

1. Report No. FHWA/TX-11/9-1001-1		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle EVALUATION OF TRAFFIC CONTROL DEVICES, YEAR 2				5. Report Date November 2010 Published: March 2011	
				6. Performing Organization Code	
7. Author(s) Paul J. Carlson, Adam M. Pike, Jeffrey D. Miles, Brooke R. Ullman, Roma Stevens, and Darrell W. Borchardt				8. Performing Organization Report No. Report 9-1001-1	
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. Project 9-1001	
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080				13. Type of Report and Period Covered Technical Report: September 2009–August 2010	
				14. Sponsoring Agency Code	
15. Supplementary Notes Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration. Project Title: Traffic Control Device Evaluation Program URL: http://tti.tamu.edu/documents/9-1001-1.pdf					
16. Abstract This project was established to provide a means of conducting small-scale research activities on an as-needed basis so that the results could be available within months of starting the specific research. This report summarizes the research activities that were conducted between September 2009 and August 2010. There were five primary activities and five secondary activities. The five primary activities were: studying the impact of using high brightness retroreflective sign sheeting in rural areas, synthesizing the technologies available to potentially automate no-passing zone markings, providing hurricane evacuation support for the Corpus Christi District, monitoring lead-free thermoplastic pavement marking test decks, and demonstrating daytime and nighttime operations of traffic signs supplemented with light emitting diodes. In addition, the researchers also provided support for specification revisions, prototype traffic control device evaluations, technical support for Traffic Operations Division, and initiated a study on contrast pavement markings.					
17. Key Words Traffic Control Devices, Retroreflective Sign Sheeting, Hurricane Evacuation, Pavement Marking Retroreflectivity, Contrast Marking, LED Signs			18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov		
19. Security Classif.(of this report) Unclassified		20. Security Classif.(of this page) Unclassified		21. No. of Pages 114	22. Price

EVALUATION OF TRAFFIC CONTROL DEVICES, YEAR 2

by

Paul J. Carlson, Ph.D., P.E.
Research Engineer
Texas Transportation Institute

Brooke R. Ullman, P.E.
Assistant Research Engineer
Texas Transportation Institute

Adam M. Pike, P.E.
Assistant Research Engineer
Texas Transportation Institute

Roma Stevens, P.E.
Assistant Research Engineer
Texas Transportation Institute

Jeffrey D. Miles, P.E.
Assistant Research Engineer
Texas Transportation Institute

Darrell W. Borchardt, P.E.
Senior Research Engineer
Texas Transportation Institute

Report 9-1001-1
Project 9-1001
Project Title: Traffic Control Device Evaluation Program

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

November 2010
Published: March 2011

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the 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 FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The engineer in charge of this project was Paul J. Carlson, P.E. #85402.

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

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The authors would like to thank the project director, Michael Chacon of the TxDOT Traffic Operations Division, for providing guidance and expertise on this project. Wade Odell of the TxDOT Research and Technology Implementation Office was the research engineer. The other members of the project monitoring committee included the following project advisors:

- Ricardo Castaneda, TxDOT San Antonio District.
- John Gianotti, TxDOT San Antonio District.
- Carlos Ibarra, TxDOT Atlanta District.
- Sylvester Onwas, TxDOT Houston District.
- Ismael Soto, TxDOT Corpus Christi District.
- Roy Wright, TxDOT Abilene District.

The research team would also like to thank the following groups for their contributions to the demonstrations described in Chapter 6: Dorman Varitext, K&K Systems, LED Sign Inc., McCain Inc., One2See Signs, SolarPath Sun Solutions - USA, Solar Traffic Systems Inc., StarCom Solar Inc., Sun Inno Tech, Traffic and Parking Control Co. (TAPCO), Transportation Technologies (Trans-Tech), and Diversified Highway Technologies.

TABLE OF CONTENTS

	Page
LIST OF FIGURES	ix
LIST OF TABLES	xi
CHAPTER 1: OVERVIEW	1
CHAPTER 2: SIGN SHEETING	3
Sign Brightness Evaluation Study	3
Sign Legibility	3
Object Detection	3
Study Course	4
Equipment	6
Procedure	9
Field Data Collection Summary	12
CHAPTER 3: SYNTHESIS OF NO-PASSING ZONE TECHNOLOGIES	15
Introduction	15
Study Objectives	16
Methods for Determining No-Passing Zone	16
Literature Review	18
State DOT Survey	19
Range Tracker System	21
RoadMaster™ NPZ System	22
The Rhode Island Method	22
Technologies Identified for Review	23
GPS	23
Techniques for Accuracy Improvement of GPS Data	25
GPS Applications and Limitations	25
Potential for Application to No-Passing Zone Location	26
Inertial Navigation Systems	27
Inertial Systems Aided with GPS Receiver	29
Potential for Application to No-Passing Zone Location	29
LIDAR (Light Detection and Ranging)	30
Current Applications and Limitations of LIDAR Technology	31
Potential for Application to No-Passing Zone Location	31
Synthetic APERTURE Radar Interferometry (InSAR)	32
Current Applications	33
Potential for Application to No-Passing Zone Location	33
Summary of Findings	33
Recommendations	35
CHAPTER 4: SUPPORT DISTRICT-LEVEL HURRICANE EVACUATION ROUTING	37

I-37 Hurricane EVACUATION, Corpus Christi, Texas.....	37
Stage I	38
Stage II	39
Stage III.....	40
CHAPTER 5: CONTINUED EVALUATION OF LEAD-FREE THERMOPLASTIC PAVEMENT MARKINGS	43
Study Design.....	43
Measurements	45
Results.....	46
Retroreflectivity	46
Color – 30 Meter.....	48
Color – 45/0	50
Findings.....	53
Summary.....	55
CHAPTER 6: LED SIGN TECHNOLOGIES	57
Background.....	57
Demonstration Procedure.....	59
Signs Displayed	59
Stop Signs	59
Chevron Signs.....	63
Miscellaneous Signs.....	66
Comments	70
Retroreflective Powder Coated Materials.....	71
CHAPTER 7: ADDITIONAL RESEARCH ACTIVITIES.....	73
Updates to Pavement Marking Retroreflectivity Specifications.....	73
Update to Mobile Retroreflectivity Certification Guide.....	73
Update to Special Specification 8251: Retroreflectorized Pavement Markings with Retroreflective Requirements	76
Technical Support for Traffic Operations Division	80
Durability of Thermoplastic Pavement Markings.....	80
Pavement Marking Material Shortage Support.....	81
Prototype Automated Flagging Assistance Device.....	82
Update on Contrast Pavement Markings (On-Going)	83
Treatments.....	83
Study Design.....	84
Task Activities	85
REFERENCES.....	87
APPENDIX: ALTERNATE HURRICANE EVACUATION ROUTES	91

LIST OF FIGURES

	Page
Figure 1. TTI Study Objects.....	4
Figure 2. Proposed Study Course Layout.....	5
Figure 3. Instrumented Vehicle.....	6
Figure 4. DAS and Supporting Equipment.....	7
Figure 5. Eye Tracker.....	8
Figure 6. Riverside Campus.....	10
Figure 7. GPS System Segments.....	24
Figure 8. Working of an Inertial System Aided with GPS Receivers.....	29
Figure 9. SH 21 Lead-Free Thermoplastic Installation.....	44
Figure 10. Yellow Thermoplastic Retroreflectivity Summary (Test Deck 2).....	48
Figure 11. Yellow Thermoplastic Retroreflectivity Summary (Test Deck 3).....	48
Figure 12. Avg. 30 Meter Night Color of Lead Free Thermoplastic on Test Deck 2.....	49
Figure 13. Avg. 30 Meter Night Color of Lead Free Thermoplastic on Test Deck 3.....	50
Figure 14. Avg. Daytime Color with 2 Degree Standard Observer on Test Deck 2.....	51
Figure 15. Avg. Daytime Color with 10 Degree Standard Observer on Test Deck 2.....	51
Figure 16. Avg. Nighttime Color with 2 Degree Standard Observer on Test Deck 2.....	52
Figure 17. Avg. Daytime Color with 2 Degree Standard Observer on Test Deck 3.....	52
Figure 18. LED Stop Sign Type 1.....	60
Figure 19. LED Stop Sign Type 2.....	60
Figure 20. LED Stop Sign Type 3.....	61
Figure 21. LED Stop Sign Type 4.....	61
Figure 22. LED Stop Sign Type 5.....	61
Figure 23. LED Stop Sign Type 6.....	62
Figure 24. LED Stop Sign Type 7.....	62
Figure 25. LED Stop Sign Type 8.....	62
Figure 26. LED Chevron Sign Type 1.....	63
Figure 27. LED Chevron Sign Type 2.....	64
Figure 28. LED Chevron Sign Type 3.....	64
Figure 29. LED Chevron Sign Type 4.....	65
Figure 30. LED Chevron Sign Type 5.....	65
Figure 31. LED Speed Limit Sign Type 1.....	66
Figure 32. LED Speed Limit Sign Type 2.....	67
Figure 33. LED School Speed Limit Sign.....	67
Figure 34. LED Pedestrian Crossing Sign Type 1.....	68
Figure 35. LED Pedestrian Crossing Sign Type 2.....	68
Figure 36. LED Arrow Sign.....	69
Figure 37. LED No Right Turn Sign Type 1.....	69
Figure 38. LED No Right Turn Sign Type 2.....	70
Figure 39. Retroreflective Powder Coated Guard Rail.....	71
Figure 40. Prototype AFAD Devices.....	82
Figure 41. Contrast Marking Example.....	83
Figure 42. Visibility Study.....	84

Figure 43. ALT 1 to Houston.....	91
Figure 44. ALT 1a Leaving Corpus Christi via US 181.....	92
Figure 45. ALT 2 to Austin via US 183.....	92
Figure 46. ALT 2a Leaving Corpus Christi via US 181.....	93
Figure 47. ALT 2b Exit to US 183 in Refugio.	93
Figure 48. ALT 3 to San Antonio via I-35.....	94
Figure 49. ALT 3a Continues on SH-44 through Robstown.	94
Figure 50. ALT 3b Continues on SH-44 through Alice and Freer.	95
Figure 51. ALT 3c Turns North on I-35 in Encinal.....	95
Figure 52. ALT 4 to San Antonio via FM 624 and SH 16.....	96
Figure 53. ALT 4a Leaving Corpus Christi via FM 624.	96
Figure 54. ALT 4b Turns North on SH 16.....	97
Figure 55. ALT 5 to San Antonio via US 181.....	97
Figure 56. ALT 5a Takes US 77 to Sinton then Turns North on US 181.....	98
Figure 57. ALT 5b Takes US 181 to Portland.....	98
Figure 58. I-37 Hurricane Shoulder Evacuation Lane Pamphlet (Part 1 of 2).	99
Figure 59. I-37 Hurricane Shoulder Evacuation Lane Pamphlet (Part 2 of 2).	100
Figure 60. I-37 Hurricane Evacuation Contraflow Route Motorist Advisory (Part 1 of 2).....	101
Figure 61. I-37 Hurricane Evacuation Contraflow Route Motorist Advisory (Part 2 of 2).....	102

LIST OF TABLES

	Page
Table 1. Summary of Research Activities.	1
Table 2. Results of State DOT Email Survey.	20
Table 3. Test Deck Locations and Characteristics.	43
Table 4. Lead-Free Yellow Thermoplastic Pavement Marking Measurements.	46
Table 5. Stop Sign Descriptions.....	60
Table 6. Chevron Sign Descriptions.	63
Table 7. Miscellaneous Sign Descriptions.....	66
Table 8. Estimated Thermoplastic Service Life (yrs)	81
Table 9. Study Treatments.	84

CHAPTER 1: OVERVIEW

This research project was established to be used as a mechanism for quick research results on high priority traffic control device topics that cannot be programmed in the traditional research program because of the need for a smaller scope and quicker turnaround time. This project originally began as TxDOT project 0-4701, which was active for five years (1-5). Upon the completion of 0-4701 a new TxDOT project was started with a similar objective, project 0-6384 (6). This report presents the year two activities of the new project, which has been renumbered to 9-1001 (from 0-6384). Table 1 summarizes details of each activity performed this year.

Table 1. Summary of Research Activities.

Activity (Report Chapter)	Result	Status
Tested retroreflective sign sheeting materials to determine if they can be too bright in rural areas (2)	A human factors study was designed and conducted. The research is described but the analyses are continuing.	The analyses of the collected data are continuing.
Reported on the latest technologies available to potentially automate no-passing zone markings (3)	The two-vehicle is still the most common method to mark no-passing zones in the U.S.	Technologies are available that show promise in terms of being able to automate the marking of no-passing zones.
Provided District support for hurricane evacuation routing (4)	Worked with the Corpus Christi District to provide assistance as directed.	Will continue this effort in the following year with the Corpus Christi District and potentially other coastal Districts.
Monitored lead-free thermoplastic pavement markings (5)	Nighttime color of yellow lead free thermoplastic has fallen out of TxDOT color box and is approaching limits of the more forgiving FHWA color box.	Will continue to monitor the existing lead free thermoplastic pavement marking test decks.
Demonstration traffic signs with supplemental light emitting diodes (6)	Both daytime and nighttime observations were made of a wide range of traffic signs.	Some configurations work better than others. Some LEDs are overpowering. Additional work is needed.
Other research activities: Pavement markings and prototype traffic control devices (7)	Revised pavement marking specifications, developed estimates for thermoplastic durability, studied pavement marking raw material shortage, initiated study on contrast pavement markings, and evaluated prototype automated flagging assistance device.	Study on contrast pavement markings is continuing.

CHAPTER 2: SIGN SHEETING

SIGN BRIGHTNESS EVALUATION STUDY

In this task, the research team explored the visibility of traffic signs at different brightness levels and their impact on visibility beyond the sign. The objective was to investigate whether traffic signs in certain conditions could be so bright that they create glare, reduce visibility, and ultimately create a risk to the nighttime driver. Visibility metrics included sign legibility as well as object detection. The researchers measured threshold sign legibility distance using traffic signs with different retroreflective sign sheeting materials and different headlamp settings. The researchers also measured object detection with and without the traffic sign present. Using an eye tracker, the researchers also recorded glance duration at the point of object detection or sign legibility.

Sign Legibility

For the legibility task, the researchers used speed limit signs of different speeds with a 10-inch legend (see [Figure 1](#)). The speed limit signs were changed throughout the course of the study from 30 to 55 mph. While the speed limits were changed, the participants were asked to drive approximately 35 mph throughout the study course and told that they may need to slow down for some of the horizontal curves. Two levels of sign sheeting materials were used (ASTM Type III and ASTM Type XI), which when combined with two headlamp levels (i.e., low- and high-beam), provided up to four levels of sign luminance. The traffic signs were located such that there was ample tangent distance approaching the sign to accommodate driver adaption while capturing even the longest legibility distances.

Object Detection

For the detection task, the researchers used a standard gray target, a pedestrian in blue medical scrubs, and a rear view of a parked car for the objects (see [Figure 1](#)). The gray target and pedestrian were chosen because they consisted of uniform diffuse surfaces and are common object detection targets. The rear view of a parked car was chosen to evaluate a potential driving scenario of concern to nighttime drivers and to compare the results to previous studies. The researchers recorded the detection distance for each object as well as the percent of objects

missed. When the objects were used in proximity to traffic signs, they were set at a distance of 200 ft beyond the traffic signs. Objects were also viewed in isolation.

