA-B	STA-B	LTA-B	STA-B	LTA-B
Control Point 1	0.9	-14.9	0.9	-2.7	0.6	-0.6
Control Point 2	-9.0	-1.2	-18.8	-2.1	-12.3	-4.5
Control Point 3	-10.4	-10.0	-24.4	-17.0	-16.1	-10.4

Table A-13. Nighttime Percent Exceeding Results for FM 39, All Vehicles.

Location	Percent Exceeding 65 mph		
	B (HI_s)	STA (HI_R)	LTA (HI_R)
Control Point 1	73.3	67.9	51.0
Control Point 2	27.3	10.8	22.8
Control Point 3	27.6	12.7	17.4
Location	**Percent Exceeding 60 mph**		
	B (HI_s)	**STA (HI_R)**	**LTA (HI_R)**
Control Point 1	94.4	89.6	82.6
Control Point 2	53.4	34.3	60.0
Control Point 3	58.8	31.7	40.6
Location	**Percent Exceeding 55 mph**		
	B (HI_s)	**STA (HI_R)**	**LTA (HI_R)**
Control Point 1	99.4	97.8	95.1
Control Point 2	86.4	68.3	86.0
Control Point 3	88.7	65.7	75.9

Table A-14. Change in Nighttime Percent Exceeding Results for FM 39, All Vehicles.

Location	Change in Percent Exceeding:					
	65 mph		60 mph		55 mph	
	STA-B	LTA-B	STA-B	LTA-B	STA-B	LTA-B
Control Point 1	-5.4	-22.3	-4.8	-11.8	-1.6	-4.3
Control Point 2	-16.5	-4.5	-19.1	6.6	-18.1	-0.4
Control Point 3	-14.9	-10.2	-27.1	-18.2	-23.0	-12.8

Table A-15. Daytime Percent Exceeding Results for SH 7, All Vehicles.

Location	Percent Exceeding 70 mph		
	B (HI_S)	STA (HI_R)	LTA (HI_R)
Control Point 1	30.1	58.0	32.5
Control Point 2	19.6	62.7	69.6
Control Point 3	10.9	8.0	11.6
Location	**Percent Exceeding 60 mph**		
	B (HI_S)	**STA (HI_R)**	**LTA (HI_R)**
Control Point 1	88.2	93.8	87.9
Control Point 2	77.3	95.8	97.5
Control Point 3	57.4	45.4	54.7
Location	**Percent Exceeding 55 mph**		
	B (HI_S)	**STA (HI_R)**	**LTA (HI_R)**
Control Point 1	96.9	98.6	96.1
Control Point 2	94.3	99.4	99.3
Control Point 3	82.8	76.4	82.8

Table A-16. Change in Daytime Percent Exceeding Results for SH 7, All Vehicles.

Location	Change in Percent Exceeding:					
	70 mph		60 mph		55 mph	
	STA-B	LTA-B	STA-B	LTA-B	STA-B	LTA-B
Control Point 1	27.9	2.4	5.6	-0.3	1.7	-0.8
Control Point 2	43.1	50.0	18.5	20.2	5.1	5.0
Control Point 3	-2.9	0.7	-12.0	-2.7	-6.4	0.0

Table A-17. Nighttime Percent Exceeding Results for SH 7, All Vehicles.

Location	Percent Exceeding 65 mph		
	B (HI_S)	STA (HI_R)	LTA (HI_R)
Control Point 1	47.2	72.4	52.0
Control Point 2	27.3	70.9	74.0
Control Point 3	15.4	15.3	15.3
Location	**Percent Exceeding 60 mph**		
	B (HI_S)	STA (HI_R)	LTA (HI_R)
Control Point 1	81.2	89.4	80.6
Control Point 2	58.6	89.0	91.8
Control Point 3	37.0	34.0	35.2
Location	**Percent Exceeding 55 mph**		
	B (HI_S)	STA (HI_R)	LTA (HI_R)
Control Point 1	95.6	96.8	94.9
Control Point 2	84.4	96.8	98.7
Control Point 3	68.7	62.4	69.6

Table A-18. Change in Nighttime Percent Exceeding Results for SH 7, All Vehicles.

Location	Change in Percent Exceeding:					
	65 mph		60 mph		55 mph	
	STA-B	LTA-B	STA-B	LTA-B	STA-B	LTA-B
Control Point 1	25.2	4.8	8.2	-0.6	1.2	-0.7
Control Point 2	43.6	46.7	30.4	33.2	12.4	14.3
Control Point 3	-0.1	-0.1	-3.0	-1.8	-6.3	0.9