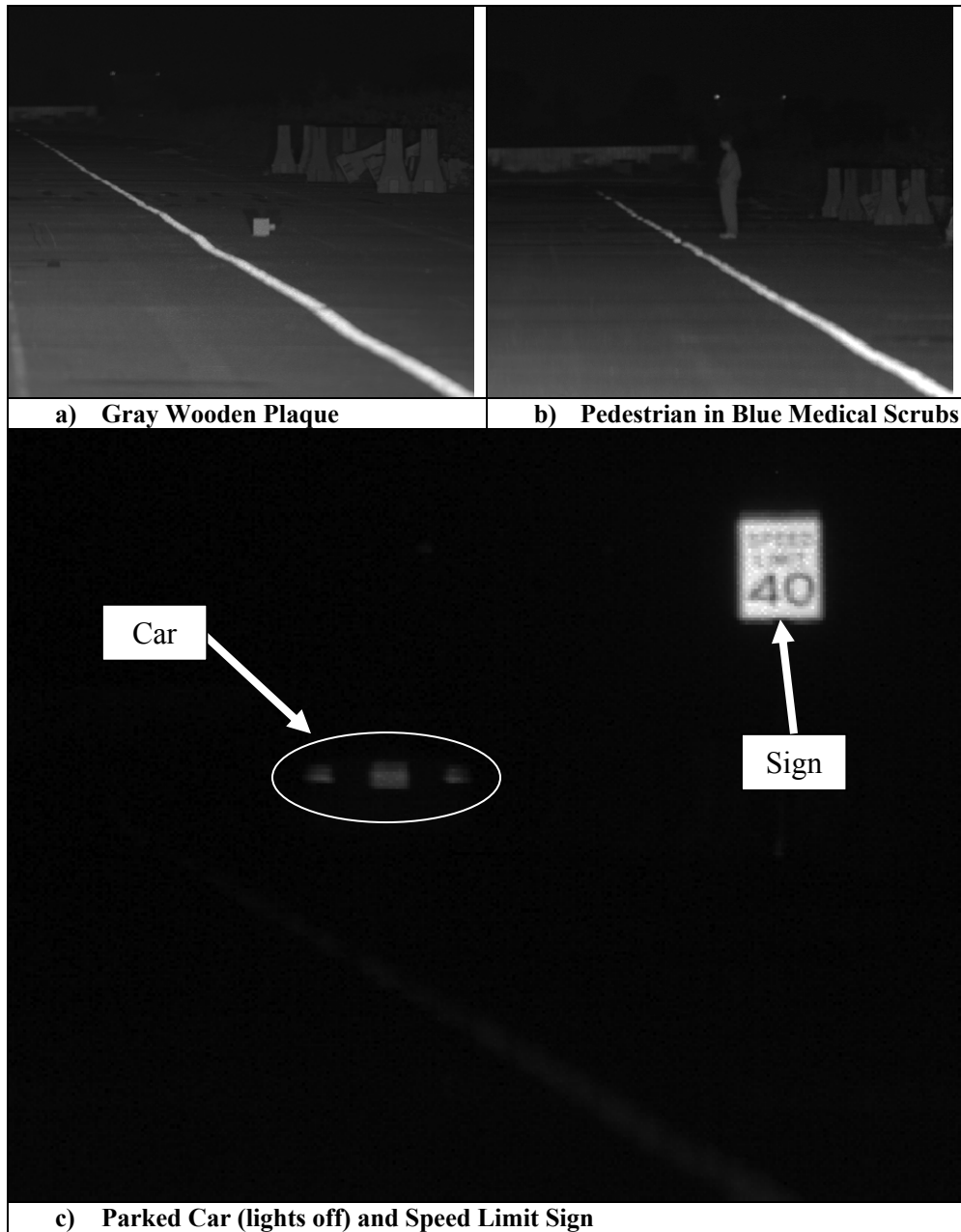


Figure 1. TTI Study Objects.

Study Course

Figure 2 shows the TTI study course. The course was intermixed with signs and objects that were changed between laps for each study participant. As stated in the key of Figure 2, the letter “O” indicates a location for objects, and “L” indicates a location for speed limit signs. The

alpha-numeric combination only served for the purpose of coordinating treatments throughout the study.

The researchers determined that a minimum of five laps would be needed to have a counterbalanced random design. This design was based on the number of available object and sign locations, using two different headlamp settings (low-beam and high-beam), using two different sign sheeting materials, having conditions without a sign but with an object, and using three different types of objects. This also assumed that there was not an impact of approach direction along the tangent segments of the study course. In order to add additional power for statistical analyses, some repetition was built into the data collection such that each participant completed at least six laps, and sometimes up to eight laps, as long as the evaluation time did not exceed 60 minutes.

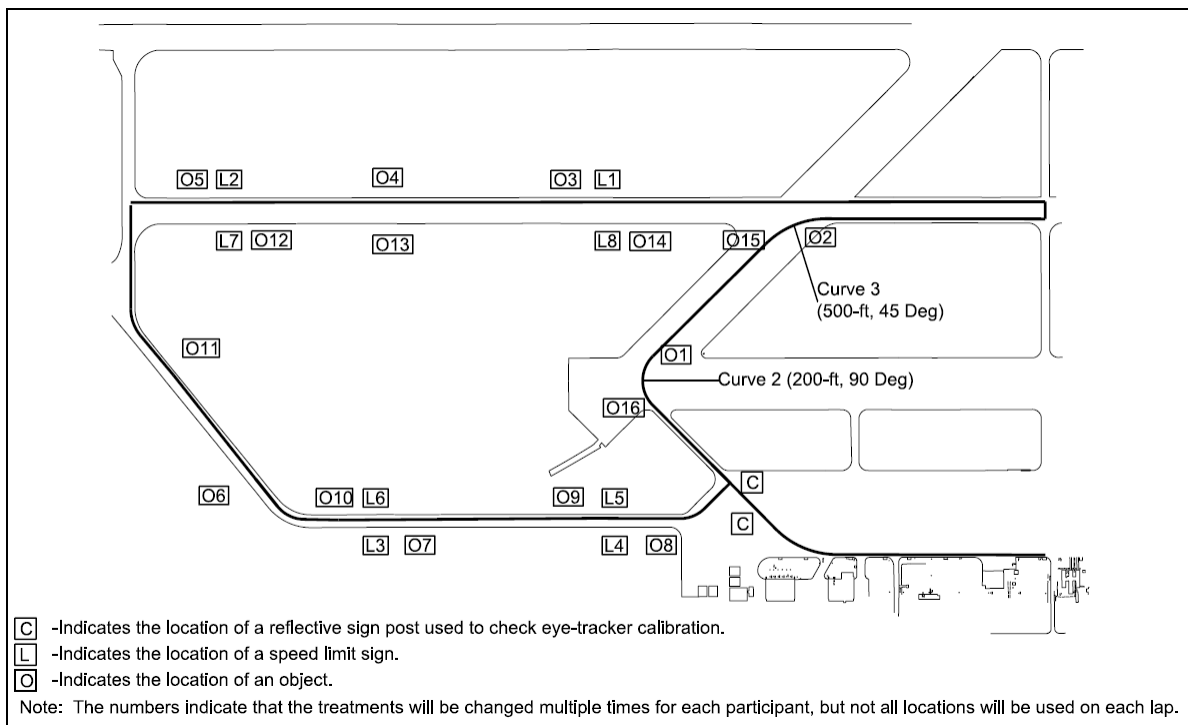


Figure 2. Proposed Study Course Layout.

In [Figure 2](#) there is also a reference to a calibration check point for the eye tracker, “C.” This consisted of a single pole set approximately 200 ft in front of the vehicle and on a shoulder offset of 12 ft. A reflective strip was attached 8 ft above the pavement, and another reflective strip was placed at the base of the pole to assess any vertical or horizontal shift in the eye-

tracking calibration. This calibration also allowed the researchers to test the aim of the forward camera of the eye-tracker system. For data reduction purposes, the calibration check also provides technicians a reference to make distance measurements using parallax, a special case of the principle of triangulation.

Equipment

There were several pieces of state-of-the-art equipment installed in the TTI Highlander instrumented vehicle (see [Figure 3](#)). The heart of the equipment was a data acquisition system (DAS) created using a small profile computer using an Intel Core 2 Quad Q9500 2.83 gigahertz processor with 4 gigabytes of DDR2 RAM and two 1 terabyte internal hard drives. While there was ample internal memory storage, the DAS transferred the data directly to a 1 terabyte external hard drive using an e-SATA connection. The external hard drive enhanced the portability of the data, especially when considering that each participant required approximately 100 gigabytes of data storage.



Figure 3. Instrumented Vehicle.

The DAS recorded data from several different devices (see [Figure 4](#)). Data were collected with a video camera, an eye tracker, and a global positioning system (GPS). A video camera was aimed out of the front windshield and was calibrated to record video images at 3 frames per second (fps) at three different shutter rates. The shutter rates were 50, 100, and 250 milliseconds. This device was used to assess the luminance of the various objects, signs, and pavement markings placed throughout the study course.

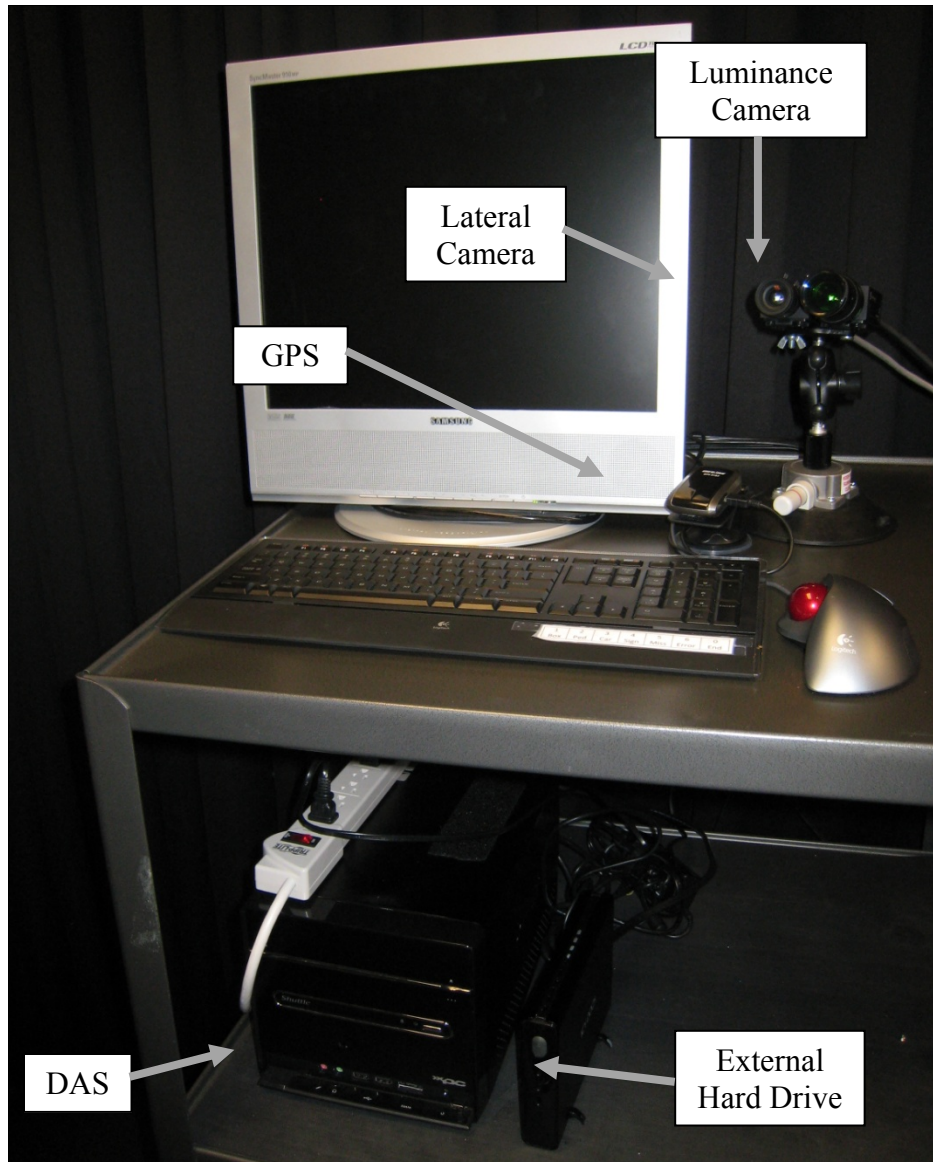


Figure 4. DAS and Supporting Equipment.

The GPS data were recorded at 5 Hz and were used to geocode all of the other data collected. A separate software package was developed to record GPS data at 5 Hz, and that data were exported and processed into X, Y, and Z coordinates with respect to the radius of the Earth. Each coordinate had an associated time code accurate to within 200 ms, which would be used to select the GPS location of each object detection and legibility glance reported by each participant. Prior to the start of the study, all of the GPS locations of the object and sign locations were recorded, and the distance formula was used during the data reduction to calculate detection distances.

The Arrington ViewPoint EyeTracker[®] combined video data and eye-tracker data. The eye tracker is depicted in Figure 5a, with the various components of the system listed. The video data were collected using a forward-facing miniature video camera attached to the eye tracker at 30 frames per second (30 hertz). The eye-tracker fixations were captured through two additional miniature video cameras at 60 hertz. Two infrared lights were used in conjunction with the eye-tracker cameras to illuminate the iris of a study participant's eyes (see Figure 5b). It was the point of convergence of the two illuminated irises, the point where a study participant was fixating, that was overlaid with a dot onto the video from the forward-facing video camera. The images in Figure 5c show a progression from left to right of an example of a study participant looking at a sign in the distance and then moving his fixation off the sign to the next sign. The ability of the eye tracker to accurately record a study participant's eye fixations was the direct result of the calibration of the eye tracker.

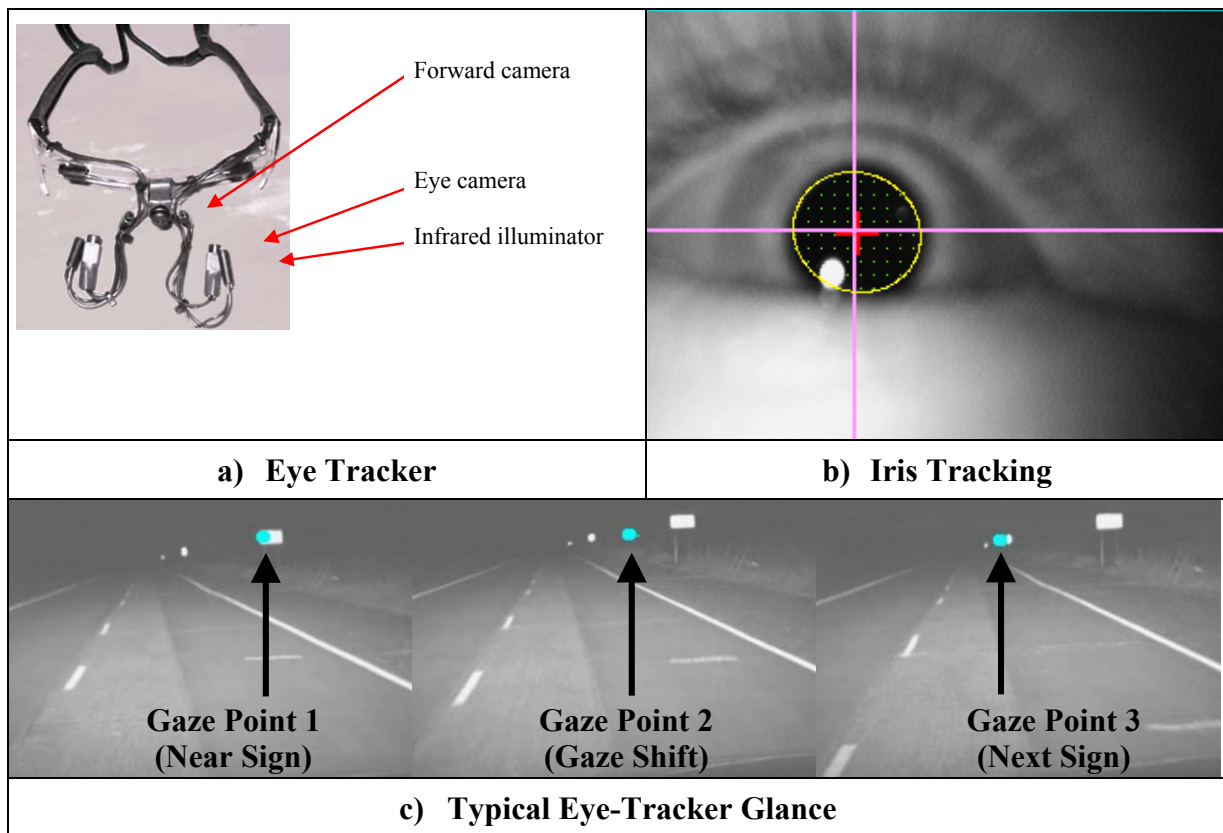


Figure 5. Eye Tracker.

The software for the eye tracker was used to not only record the gazes, but also to log object detection and legibility glances. The software has a single ASCII character coding

interface that allowed for a researcher to code in a single character with each reported glance by the participant. The researchers used the coding structure listed below to annotate the glances in the data. A “miss” was defined as an object that was either not acknowledged by the participant, or incorrectly identified. The latter case only resulted when a speed limit was incorrectly stated. An “error” was defined as a mistake made by the researcher, such as incorrectly coding a response, or upon occasion, the researcher made inadvertent button presses due to bumps along the study course. If the researcher incorrectly coded a response, he/she would immediately press a “6” followed by the correct button press, and all calculations would be based off the first incorrect button press, and the original button press would be recorded during the data reduction phase of the study. The coded responses were:

- 0 – End of a lap
- 1 – Wooden object
- 2 – Pedestrian
- 3 – Car
- 4 – Sign
- 5 – Miss
- 6 – Error

Procedure

Participants were scheduled to drive through a closed course route at the Texas A&M University Riverside Campus (see [Figure 6](#)) at night. The participants were met at the entrance to the Riverside Campus by TTI staff and then escorted to an office where they completed an informed consent form, a demographics questionnaire, a Snell visual-acuity test, and a color blindness test.



Figure 6. Riverside Campus.

Prior to starting the study, the participants completed a few additional tasks. First, they were given some brief instructions about what was required of them. Provided they did not have any reservations about conducting the tasks described to them, a participant was then escorted to the instrumented vehicle. Once in the vehicle, each participant was given an opportunity to familiarize him/herself with the controls of the vehicle (i.e., climate control, lights, and mirrors) and adjust the vehicle to his/her preferences. The participant was instructed to wear a seatbelt at all times during the testing, and to alert the researcher to any concerns throughout the study. The participant was also instructed to stop the vehicle at any point that he/she felt it was necessary.

When the participant was comfortable in the vehicle, he/she was directed to the eye-tracker calibration section. This section is not to be confused with the calibration check locations along the course (marked as “C” in [Figure 2](#)). At the eye-tracker calibration section, each participant was instructed to gaze at 16 points aligned in a four by four matrix on a large flat vertical wall. The second row of four points was aligned just above the bottom of the building to allow for the bottom row to be on the pavement. This appeared to improve the calibration with respect to tracking gazes between the pavement and above the pavement.

The eye-tracker was installed on the participant's head, and the infrared illuminators and cameras were adjusted on the device. The researcher guided the participant's gaze to each of the 16 points with a red laser, and instructed them to tell the researcher once he/she had fixed his/her gaze on the red laser dot. The laser clearly showed in the forward camera image from the eye tracker, and with each input point, the tracking of the gaze improved. Individual points could be retested if necessary. Once the calibration was complete, the participant was directed to the beginning of the study course, and reminded of the study instructions one more time, which are discussed in detail in the next section.

The on-course study procedure was designed to be similar to what you would expect a driver to do at night, such as identify speed limits for speed adjustments and detect potential objects along the roadway that could affect the intended drive path. Prior to starting the study, each participant was instructed to alert the researcher to the instant that he/she detected an object, and with respect to the sign, he/she was instructed to state the speed limit once it became clear as to the approaching speed. The participant was instructed to correct him/herself as soon as possible if he/she incorrectly stated an observation. Based on the suggested course speed of 35 mph and the distance between each of the potential object locations, the estimated minimum amount of time between responses was expected to not be less than 4 seconds.

To minimize confusion and response time between the participant and the researcher, the researcher encouraged the participant to select a specific term for each object and use it consistently throughout the data collection. The researcher did provide suggested terms to help encourage the participant making a selection. The suggested terms were "wood" or "box" for the wooden plaque, "pedestrian" for the pedestrian in blue medical scrubs, "car" for the parked car, and "55" for the sign. Box was used most often as many participants thought the wooden plaque resembled a gray electrical box as used in buildings. On the first lap, either a portion or the entire lap was used by the participant to familiarize him/her with the procedure.

Each participant was guided throughout the driving course by the researcher. For the majority of the time during data collection, the researcher remained silent and allowed the participant to follow the direction of the pavement markings. Red reflectorized raised pavement markers were also placed throughout the course at key turning points and stop locations. There was also a section of cones set out to guide each participant through an 80-ft radius U-turn. At the end of each lap, the participants were asked to indicate if he/she had any general or specific

comments with respect to the visibility of any of the objects or signs along the study course during the previous lap.

After answering any questions, the researcher walked each participant through several steps to check the calibration of the eye tracker. The participants were instructed to gaze at the top of the calibration check pole for approximately 3 seconds and then to the bottom of the pole for 3 seconds. This was repeated two to three times, and then, the participants were instructed to do the same procedure between the top of the pole and a barrel placed in between the instrumented vehicle and the calibration check pole. If the eye-tracking was off the screen, or inconsistent and there were additional laps to complete, the participant was guided back to the calibration section, and the eye tracker was recalibrated. Full calibration took between 5 to 10 minutes, and it was common to have to recalibrate at least once for each participant, each night.

If there were additional laps, and the eye tracker did not require recalibrating, each participant was guided through several steps to prepare for the next successive lap. He/she was instructed to either turn left or right onto the intersecting roadway and come to a stop, or instructed to conduct a U-turn around the barrel in front of him/her and realign the vehicle in the adjacent lane and come to a stop. Once in a stopped position, the participant was instructed to put the vehicle in park, and adjust the headlights to the appropriate lighting level for the next lap. Once the field crew that changed each treatment had completed the setup for the next successive lap, the participant was instructed to put the vehicle in drive and start the next lap. Prior to the start of each additional lap, the researcher checked the input from all of the equipment and tried to reemphasize the requirements on the participant for each lap. After completing the final lap, each participant was directed back to the office that he/she was inducted, paid for his/her time, and escorted back off the premises.

Field Data Collection Summary

A total of 31 participants completed the study. All of the participants had 20/40 vision or better, and were not color-blind. Initially, the intent was to include 24 participants with an equal gender split of two equally sized groups aged 18 to 35 years, and 65 and older. There were actually five additional male participants in the age group 18 to 35. Data collection was started in July 2010 and completed in August 2010.

The data reduction was completed in September 2010. The month of October was spent trimming the data set of input errors and collecting additional luminance data to supplement the data already collected. Data analysis of over 1500 measurements taken with the 31 participants started in November 2010 and will be completed sometime in early 2011.

CHAPTER 3: SYNTHESIS OF NO-PASSING ZONE TECHNOLOGIES

INTRODUCTION

The ability to perform passing maneuvers on two-lane roadways may impact safety, level of service, and operational capacity of these roadways. As per the American Association of State Highway and Transportation Officials (AASHTO) *A Policy on Geometric Design of Highways and Streets*, “If passing is to be accomplished safely, the passing driver should be able to see a sufficient distance ahead, clear of traffic, to complete the passing maneuver without cutting off the passed vehicle before meeting an opposing vehicle that appears during the maneuver” (7). Based on this statement when sufficient sight distance (known as the minimum passing sight distance) is not available, a roadway section should be delineated as a no-passing zone for motorists.

The *Texas Manual on Uniform Traffic Control Devices (TxMUTCD)* states the following regarding no-passing zones: “On two-way, two- or three-lane roadways where centerline markings are installed, no-passing zones shall be established at vertical and horizontal curves and other locations where an engineering study indicates that passing must be prohibited because of inadequate sight distances or other special conditions” (8). The TxMUTCD has standards for minimum required passing sight distance and describes the passing sight distance on a vertical curve as “the distance at which an object 3.5 ft above the pavement surface can be seen from a point 3.5 ft above the pavement” (8). For a horizontal curve, passing sight distance is measured along the center line of the roadway between two points 3.5 ft above the pavement on a tangent to the obstruction that limits the view on the inside of the curve.

The beginning of a no-passing zone is the point where the passing sight distance first becomes less than the minimum required passing sight distance and the end point is the point where the passing sight distance is again equal to or greater than the minimum required passing sight distance. The *Traffic Control Devices Handbook* describes 11 methods that are currently used by highway agencies to determine the limits of a no-passing zone (9).

TxDOT practice regarding delineation of no-passing zones is currently determined at the district level. From discussions with TxDOT staff, it does not appear that there is a recommended statewide method for determining no-passing zones. Individual district engineers

decide their own method for use based on the staff and equipment available in their district. However, most of the currently used methods are complicated, slow, and dependent upon human observation to accurately determine the limits of a no-passing zone. In addition, the methods pose safety concerns both for field crew and road users due to the need for frequent stopping or significant slowing down at roadway sections that have only two lanes, with two-way traffic, and may have limited sight distance. This effort was intended to address TxDOT questions about methods or technologies that could potentially be utilized to determine the beginning and end points of no-passing zones. These new methods would offer safer, more efficient, and accurate determination of the no-passing zone, as well as be more automated.

Study Objectives

The goal of this research was to identify technologies that may be applied to determine the beginning and end points of a no-passing zone, as well as address some (or all) of the difficulties and concerns associated with existing methods. The objectives for this effort were:

- Using a state department of transportations (DOT) survey, gather and review information regarding methods that are either currently or previously used by other state DOTs to determine no-passing zones that may prove to be viable options for TxDOT.
- Identify existing, new, and/or emerging technologies that show potential for use in locating no-passing zones.
- Review each of the technologies identified in the previous step to understand how the technology works, its current applications and limitations, and if the technology can be utilized to determine no-passing zones.

Methods for Determining No-Passing Zone

As mentioned previously, highway agencies use various methods to determine the beginning and end points of a no-passing zone. Some of the commonly used methods are described below:

- The Walking Method – employs a two-person crew walking along the centerline of the roadway at a distance equal to the minimum passing sight distance for the roadway and carrying a target to establish the eye height. The distance between the two persons is maintained by using a rope, chain, or wire equal in length to the

- required distance. A no-passing zone begins where the target is no longer visible to the rear crew member and ends where the target becomes visible again (9).
- The Eyeball Method – driver and the observer driving along in a single vehicle estimate within 50 to 100 ft where the no-passing zone should begin and end. This method is seldom used and only by an experienced field crew (9).
 - The Towed-Target Method – employs a vehicle that tows a target (or a second vehicle) at the end of a cable or chain. The length of the cable is equal to the minimum passing distance required for the roadway. The vehicle is driven on the roadway and the operator of the vehicle or an observer keeps an eye on the target. When the target gets out of sight, the vehicle is stopped to mark the roadway. This point is the beginning of the no-passing zone. The driving is then resumed, and when the target appears again the vehicle is stopped again to mark the roadway indicating the end of the no-passing zone (9).
 - The Laser or Optical Rangefinder Method – measures distance to a vehicle disappearing out of sight over or around a curve from several points using a laser or optical rangefinder. Interpolation is then used to determine the beginning of the no-passing zone location. The approximate beginning point of the no-passing zone is estimated using the eyeball method (9).
 - The Speed and Distance Method – uses the speed, distance, and time equation. The time it takes for a vehicle to travel from the observer and disappear from the observer's view as well as the average speed of the vehicle are used to estimate the available sight distance. The time and speed are recorded from several points and this data is then interpolated to determine the no-passing zone (9).
 - The One-Vehicle Method – employs one vehicle equipped with a distance measuring instrument (DMI) and an operator. The operator slowly drives through the horizontal or vertical curve and notes the point where the vista opens up and sufficient sight distance is available. This marks the end of the no-passing zone for the direction of travel. The operator sets the DMI to zero and travels a distance equal to the required passing sight distance and marks a point. This point is the beginning of the no-passing zone in the opposite direction. The same procedure is repeated while

- traveling in the opposite direction to find the beginning and end of the no-passing zone (9).
- The Two-Vehicle Method – uses two vehicles equipped with two-way radios, DMIs or odometers, a paint sprayer operated from within the vehicles, and a suitable target on the front vehicle. The vehicles travel through the curve a certain distance (equal to the minimum passing sight distance for the roadway) apart, which is calculated by the DMI and maintained by adjusting the speed of the rear vehicle. A mark is spray painted on the pavement by the rear vehicle driver when the target on the front vehicle disappears and then appears again (9).
 - The Plan Profile Method – uses roadway profile plans to determine line of sight starting at each mile marker. The sections where available sight distance is found to be less than the required minimum passing sight distance are marked as no-passing zones (7).
 - The Videolog (or Photolog) Method – uses a specialized data collection vehicle that collects video or photologs of the roadway and roadside integrated with geographical references such as mileposts or latitude/longitude coordinates. These videologs/photologs are then reviewed to determine the location of no-passing zones (9).

LITERATURE REVIEW

This section presents a review of the previous research to use GPS data for determining the no-passing zones. A recently completed TxDOT research project 0-4701, *Evaluation of Traffic Control Devices*, reviewed the methods currently in use by other highway agencies and experimented with the use of GPS data to determine no-passing zones. The first year activities of this project reviewed methods currently being used by highway agencies. Results of the study suggested methods that use instrumented vehicles offer better accuracy and speed over more manual methods and should be periodically reviewed for future implementation in delineating no-passing zones (1).

During the fourth year activities of the abovementioned project, researchers investigated the use of GPS technologies to locate no-passing zones caused by sight obstructions due to vertical curves. Researchers developed a data processing algorithm that was used to smooth

GPS raw data and create a vertical profile of the roadway, and a no-passing zone location algorithm that located the start and end points of no-passing zones based on sight distance requirements for the posted speeds.

The researchers used a specially instrumented vehicle equipped with a Dewetron computer, a Trimble 232 DMS GPS unit, a DMI, and a video data collection system. The GPS receiver was equipped with a differential GPS antenna and used the OmniSTAR differential correction service. Researchers collected horizontal and vertical GPS data at three sites by making multiple runs for each test site and driving at the speed of traffic. GPS data were used to determine the location of no-passing zones while video and superimposed DMI data were used to determine the location of existing no-passing zones. After comparing the existing no-passing zone locations with the computed locations from the GPS data, researchers concluded that although the research provided proof-of-concept, the automated method using GPS data was not ready for implementation. The researchers' conclusions were based on variations in the quality and lack of repeatability in the collected GPS data (4).

In a Canadian effort, researchers at the University of Quebec at Trois-Rivieres, Canada, developed a software tool for locating no-passing zones using GPS data. The project suggested a methodology to standardize the process of no-passing zone locations and developed a software tool based on GIS technology and GPS data to establish road profiles and calculate the corresponding line of sight for no-passing zone locations. The researchers collected data using two GPS receivers (CMT-Z33 from Corvalis Microtechnology and G17N with WAAS from Garmin) at two test sites while driving at an average speed of 40 km/hour and collecting data at the rate of one data point per second. After comparing existing and computed no-passing zone locations, researchers concluded that the automated method can be used for no-passing zone locations but needs improvement to overcome erroneous altitude values and gaps in data collection caused by GPS signal loss (10).

STATE DOT SURVEY

Researchers conducted a state DOT survey to gather information regarding methods either currently being used or previously considered for use by other state DOTs for locating no-passing zones. The goal of the email-based survey was to identify new or different methods being utilized by other state DOTs that may provide a viable option for TxDOT.

To collect this information, an email inquiry was sent to each of the state DOT chief traffic engineers, excluding Texas. Twenty states responded to the survey, of which two states stated that they use national or state MUTCD guidelines and did not respond to further queries regarding specific methods used for determining the available sight distance in the field. [Table 2](#) summarizes the results of the state DOT survey.

Table 2. Results of State DOT Email Survey.

State	Method Used
Alaska	Two-vehicle method with DMIs for spot checking and the same method in combination with as-built striping data for restriping and maintenance projects
Arizona	Two-vehicle method with DMIs accurate to nearest foot
Colorado	RoadMaster NPZ System from Mastermind Inc.
Connecticut	One-vehicle method
Florida	Two-vehicle method using range tracker system
Hawaii	Roadway plans, manual sight lines, and roller devices
Iowa	Two car method with range finder or DMI
Kentucky	Two-vehicle method
Massachusetts	Plan review or AASHTO method
Michigan	Two-vehicle method with DMIs and radio in both vehicles
Minnesota	Manual methods using laser distance measuring devices
Mississippi	Rope method
Missouri	Two-vehicle method using range tracker system
Montana	Plan review method
North Carolina	One-vehicle method and two-vehicle method
North Dakota	One-vehicle with DMI
Oregon	Up to the engineer, distance measuring wheels (walking) using traffic cones
Rhode Island	Hired a contractor who used a device that measured changes in the vehicle's orientation as it went along the roadway

Survey results identified the use of the laser rangefinder method, rope method, plan review method, one-vehicle method, two-vehicle method, a method described by Rhode Island DOT, and two commercial systems. Based on the survey results, new or different methods/systems that may provide a viable alternative to the currently used methods include:

1. Range Tracker System.
2. RoadMaster NPZ System.
3. The Rhode Island Method.

More detail on each of these methods/systems is described in the following sections.

Range Tracker System

The range tracker system is a variation of the two-vehicle method. The system consists of two vehicles, a lead vehicle equipped with a DMI, an RF modem, and telemetry, and a following vehicle equipped with a DMI, a modem, and a computer system to log data.

Two vehicles travel simultaneously at a certain distance apart, which is kept fairly close to the required minimum sight distance for a safe passing maneuver through constant monitoring and speed adjustment by the driver of the following vehicle. The lead vehicle transmits its travel distance to the following vehicle and the travel distance of the following vehicle (known from its own DMI) is subtracted and the distance between the two vehicles is logged in the computer system continuously. The passing and no-passing zones are located by recording the distances where the target on the lead vehicle gets out of sight and becomes visible again to the driver of the following vehicle.

Many state DOTs use this system for locating no-passing zones. An email communication with Mr. James A. Brocksmith from Missouri DOT indicated that Missouri DOT purchased these systems in 2006 at a cost of \$20,850 per unit. In response to the researchers' inquiry about current prices for the system, a Nu-Metrics sales representative indicated the system is no longer available for sale.

Advantages and disadvantages of the range tracker system include:

- The range tracker system has been tested and tried by other state DOTs and has been found useful.
- Repeat trips to the field are not needed, as data collection and field marking of no-passing zones can be completed in a single trip.
- The range tracker system uses driver judgment to determine the in/out visibility of the target and is thus subjective and prone to human error.
- On high-volume roadways, maintaining proper distance between the two vehicles may be difficult.
- The system requires two vehicles and at least two personnel.

RoadMaster™ NPZ System

The RoadMaster™ NPZ system is a patented product of MasterMind Systems, Inc. The system creates striping maps based on the no-passing zone location (start and end points) information provided by the operator. The system is used by the Colorado and Ohio DOTs. The software package provides striping information for no-passing zones based on the control points, and in- and out- visibility points entered by the operator.

Vidal Gabriela, Branch Manager, Colorado DOT Safety and Traffic Engineering, Denver explained the working of the RoadMaster NPZ system described in this paragraph. The software package requires the use of a laptop connected to a DMI. Within the software, the equipment operator selects whether no-passing zones are being located for horizontal/vertical curves or at an intersection. The operator then names the file and inputs the posted speed. After this the operator sets the DMI to zero and enters a control point for the milepost. The in- and out-visibility points are determined using either a single-vehicle method or a two-vehicle method. Colorado DOT uses a single-vehicle method and two personnel in the vehicle. The driver calls out the loss of visibility and the equipment operator enters the appropriate key to mark this location. The software then calculates the beginning of the no-passing zone in advance of the curve based on speed limit and other information already input in the computer before the start of the run. Once again the driver calls out when the visibility is regained, and the equipment operator enters another key and the software calculates the end of the no-passing zone. In response to the researcher's inquiry about current cost estimates for the service, Mastermind, Inc. representative said the cost for the service is based on the number of miles and is negotiable.

The Rhode Island Method

This method was used by a Rhode Island DOT contractor to establish no-passing zones. The method used an automated device placed inside a moving vehicle to collect roadway data. The device measured changes in the vehicle's orientation as it went along the roadway. This information was then converted into roadway profile data by combining the initial position at the beginning of the run. The profile data were then used to determine the beginning and end points of the no-passing zone. No additional information, regarding the specific name or technology used, could be found during survey communications. From the description of the data collection methodology, it seems likely that the device was an inertial measurement unit of some kind.

Inertial measurement technology and use of inertial systems for collecting roadway profile data were investigated and has been described in another section of this chapter.

TECHNOLOGIES IDENTIFIED FOR REVIEW

Using data searches on the Transportation Research Board online database and other internet based resources, the researchers identified a number of technologies that indicated some application potential (actual or perceived) for locating no-passing zones. Technologies identified for further review include:

- GPS.
- Inertial navigation systems.
- Light detection and ranging (LIDAR).
- Synthetic aperture radar interferometry.

The technology review was completed using available literature and information from device manufacturers. Some other commercially available systems specially designed for locating no-passing zones and used by other state DOTs are also described at the end of this chapter. Note that any specific brand names used in this chapter are only for informational purposes and are not meant as an endorsement of any kind.

GPS

GPS is a space-based radio navigation system developed by the U.S. Department of Defense that provides reliable positioning, navigation, and time information. It is composed of three segments: the space segment, the control segment, and the user segment. The space segment consists of 24 to 32 satellites that orbit the Earth. The control segment consists of the master control station, an alternate master control station, and ground antennas and monitor stations that track and send corrections to the GPS satellites. The user segment includes anyone who has a GPS receiver (*11*). [Figure 7](#) shows the three GPS segments.

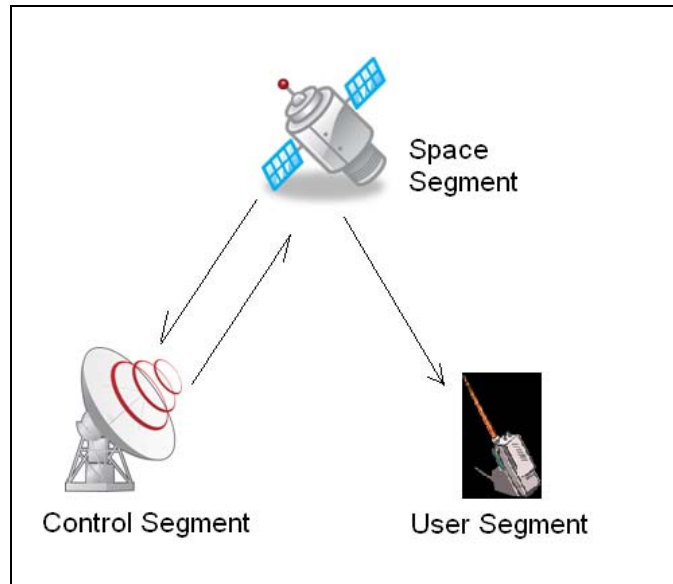


Figure 7. GPS System Segments.

Each GPS satellite transmits signals indicating its location and the current time. All GPS satellites are synchronized such that signals are transmitted at the same time. A GPS receiver receives these signals at slightly different times because some satellites are located farther away than others. Three-dimension position data (latitude, longitude, and elevation) for the GPS receiver is determined by calculating the distance of at least four satellites from the GPS receiver (12).

However, GPS positional data are not always accurate. The accuracy of GPS data is affected by satellite positions, noise in the signal, atmospheric conditions, and natural barriers to the signal. A standard GPS service can currently provide a position accuracy of 10 meters. Accuracy of GPS data can be improved by using certain techniques and additional antennas. These techniques are described in the next section. In addition to the use of these techniques, the United States government has laid out a GPS modernization plan as part of the 2005 Federal Radionavigation Plan in order to improve the accuracy and availability of GPS signals for all user segments (13).

GPS modernization is a multi-phase effort that will be completed over the next 15 years. Additional signals will be added to the two existing L1 and L2 signals. The first new civil code signal on the L2 frequency (L2C - 1227.60 MHz) will enable dual frequency civil receivers to correct for ionospheric error. Another civil signal on the L5 frequency (1176.45 MHz) for safety-of-life applications and other applications will also be added. In addition, a new Military

Code (M-Code) will be broadcast on the L1 and L2 frequencies. The modernization plan foresees 24 L2C capable GPS satellites to be in orbit by approximately 2013, and 24 L5 capable satellites to be in orbit by approximately 2015 (13).

Techniques for Accuracy Improvement of GPS Data

Accuracy of GPS position data can also be improved by using various augmentation systems. These systems, commonly known as differential GPS (DGPS) for surface users and Wide Area Augmentation System for aviation users, integrate external information into the calculation process to improve the accuracy of the calculated position. Some other techniques such as carrier phase tracking or real-time kinematic (RTK) positioning are sometimes used in combination with DGPS to further improve the accuracy of the GPS data as described below.

- The DGPS method calculates the error correction based on the knowledge of fixed location of the base station. The perceived base location from the current received satellite information is computed and the difference between the known location and the perceived location of the base station are used to calculate the error correction vector. These differential corrections are then sent to GPS users, who apply the corrections to their received GPS signals or computed positions. A standard DGPS technique can provide accuracies up to one meter (14, 15).
- Carrier Phase Tracking is a technique that monitors both the signal code and the signal carrier. For GPS signals, carrier wavelength is 100 times smaller than the signal code wavelength, thus data accuracy using RTK is improved 100 times as compared to standard DGPS. With subsequent signal processing, carrier phase tracking can produce measurements as precise as one to five millimeters. Thus, the technique is sometimes used for surveying applications. The difficulty with using carrier phase tracking is determining the exact number of carrier wave cycles between the GPS satellites and the receiver. This technique when used for real-time applications is known as real-time kinematics (14, 15).

GPS Applications and Limitations

Current usage of GPS technology includes both military and civilian applications. Military applications of GPS include navigation, target tracking, tactile guidance, and map creation. Civilian applications of GPS systems are diverse and increasing. Some of the more

common applications include navigation, surveying, use in mobile phones, vehicle tracking systems, autopilot, precision agriculture, and recreation. GPS signals are prone to jamming and are subject to errors. GPS outages in urban areas with tall buildings and/or indoors limit the use of GPS for certain applications (16).

Potential for Application to No-Passing Zone Location

Use of GPS data for locating no-passing zone locations has been investigated in the past and these work efforts are summarized in an earlier section of this chapter. These past efforts, along with research completed during this task, indicate that there is potential for the application of GPS data in determining no-passing zone locations. However due to concerns of accuracy, availability, and repeatability of GPS data, the use of GPS data for locating no-passing zones has been limited to date.

Accuracy and availability of GPS data are likely to improve in the future as described in earlier paragraphs under GPS modernization and accuracy enhancement of GPS. A product survey of RTK DGPS receivers conducted by HYDRO International in 2007 suggests centimeter level accuracies for X, Y, and Z coordinates are obtainable using DGPS receivers with real-time kinematic technologies (17). Considering the information provided in the above mentioned product survey, it seems that GPS receivers equipped with RTK antennas could provide sufficiently accurate profile and alignment data of a roadway so as to determine the start and end points of a no-passing zone. The cost of a GPS receiver equipped with differential GPS and RTK technologies can vary from \$15,000 to \$20,000.

Advantages and disadvantages of using GPS receivers for locating no-passing zones may include:

1. Current and expected widespread use of GPS technology will further lower the cost of GPS data acquisition and processing.
2. Only one person in a vehicle traveling at the speed of traffic can collect the necessary data.
3. Location of a no-passing zone is identified using latitude and longitude coordinates, thus no-passing zones can be accurately located after maintenance activities without the need for repeat surveys or mile markers.

4. GPS signals may not be available in areas with dense forestation or with high buildings.
5. Accuracy of GPS data is dependent upon the number of satellites available to the receiver.
6. Vertical or altitude accuracy of GPS data is usually less than the horizontal accuracy of the system, thus the technology may be better suited for locating no-passing zones due to horizontal curvature.
7. Low rate of data sampling combined with loss of signal can result in long gaps in data and may require data collection staff to go back in the field for another pass.
8. GPS receivers do not provide any information related to sight obstructions due to vegetation or roadside objects.
9. Lack of repeatability of GPS data can lower confidence in the application of this technology, though with modernization of GPS, it may become a non-issue in the future.

INERTIAL NAVIGATION SYSTEMS

An inertial navigational system (INS) calculates the position, orientation, and velocity of a moving object using its motion and rotation sensors without the need for an external reference once an initial position is provided from an external source such as GPS. The system usually consists of motion sensors (accelerometers), rotation sensors (gyroscopes), and a computer. Early inertial navigation systems (in the 1950s) consisted of electromagnetic devices that were large in size and weighed several hundred pounds. In comparison, present-day inertial navigation systems use solid state components that can be integrated on a small single chip and in some cases weigh less than a pound (18).

The gyro sensors of an inertial system measure angular rate with respect to an inertial frame and accelerometers measure linear acceleration again with respect to the inertial frame. By integrating the angular velocity provided by the gyro and using the original known orientation of the system, current orientation of the system can be determined at any point in time. Similarly, integration of the linear acceleration (which is an output of accelerometers) provides the linear velocity, and integration of the linear velocity provides the relative position of the object. Combining the known original position with the relative position and orientation

from gyroscope output, the absolute position and orientation of the object can be calculated. Gyros and accelerometers are single axis devices, thus three accelerometers and three gyros are generally used in an inertial system to measure changes in X, Y, and Z directions (19, 20).

Theoretically it would seem that an INS device could be used to measure the relative change in grade or alignment of a moving vehicle with respect to its initial position and thus provide the horizontal and vertical profile of a roadway, which can then be used to locate no-passing zones either manually or using a computer algorithm. However practically, inertial systems suffer from sensor errors or random disturbances. Major errors for inertial sensors include bias errors and scale factor errors. A bias error is a constant signal on the output of a sensor that does not change during a given run but can change if the system is turned off and on. Bias errors are measured in degrees/hour for the gyro bias and micro g (g being the gravitational acceleration) for accelerometer bias. A scale factor error is a linear error, proportional to the input signal. Scale factor errors are measured in parts per million of the sensed inertial quantity (19).

Sensor errors in the measurement of acceleration and angular velocity get integrated into progressively larger errors in velocity, which result in even greater errors in position. Since a new position is calculated from the previous position and measured acceleration and angular velocity, these errors are cumulative and increase with time elapsed since the initial position was provided. Thus for high accuracy survey application, supplemental systems such as GPS and/or laser scanning are integrated with inertial measurement units and are described in the next section.

Until a few years ago, inertial navigation systems were mostly used only in space, military, and air navigation systems due to their high cost and complexity involved in manufacturing a highly accurate inertial system. The development of solid state inertial measurement units has lowered the costs and increased their application in everyday life such as video games and cell phones, to provide position information for manned and unmanned vehicle systems (18).

Future trends in the inertial navigation systems suggest use of ultra-cold atom interferometers to replace GPS position updates for inertial systems, thus developing an entirely inertial system with near GPS accuracies without the limitation of GPS. A high-precision atom

interferometer inertial navigation system will likely be demonstrated on an aircraft by the year 2013 (21).

Inertial Systems Aided with GPS Receiver

Inertial systems integrated with GPS provide better position information than any single system by eliminating the errors due to inertial sensors and providing the position information for gaps due to GPS outages. GPS integrated inertial systems use periodic position updates from GPS service such that the errors caused by the inertial system are reset as close to zero as possible. Overall position accuracy of the GPS integrated inertial system is dependent upon the accuracy of the inertial system as well as the accuracy of the integrated GPS receiver. Figure 8 depicts the working of an inertial system aided with a GPS receiver in a simplified form.

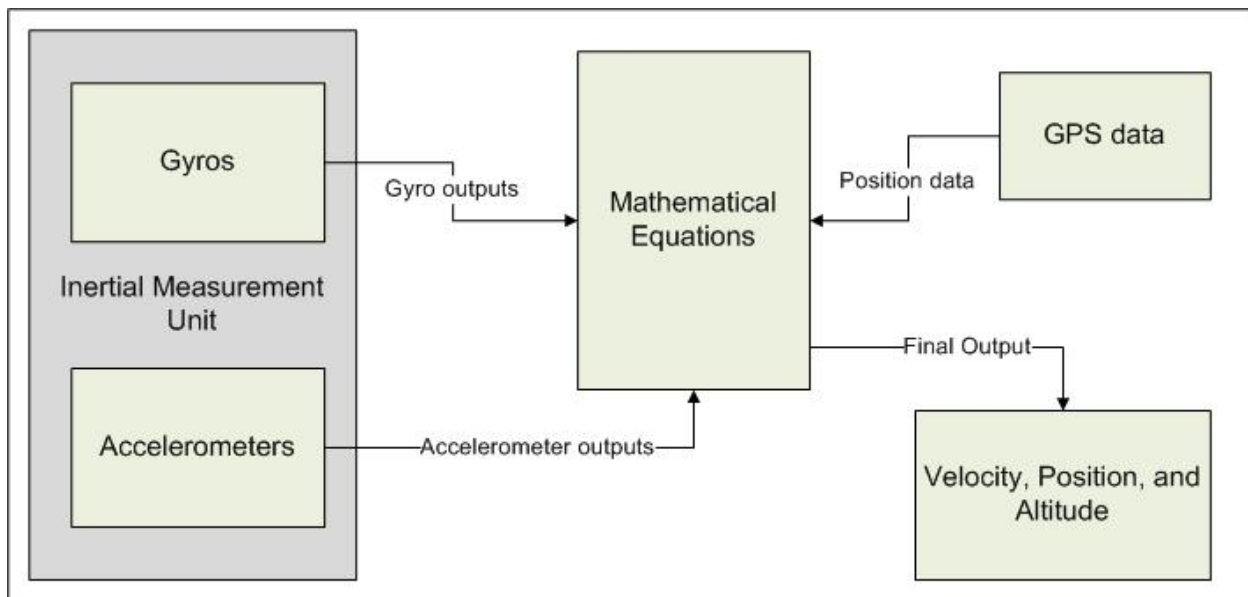


Figure 8. Working of an Inertial System Aided with GPS Receivers.

Potential for Application to No-Passing Zone Location

A highly accurate geo-positioning system (accurate to few centimeters) consisting of a GPS receiver equipped with differential and RTK technologies, an inertial measurement unit, a distance measuring instrument, and integrated with a data processing computer have the potential to collect roadway profile data. Example of one such orientation system is POS LV by Applanix Corporation. The system when installed inside a surveying vehicle will measure changes in the

vehicle's orientation as the vehicle moves along the roadway, integrate it with GPS data, and provide the vehicle position in three coordinate axes, which can then be converted to roadway profiles. In response to the state DOT survey, Rhode Island DOT described using a similar method for collecting roadway profile data, which was then used to locate no-passing zones. Using the profile method, beginning and end points of a no-passing zone can then be located. A specially developed software module can convert the position data from orientation system into roadway profiles and determine the no-passing zone locations based on the plan profile method.

A GPS aided inertial system to collect roadway profile data will provide all the advantages of stand-alone GPS receivers, allow higher data sampling rates, and reduce the data gaps due to GPS outages. However, GPS-aided inertial systems just like the stand-alone GPS receivers do not provide any information related to sight obstructions due to vegetation or roadside objects. In some cases, post processing of the field data may be required for drawing roadway profiles and determining the limits of a no-passing zone. Furthermore, GPS aided inertial systems require calibration of various components prior to conducting a survey run and some skill level is necessary for proper system operation. The cost of a commercially available preassembled orientation system that includes the software for data processing can vary from \$85,000 to \$100,000 for a basic unit. A basic unit is capable of providing accuracies in the range of 2 to 3 inches in an area with fairly good GPS reception.

LIDAR (LIGHT DETECTION AND RANGING)

LIDAR is an optical remote sensing technique that uses properties of light waves to measure distance and other properties of a target. A LIDAR system used in airborne mapping applications includes a laser source and receiver, an accurate GPS system for geo-referencing, a scanning mechanism and controller, and a computer. The system sends laser pulses to a target and records the time it takes for the pulse to return to the receiver, thereby determining the distance of the object from the source. The GPS/INS component of the system provides the position data for the scanned target (22). The accuracy of an airborne laser ranging is considered in the range of 1–5 cm as suggested by ground tests and calibrations conducted by laser manufacturers (22, 23).

Current Applications and Limitations of LIDAR Technology

Current applications of laser detection and ranging include airborne mapping to develop digital elevation models, to detect vegetation encroachment in power line corridors, as a scanning/ imaging sensor for land-based mobile mapping, to determine vehicle speeds, to count and classify vehicles, as adaptive cruise control systems for vehicles, and in the field of medical technology. Widespread use of airborne LIDAR for mapping has led researchers to explore the use of LIDAR in land-based mobile mapping to collect highway features and related highway asset data.

LIDAR has difficulty mapping earth surfaces with dense vegetation due to scatter and reflection of pulses within vegetation when used in airborne applications. Land vehicle-based LIDAR systems will likely not have this limitation. Position accuracy of a scan is limited by the inherent errors of the referencing system being used such as GPS, and the inertial measurement unit. Near-infrared radiations used by most LIDARs are absorbed by certain materials and surfaces, causing null or poor returns (24).

Potential for Application to No-Passing Zone Location

For the purposes of identifying no-passing zones, researchers believe a survey vehicle equipped with laser detection and ranging system and an orientation system can provide the necessary profile data and possibly identify any obstructions in sight distance due to vegetation encroachments or other objects. For example, a mobile mapping system equipped with laser sensors measures the distance between sensors and road surface as relative measurement. Using the control data from GPS/INS and depth data from laser sensors, the digital road surface model (DRSM) can be generated or the relative data can be used to develop the profile of the roadway relative to a base station point. Computer programs can then be used to identify the beginning and end points of a no-passing zone. In addition, DRSM can be used to detect the location, size, and shape of road surface cracks (25).

In order to scan the area for vegetation or obstructions other than due to road profile, multiple return laser scanners can be used. Multiple return laser scanners can measure the distance to multiple targets (up to five) encountered by the laser pulse, providing information about vegetation or other objects in the beam path before reaching the ground surface. Another

possibility is to employ an additional laser scanner that can scan the area along the line of sight for any obstructions.

Examples of land-based mobile mapping systems that utilize LIDAR technology include GEOVAN (designed and built at the ICC, Barcelona, Spain, and equipped with an orientation system, an imaging system that includes camera and laser sensors, and a calibration subsystem); TruckMAP (developed by John E. Chance and Associates, Inc. and equipped with Dual antenna GPS, digital altitude sensor and reflectorless laser range finder); Laserscanner MMS (developed by Wuhan Technical University and equipped with a GPS, a CCD digital camera and a laser scanner); and HARRIS2 (developed by TRL Limited and equipped with a DGPS, IMU, color digital cameras, and LIDAR) (26, 27).

A mobile surveying vehicle such as GEOVAN will have the capability to provide roadway profile and alignment data directly applicable for no-passing zone applications as well as additional roadway data such as roadway signing and striping inventory data, pavement condition data, safety barrier data, and sight obstructions due to vegetation and other objects (28). However, addition of a LIDAR scanner to a mobile mapping system will mean a more expensive system and higher level of skill for calibration and operation of the system. The cost of a mobile mapping system can vary from \$250,000 to \$1 million, depending upon the specifications of the system components, number of laser scanners and cameras, and type of vehicle. Post processing packages for image and LIDAR data processing can add to the initial as well as to the operating cost of the system. The system may or may not be a cost-effective solution, if used only for determining no-passing zones.

SYNTHETIC APERTURE RADAR INTERFEROMETRY (INSAR)

Interferometric synthetic aperture radar (InSAR) is a radar-based technique that uses two or more synthetic aperture radar images of a given surface to develop the elevation map or change in elevation measurements of that surface by measuring the differences in the phase of radar waves returning to the satellite.

InSAR methods for developing digital elevation models (DEMs) employ a configuration of two antennas located at a fixed distance on a single platform such as NASA's TOPSAR. One antenna emits a microwave signal while backscattered energy is received by both antennas. Another configuration also known as dual-pass or repeat-track interferometry is used with space

systems. Most spacecraft have only one antenna on one satellite and the spacecraft repeats the initial orbit to produce a second SAR image for interferometry or two separate satellites, such as ERS-1 and ERS-2, follow each other along the same orbit so that same area is imaged at a short time separation to allow for the generation of digital elevation models (29). These maps can provide a spatial sampling density of 100 pixels per sq km and a precision of 1 cm (30).

Current Applications

Current applications of InSAR include measurements of deformations associated with volcanic and seismic activity, ground subsidence caused by subsurface mining or collapse of old mines, monitoring stability of landscape features, built structures, digital elevation maps, and movement of coastlines and flood plains (29, 30).

Potential for Application to No-Passing Zone Location

Currently radar imaging is performed either using a spacecraft or an aircraft. During the course of this research, no references were found that applied synthetic aperture radar interferometry techniques in land-based mobile surveying. For the purposes of identifying no-passing zone locations in the field, researchers believe that the use of airborne interferometric techniques may not be a viable option in the near term. However, future advancements in the field of InSAR may make it a potential technology for land-based surveying and thereby for locating no-passing zones.

SUMMARY OF FINDINGS

Based on the research activities completed in this chapter, the researchers concluded the following:

- The two-vehicle method with DMI for locating no-passing zones was found to be the most commonly used method among states that responded to the survey. This method when used in combination with a real-time communications link between the two vehicles to transfer the DMI data in real-time has the potential to provide a viable alternative to some of the more manual methods such as the walking method and the towed-target method.
- The range tracker system uses telemetry, radio communications, and distance measuring instruments in a two-vehicle method for locating no-passing zones. The

system either as provided by Nu-Metrics or its variations is used by many state DOTs. Two vehicles and at least two persons are needed to complete the operation. Also maintaining proper distance between the two vehicles can be challenging on high volume roadways.

- The RoadMaster™ NPZ system provided by MasterMind Systems Inc. requires all data regarding the beginning and end points of the no-passing zone location to be entered manually using mileposts as control points. The software provides the striping strip maps for the roadway based on data entered and standard distances needed for no-passing zones. The system is currently used by the Colorado DOT and was mentioned as expensive and complicated.
- GPS receivers equipped with real-time kinematic antennas have the potential to provide reasonably accurate geo-positioning data for creating roadway profiles and thereby locating no-passing zones caused by sight obstructions due to a roadway's horizontal and/or vertical alignment. In the future, after completion of GPS modernization, availability and accuracy of GPS data will likely improve, thereby reducing or eliminating currently encountered concerns with GPS data.
- Inertial systems aided with GPS receivers provide another means to collect geo-positioning data for creating roadway profiles from a vehicle moving at the speed of traffic. These systems when equipped with DGPS and real-time kinematics technology can provide accuracies of a few inches (1 to 4 inches). These systems also have the capability of providing positioning data in the absence of GPS signals. However, the cost of inertial systems aided with DGPS and real-time kinematics technology can be significant. In addition, the overall accuracy of the data provided by these systems is dependent upon the accuracy of the GPS data provided by the GPS receiver being used.
- LIDAR scanning geo-referenced with GPS or inertial systems has the potential to provide accurate elevation data for the roadway as well as provide visual imagery to identify sight obstructions due to vegetation and other objects. Moreover, LIDAR scanning systems can provide additional data about the roadway environment to help with roadway asset management. However, additional components in a LIDAR scanning system make the system more complex thus requiring a higher skill level for

system calibration, data collection, and data processing. Furthermore, if used solely for determining no-passing zones, a LIDAR scanning system may not be a cost-effective solution.

- InSAR is a mapping technique used in airborne land surveys to develop digital elevation models. Future applications of InSAR may become available for terrestrial surveying using a moving vehicle and thus be applied for locating no-passing zones.

RECOMMENDATIONS

Although no one technology or system could be identified as a clear choice for implementation, researchers recommend the following options be considered.

- A two-vehicle system that uses DMI data and real-time communications link to maintain suitable distance between vehicles, and human sight to identify the loss and gain of target visibility is a viable option. The system provides a safe and fairly accurate method for locating no-passing zones without having the field crew to get out of their vehicles; however it requires two vehicles and two personnel. Use of human sight in the process provides both the advantage of identifying sight obstructions due to vegetation or other objects and the disadvantage of introducing error. The average cost of developing such a system will likely be in the range of \$20,000 to \$25,000.
- An inertially aided GPS system that will utilize the inertial technology, differential GPS, and real-time kinematics technology is another viable option. The system installed in a vehicle can collect roadway position data while moving at the speed of traffic. The system can provide data in the absence of GPS signals, thus eliminating the data gaps due to GPS outages. A software module specially developed can then be used to convert the position data into roadway profiles and identify the start and end points of no-passing zones based on the plan profile method. This system will be fully automated, requiring only one vehicle and one person to collect roadway position data. However, the cost of developing or buying such a system is much higher as compared to the two-vehicle system and will likely exceed \$100,000. In addition, sight obstructions due to vegetation and other objects cannot be identified from the roadway position data.

Although GPS stand-alone devices are not explicitly recommended at this time due to issues with signal availability and lack of repeatability in the data, it is very likely that after the completion of GPS modernization, standard GPS receivers will become a very viable and cost-effective option for determining no-passing zones. Similarly, the LIDAR scanning system can be a viable solution if the department has a need for additional roadway inventory data collected by the system, and skilled staff is available for data collection and data processing tasks.

CHAPTER 4: SUPPORT DISTRICT-LEVEL HURRICANE EVACUATION ROUTING

I-37 HURRICANE EVACUATION, CORPUS CHRISTI, TEXAS

This chapter provides additional detailed information regarding the use and operation of I-37 during a hurricane evacuation from the city of Corpus Christi. Because of expected high traffic volumes, I-37 will not be able to handle all traffic evacuating from the city and surrounding areas. The information in this chapter is designed to be used by the media as additional guidance to provide better information to the general public during an evacuation event and to help direct motorists to alternate routes. The ability of the public to have understandable information allows for more informed decisions regarding the necessity to evacuate as well as the most ideal time to begin the trip. It is intended that the media will use the information summarized in this document to better prepare materials for either the print or broadcasts to the public in the region. This chapter is not intended for distribution to the general public as hurricane evacuation material as that information can be dynamic and may change as needed to facilitate the safe evacuations of citizens. An excellent source to direct the public for statewide hurricane evacuation is <http://www.txdot.gov/travel/hurricane.htm>.

The Texas Department of Public Safety (TxDPS), with cooperation and coordination from local jurisdictions, is the agency in charge of the traffic control during a hurricane evacuation event for the Corpus Christi region. The TxDPS will be working closely with TxDOT to deploy the resources and assistance as needed to facilitate traffic management during both voluntary and mandatory evacuations. The traffic management plan (31) includes three evacuation scenarios for I-37:

1. Implementation of the traffic management plan for evacuation for either a portion of or the entire region.
2. Implementation of the shoulder lane (EvacuLane) for evacuation along I-37.
3. Implementation of the contraflow plan for I-37.

It is anticipated that motorists will elect to use I-37 as the major evacuation route from the Corpus Christi immediate vicinity to the San Antonio area. Although there are other routes, this roadway provides the most direct route to the designated host city. Additionally, while a

limited number of motorists may be familiar with the other primary and/or secondary evacuation routes, the vast majority of local residents are familiar with I-37. Evacuation during an emergency situation can be stressful for the citizens on the roadway, and familiarity with travel along I-37 provides a comfort level as opposed to taking a less familiar path. As traffic demands along this route increase during either a voluntary or mandatory evacuation, congestion will develop along this and other routes in the region. To provide information to the public, TxDOT has designed a three-stage system of messages planned for display on the roadside dynamic message signs (DMS) located in the region. These signs will provide information directly to the public as they begin their evacuation from the city. Although the signs do provide adequate information to motorists, media resources, in particular the broadcast media, can provide audio and visual information to the public either prior to or during their evacuation. The information that follows provides some background and alternate route guidance that the media can use in broadcasts to facilitate the movement of traffic out of the Corpus Christi region.

Stage I

During Stage I of the evacuation along I-37, the freeway will operate much like on a normal workday. However, there may be increased patrols of law enforcement (local and TxDPS) to better assure that traffic along the roadway will continue to move safely and efficiently. As the additional traffic due to the evacuation increases on I-37 toward San Antonio, TxDOT will begin posting related messages on the DMS signs in Corpus Christi. The signs will indicate that there is congestion along the roadway and will encourage motorists to seek alternate routes. Some suggested alternate routes are as follows.

- For those with destinations in either the Austin or Houston areas, I-37 can be avoided by taking US 181 to Portland and continuing to US 77 in Sinton.
 - To reach Houston, motorists should take US 77 north to Victoria and then take US 59 north (See ALT 1 [Figure 43] and ALT 1a [Figure 44] in the [Appendix](#)).
 - Although there are multiple routes to travel to Austin, the recommended routing involves taking US 77 north to Refugio, and completing the trip using US 183 north (See ALT-2 [Figure 45], ALT-2a [Figure 46], and ALT-2b [Figure 47] in the [Appendix](#)). This routing passes through Goliad, Cuero, Gonzales, Luling, and

Lockhart; it is recommended that motorists destined for Austin avoid using US 181 as it may be used by some evacuation traffic for travel to San Antonio.

- Alternate routing for I-37 to San Antonio involves traveling west out of Corpus Christi before turning north to complete the trip via I-35 (See ALT-3 [Figure 48], ALT-3a [Figure 49], ALT-3b [Figure 50], and ALT-3c [Figure 51] in the Appendix).
 - The primary recommended alternate uses SH 44 accessed west of SH 358 near the Corpus Christi International Airport. Motorists should stay on SH 44 beyond Alice and Freer, finally accessing I-35 going northbound in Encinal.
 - It is not advisable to use US 281 north out of Alice as it connects with I-37 north of Three Rivers and congestion is expected to occur due to the merging of the two roadways.
- Motorists that begin their trip on I-37 north of SH 358 with a San Antonio area destination can access FM 624/Northwest Boulevard west from US 77 south (just west of I-37). To get to San Antonio, motorists should stay on FM 624 through Bluntzer, Orange Grove, Midway, and Alto Loma before turning north on SH 16 to continue toward San Antonio (see ALT-4 [Figure 52], ALT-4a [Figure 53], and ALT-4b [Figure 54] in the Appendix).
- Motorists who encounter congestion along I-37, south of the US 77 north exit may choose to take US 77 toward Sinton (see ALT-5 [Figure 55] and ALT-5a [Figure 56] in the Appendix). Once in Sinton, the alternate routing continues along US 181 North through Beeville, Kennedy, and Floresville before accessing I-37 just south of I-410 in San Antonio. To avoid congestion on I-37 and US 77, motorists may opt for using US 181 out of Corpus Christi to Portland and continuing northward (see Alt-5b [Figure 57] in the Appendix).

Stage II

The Stage II evacuation includes the opening of the EvacuLane along I-37 northward to San Antonio (see the I-37 Hurricane Shoulder Evacuation Lane pamphlet [Figure 58 and Figure 59] in the Appendix). This could be used for any size, category, or anticipated landfall of a tropical system. The EvacuLane may also be used in cases where a direct impact in the immediate Corpus Christi area is not expected, but the anticipated storm surge may increase evacuation traffic. As some individuals may delay their evacuation decision until a later time period, the use of the shoulder as a travel lane may provide the additional roadway capacity to

aid in minimizing travel delays. It has been estimated that an additional 800 vehicles per hour may be able to travel along the I-37 EvacuLane during a hurricane evacuation. While an EvacuLane may be used to facilitate traffic evacuating from Corpus Christi, there are no plans to provide for a shoulder lane to accommodate returning after the threat has passed and the population is allowed to return to the area. TxDOT has prepared a brochure explaining in detail the limits and operation of the I-37 EvacuLane extending northward to the San Antonio area (32). In the urban section of Corpus Christi, the inside (left side) shoulder will be open for traffic starting at SH 358 and continue to the north US 77 interchange, which is north of the Nueces River Bridge on I-37. For the rural areas to the north, the outside (right side) shoulder is used as an additional travel lane to the I-410 interchange Exit 133 in San Antonio.

Because of the increased traffic demands, it is expected that there will be additional delays along I-37 even after the implementation of the EvacuLane. Therefore, there is added importance to encouraging motorists to seek alternate routes. The recommended Stage II alternate routes are identical to those as described in Stage I. The TxDOT DMS will indicate that there are delays on I-37 as well as alternate route information. Additionally, the DMS will communicate that the shoulder along I-37 has been converted into a travel lane for the evacuation. In order to keep the shoulder lane open for moving traffic, it is important for the public to understand that the EvacuLane should not be used for stopping. While TxDOT and law enforcement will patrol the roadway to assist stranded motorists, any blockage of the EvacuLane will result in bottlenecks, restricted traffic flow, and increased delays for the evacuating population. The media message should include the aforementioned information as well as tell motorists to use the shoulders of the freeway for emergency stopping only. If motorists need to stop for an extended time period during the evacuation, they should do so by completely exiting the roadway at the normal freeway exit ramps. As there are no plans to close any of the northbound entrance ramps along I-37, motorists exiting the roadway will have ample opportunities to re-enter the facility. The presence of a stopped vehicle along either the EvacuLane or roadway shoulders will reduce the capacity of the roadway for evacuating traffic.

Stage III

If conditions warrant, the southbound lanes of I-37 could be converted for northbound traffic to allow for additional evacuation capacity from the Corpus Christi area. Similar to the

set-up of the EvacuLane, the size, category, and projected landfall of the approaching tropical system will be considered by the decision makers before opening the contraflow lane (see the Hurricane Evacuation Contraflow Route Motorist Advisory [Figure 60 and Figure 61] in the Appendix). It is not likely that lane reversal would be considered for tropical storms or hurricanes of Category 1 or 2. It should not be interpreted that I-37 would be reversed for all storms of higher category as each situation will be evaluated on an individual basis. Contraflow lane set-up is labor intensive and requires coordination and resource deployment among TxDOT, TxDPS, and local law enforcement personnel. It is not likely that the reversal lanes would be implemented during hours of darkness; however, that should not be ruled out if conditions warrant. Additionally, the contraflow operations will be returned to normal flow prior to landfall of the approaching tropical system. Contraflow operations would begin at the SH 358 interchange with I-37; additional entrances will be provided at Leopard Street and US 77. The reverse flow operations will end at SH 97 and FM 3006 near Pleasanton, approximately 15 miles south of Loop 1604 in San Antonio. TxDOT has prepared an informative brochure on the I-37 contraflow operation that is an excellent tool for the public to have available in either English (33) or Spanish (34).

During the contraflow operation, there will be no traffic traveling southbound between San Antonio and SH 358 along I-37. Although the reversed lanes provide for additional evacuation capacity, there are expectations of heavy traffic delays along the freeway system leaving the Corpus Christi area. In addition, there will be roadway and ramp closures as needed to facilitate traffic movement along the reversed roadways. Because of traffic high traffic demands leaving the area via I-37, motorists should expect delays along all roadways within the region and should plan for early departures. Slower than normal traffic speeds can be expected on many roadways, and any incidents will add to the congestion. Those desiring to evacuate should plan to leave early as the trip to their destination will be longer than under normal traffic conditions. The media should continue to encourage motorists to use the alternate routes as described for Stage I to help spread the traffic demands among the available roadways. There may be additional delays for those desiring to travel to Corpus Christi during the period of contraflow operation along I-37 as alternate routes will need to be used for that trip as well. One example of this is traffic approaching Corpus Christi along southbound US 77; this traffic must

detour through Portland and enter the city along US 181. However, motorists should also be encouraged to take US 59 out of Victoria as an alternate to US 77 traveling south.

CHAPTER 5: CONTINUED EVALUATION OF LEAD-FREE THERMOPLASTIC PAVEMENT MARKINGS

This chapter provides an update to the evaluation of lead-free thermoplastic pavement markings that is continued from TxDOT research project 0-6384-1 (6). Background and previous study design information is contained in research report 0-6384-1.

STUDY DESIGN

In the summer of 2007, TxDOT began experimenting with the use of lead-free thermoplastic pavement markings. In July 2007, TxDOT requested that Texas Transportation Institute (TTI) researchers assist in the evaluation of field applications of lead-free thermoplastic markings. Accordingly, TTI researchers have since monitored the installation of lead-free thermoplastic pavement markings at five sites. Characteristics of each test deck can be seen in [Table 3](#). All test decks were applied on a new surface treatment (seal coat) surface.

The first test deck was applied in July 2007 on US 79 in Franklin. The second test deck was applied during July 2007 on SH 21 just east of the Brazos River near Bryan. The third test deck was also on SH 21, but it was applied in September 2008 near Caldwell. The fourth test deck was applied in June 2010 on FM 1680 northwest of Moulton. An additional test deck was added in September 2010 on SH 85 near Dilley.

Table 3. Test Deck Locations and Characteristics.

Test Deck	Location	Date of Application	Approx. ADT	Application Type	Bead Application
1	US 79 in Franklin	July 2007	8000	Spray	Single drop
2	SH 21 near Bryan	July 2007	12000	Spray	Single drop
3	SH 21 near Caldwell	Sept. 2008	12000	Ribbon Extrude	Single and Double Drop
4	FM 1680 near Moulton	June 2010	300	Spray	Double Drop
5	SH 85 near Dilley	Sept. 2010	900	Spray	Double Drop

The US 79 site included both lead-free and standard yellow thermoplastic materials that were installed on consecutive days in a two-way left-turn lane in the city. It was anticipated to report on this site for another year, but the site was striped over at the end of summer 2009 due to the poor-looking quality of the markings. The US 79 test deck 1 site will no longer be monitored. The SH 21 test deck 2 site consisted only of lead-free thermoplastic installed as the left edge line on a divided highway, transitioning to a double solid centerline on an undivided highway (see [Figure 9](#)). Test deck 2 was monitored once in the past year resulting in slightly over 2 years worth of data collection at the test deck. Data collection was halted due to safety concerns with collection data in this area.



Figure 9. SH 21 Lead-Free Thermoplastic Installation.

At the end of summer in 2008, a third test deck was added to the continued evaluation of lead-free thermoplastic pavement markings. Test deck 3 was installed on SH 21 just east of Caldwell, Texas. The road surface was a new surface treatment (seal coat). Standard spray-applied thermoplastic with Type II beads was installed along the road as part of the contract to resurface the road. A portion of road was left without edgeline markings so that the test markings could be installed. The test marking installed was a lead-free thermoplastic that was applied by ribbon extrusion. Two different sections were applied, one section had a double drop

of Type II and Type IV beads, and the second section had just Type II beads for comparison to the standard marking.

A fourth test deck was added to a new seal coat surface treatment in June 2010 on FM 1680 near Moulton, Texas, with approximately 300 ADT. This section compared two lead free materials to an adjacent leaded material. Each material was spray applied for approximately 4 miles. The markings were applied at approximately 100 mils thick and had a double drop of Type II and III beads each applied at approximately 12 lb/100 sq ft.

The fifth test deck was applied to a 900 ADT section of road on SH 85 near Dilley, Texas, in September 2010. Three different marking materials were applied to a new seal coat surface treatment. Each test section is approximately 4 miles long. The markings were applied at approximately 100 mils thick and had a double drop of Type II and III beads each applied at approximately 12 lb/100 sq ft.

The fourth and fifth test decks are part of a new evaluation that TxDOT is conducting to see if the new lead-free thermoplastic specification can work on a typical seal coat road surface when properly installed. These test decks had close supervision by TxDOT and TTI during their installation. The thickness of the marking, bead drop rates, and bead embedment were all monitored. TxDOT does not want to disclose the results of these new test decks until after the first year of testing. The test decks will be monitored initially between 3 and 10 days, and then monitored at 30 days, 6 months, and 1 year. These new test decks will not be discussed in the results portion of this paper. Results will likely be provided in next year's report.

Measurements

The attributes measured are 30 meter retroreflectivity, 30 meter nighttime color, and 45/0 daytime and nighttime color. [Table 4](#) summarizes key elements of these measurements and the instruments used. All attributes, measurement geometries, and standard observers were measured at test decks 2 during each evaluation. At test deck 3 only retroreflectivity, 30 meter nighttime color, and 2° standard observer daytime color were measured. Two types of instruments are listed because new equipment was purchased just prior to the installation of test deck 3. All measurements after September 2008 were made using the new equipment.

Table 4. Lead-Free Yellow Thermoplastic Pavement Marking Measurements.

Attribute	Measurement Geometry	Instrument	Description
Retro-reflectivity	30 meter	LTL 2000Y/LTL 2000SY	A measure of the amount of light retroreflected to the driver from the pavement marking.
Nighttime Color	30 meter	LTL 2000Y/LTL 2000SY	A measure of the nighttime color of the pavement marking as viewed by the driver.
	45/0	BYK Gardner Color Guide/ Hunterlab MiniScan XE Plus	A measure of color using Illuminant A and the standard color measurement geometry. The 2° standard observer was used for all measurements.
Daytime Color	45/0	BYK Gardner Color Guide/ Hunterlab MiniScan XE Plus	A measure of color using Illuminant D65 and the standard color measurement geometry. Both 2° and 10° standard observers were used.

The measurements were then compared to minimum retroreflectivity levels and color boxes where appropriate. The minimum retroreflectivity level of 175 mcd/m²/lux for yellow pavement markings is contained in Special Specification 8251, Reflectorized Pavement Markings with Retroreflective Requirements (35). Several different chromaticity coordinate boxes exist for pavement markings. The TxDOT chromaticity coordinate boxes for yellow markings are contained in DMS-8220, Hot Applied Thermoplastic (36). The July 31, 2002, Final Rule by the FHWA, also established daytime (45/0) 2° standard observer and nighttime (30 meter) chromaticity coordinate boxes for traffic materials (37).

RESULTS

A summary of the results is described in the following sections.

Retroreflectivity

The retroreflectivity (R_L) measurements at test deck 2 were initially made with an LTL 2000Y retroreflectometer that was borrowed from TxDOT. The initial measurements were made the day that the markings were applied to the roadway. The second through the fourth sets of data were collected using an LTL 2000Y borrowed from FHWA. The fifth through the most

recent sets of data were collected using a new LTL 2000SY that TTI purchased. All retroreflectivity measurements on test deck 3 were made using the TTI LTL 2000SY. [Figure 10](#) and [Figure 11](#) display the average retroreflectivity values of each marking type on each test deck.

All of the initial measurements on the lead-free material of test deck 2 were above the 175 mcd/m²/lx minimum level required by TxDOT specification. Only the double drop lead-free extruded section on test deck 3 was above the minimum install retroreflectivity level. The leaded section with the standard Type II beads and the lead-free section with the single drop of the standard Type II beads were slightly below the minimum installation value. It appears that the bead type(s) used has a larger impact on retroreflectivity, than does the presence of lead in the yellow thermoplastic. The seal coat surface represents a very rough pavement surface, which may have an impact on the measured retroreflectivity. However, there was not an application site included where the lead-free marking material was applied to a smoother pavement surface.

As seen in [Figure 10](#) and [Figure 11](#) the retroreflectivity at each location is somewhat variable as the markings aged. The extruded pavement markings on test deck 3 continue to increase in retroreflectivity as they age. This is interesting in that the single drop extruded marking was slightly below the minimum retroreflectivity level initially, but almost 2 years later it is well above the minimum level.

A major observation for test deck 2 is the change in retroreflectivity values as the measuring equipment changed. All measurement procedures and calibration processes were the same between the measurement dates. During a comparison test between the TxDOT and the FHWA LTL 2000Y it was found that the FHWA device typically resulted in a lower retroreflectivity measurement than the TxDOT device (on average about 8 percent lower). The new TTI LTL 2000SY was not able to be compared to the FHWA device, but it also seems to result in measurements that are higher than the FHWA device. Comparisons were made between the TTI LTL 2000SY and other TTI pavement marking retroreflectivity devices and the resulting retroreflectivity values were similar. The resulting retroreflectivity measurements from the FHWA LTL 2000Y appear to be lower than they should be due to the equipment itself.

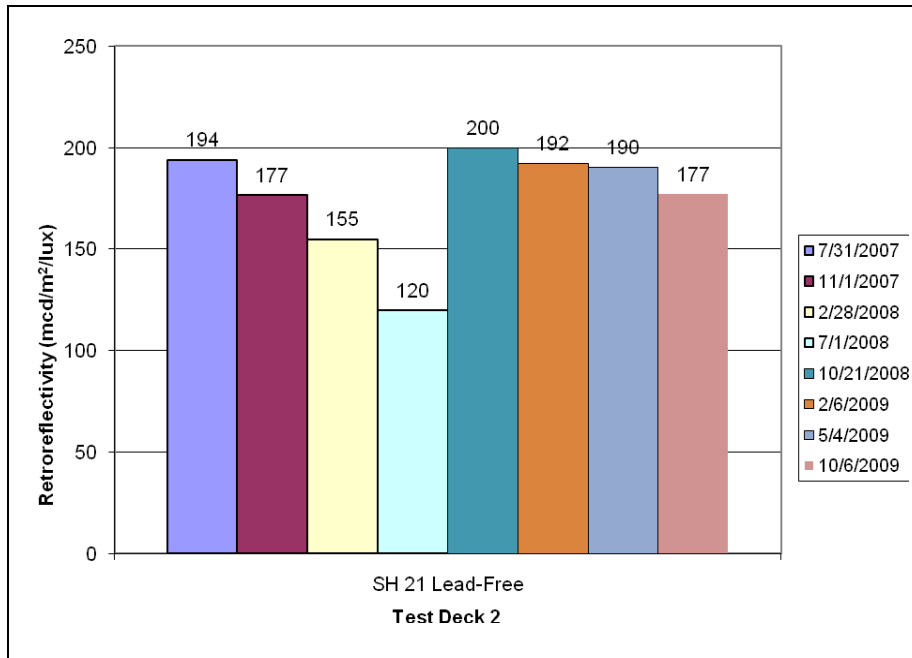


Figure 10. Yellow Thermoplastic Retroreflectivity Summary (Test Deck 2).

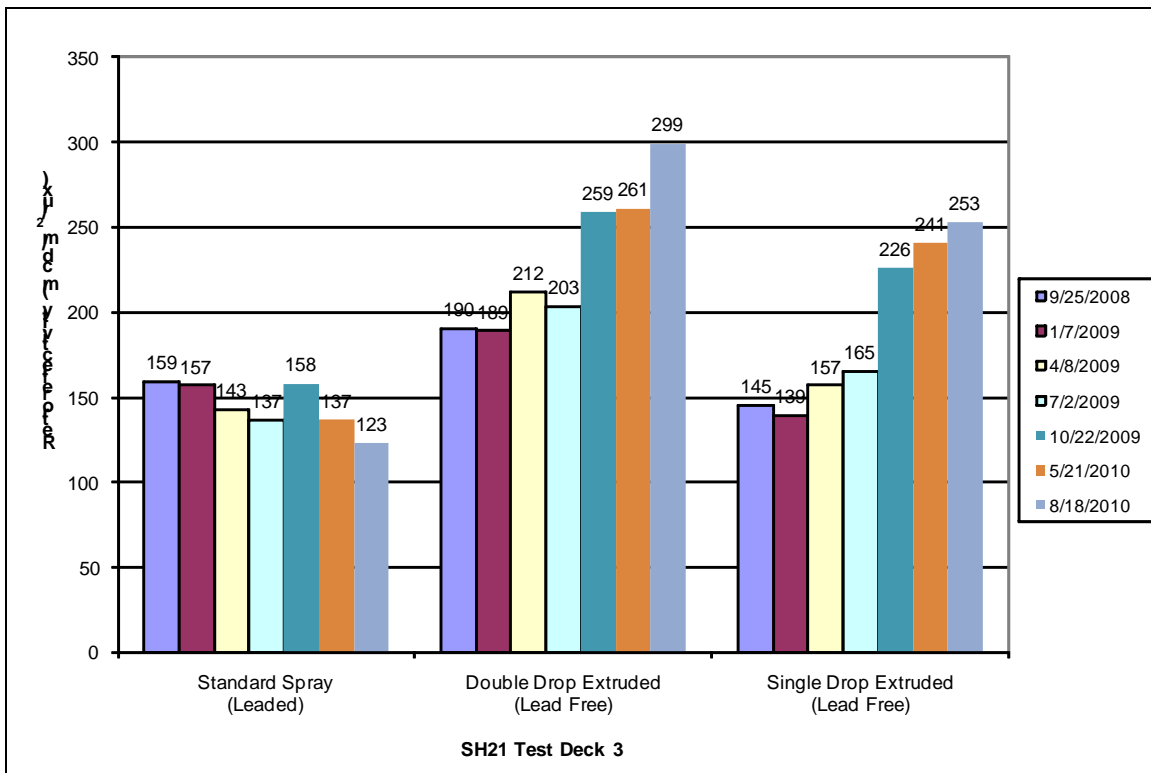


Figure 11. Yellow Thermoplastic Retroreflectivity Summary (Test Deck 3).

Color – 30 Meter

The average 30 meter color values from each data collection period were plotted against the x-y points defining the color box from the FHWA final rule on marking color. This color

box is based on Illuminant A and a viewing geometry that is the same as the 30 meter retroreflectivity geometry. The NCHRP recommended color box, which is also the 30 meter color box for TxDOT, is also illustrated to show the difference. Figure 12 and Figure 13 illustrate the plot of the average color points for the color measurements with the LTL devices at test decks 2 and 3. Unlike the retroreflectivity measurements, 30 meter color comparisons resulted in little difference between the three different LTL devices. All of the average measurements from each data collection period on both the leaded and lead-free markings are within the FHWA color box. Test deck 2 left the NCHRP color box after 2 years. Test deck 3 resulted in measurements that were on the edge or just outside of the NCHRP color box. It appears that as the markings age, both leaded and lead-free, they are trending toward the white area of the color box. The leaded marking at test deck 3 was more saturated in color initially and over time than were the lead-free markings.

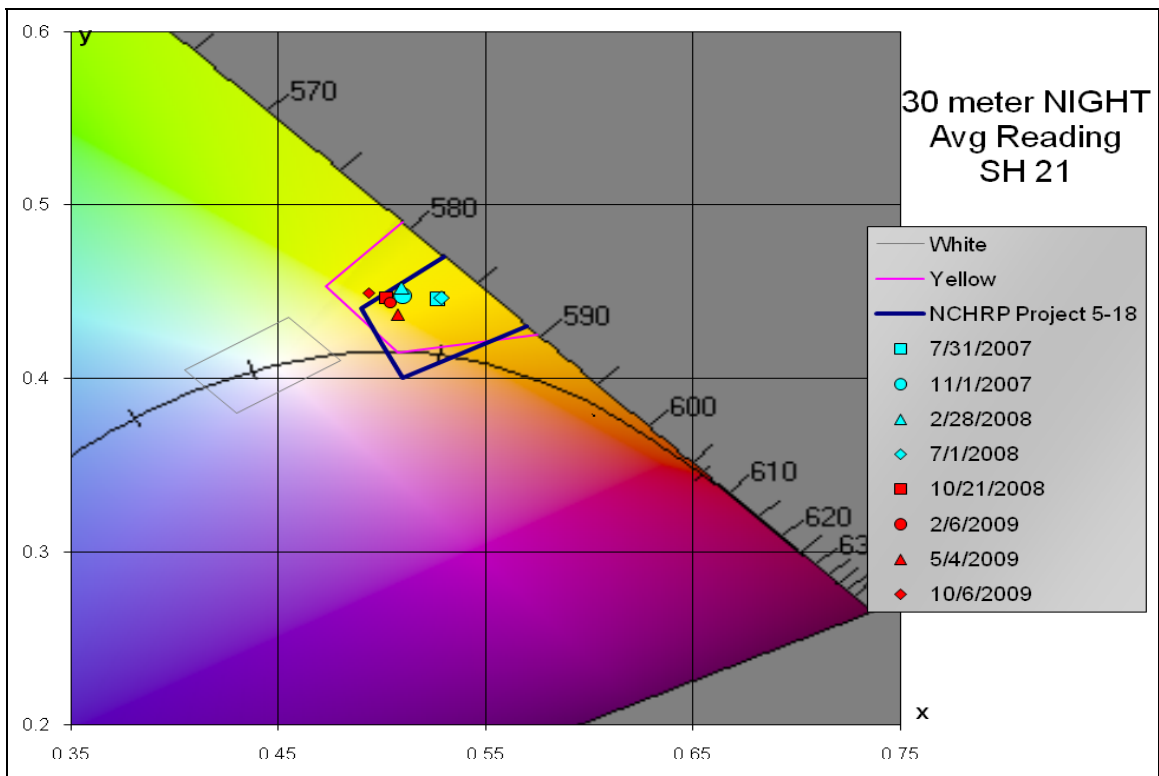


Figure 12. Avg. 30 Meter Night Color of Lead Free Thermoplastic on Test Deck 2.

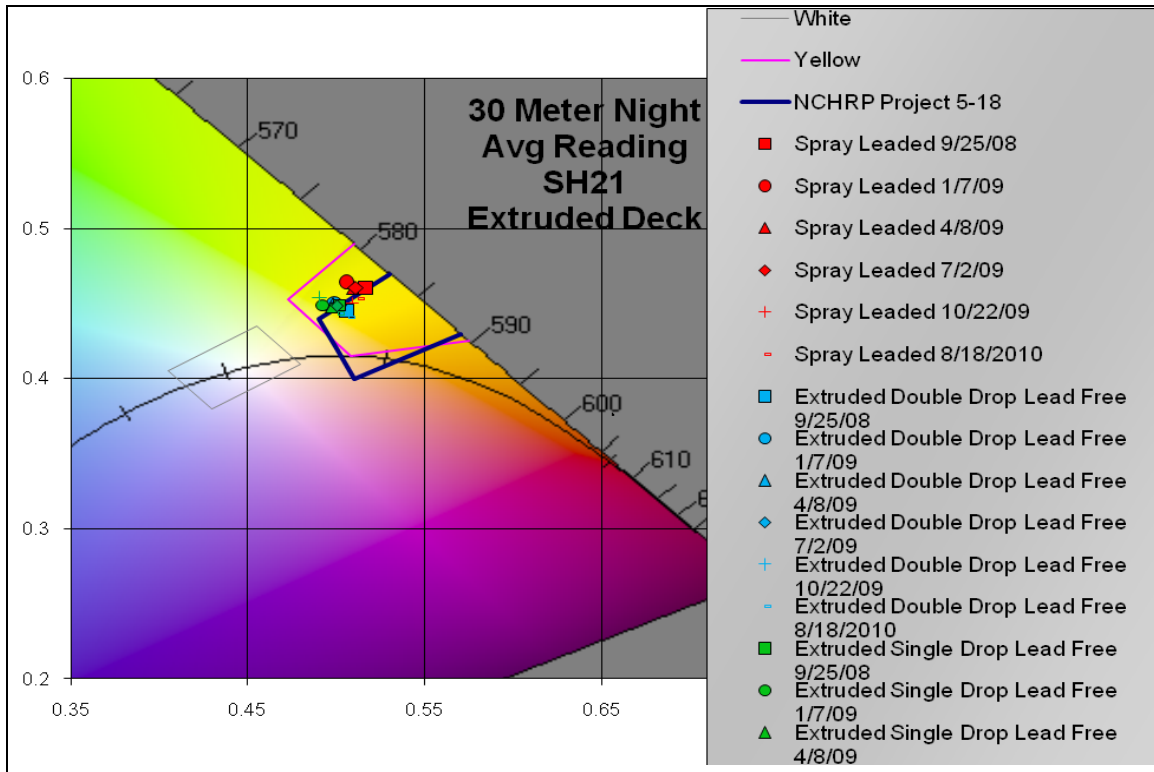


Figure 13. Avg. 30 Meter Night Color of Lead Free Thermoplastic on Test Deck 3.

Color – 45/0

The researchers also measured the color of the yellow thermoplastic marking materials containing beads and no beads using a range of illuminants and standard observers at a 45° illumination geometry and a 0° observation geometry. The color measurements on the beaded and non-beaded sections were pooled together after little difference was found between the two measurement sets. Figure 14 through Figure 17 display the average color values for each of the illuminants and standard observers for each measurement period at both locations. These points were plotted with the appropriate day or night color boxes. The TxDOT color box from DMS 8220 was used for the D65 10° standard observer measurements.

All of the initial measurements were within the TxDOT and FHWA color boxes for both standard observers. All of the Illuminant A 2° standard observer average readings at test deck 2 for each data collection period were within the FHWA and NCHRP nighttime color boxes. Looking at the daytime color measurements using Illuminant D65, some average measurements have fallen outside of the new TxDOT color box requirements. At test deck 2 the D65 10° measurements are right at the border of the new TxDOT color box. Test decks 2 and 3 D65 2°

color readings all fall within the FHWA color box for both leaded and lead-free materials, but are less saturated in color than the initial readings.

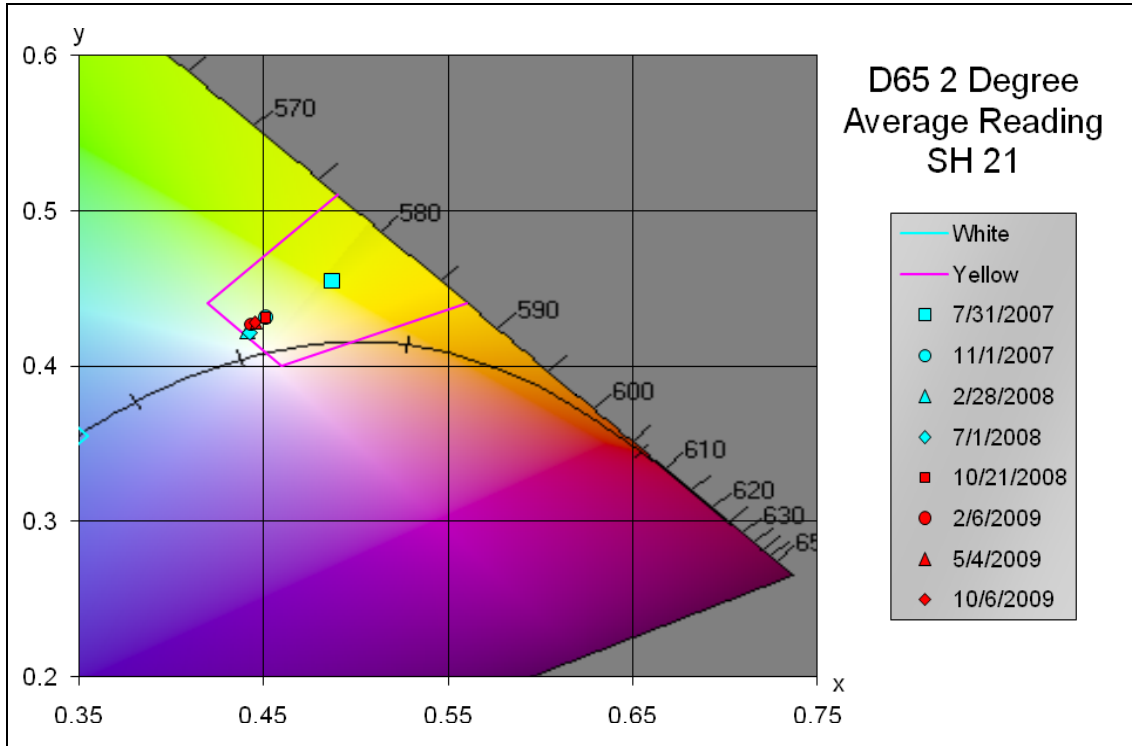


Figure 14. Avg. Daytime Color with 2 Degree Standard Observer on Test Deck 2.

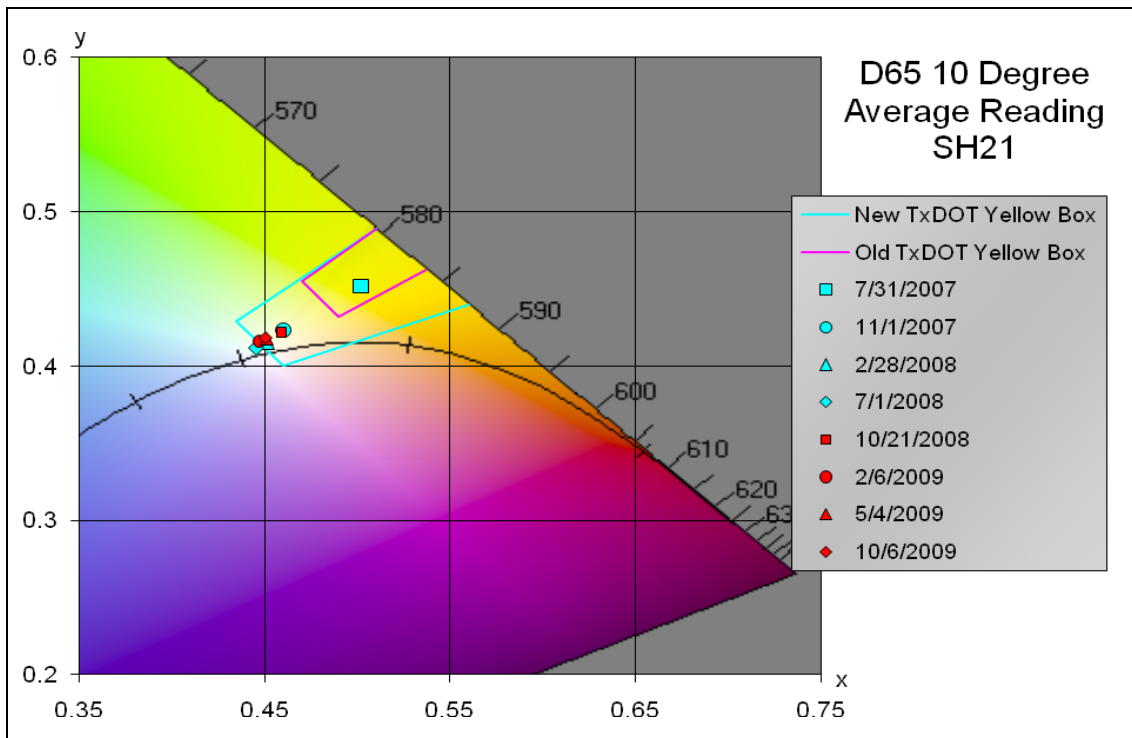


Figure 15. Avg. Daytime Color with 10 Degree Standard Observer on Test Deck 2.

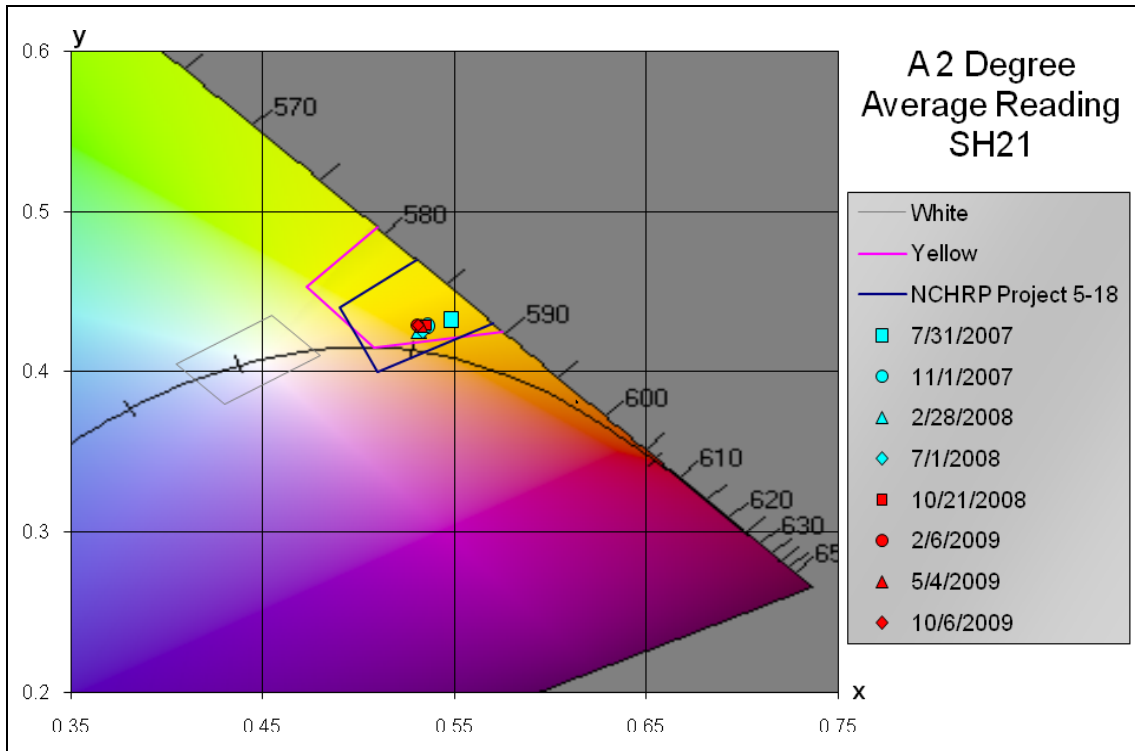


Figure 16. Avg. Nighttime Color with 2 Degree Standard Observer on Test Deck 2.

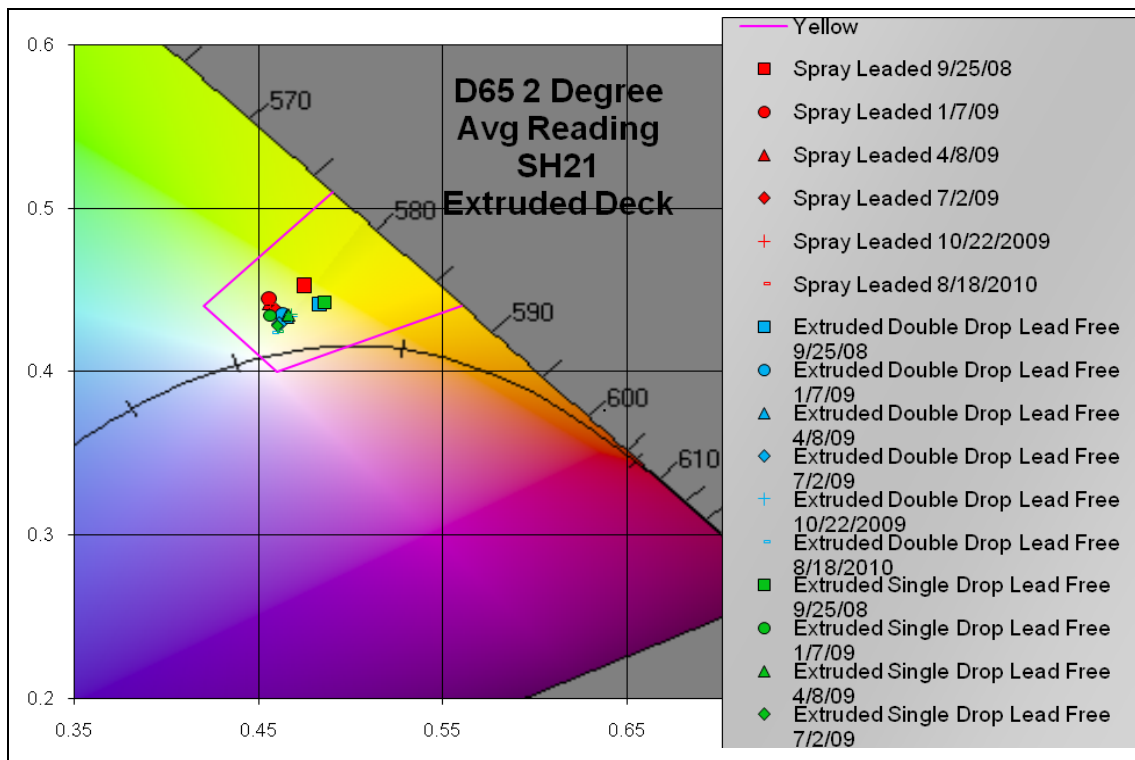


Figure 17. Avg. Daytime Color with 2 Degree Standard Observer on Test Deck 3.

FINDINGS

Based on the results of the study presented above, the researchers offer the following findings regarding retroreflectivity and color of the lead-free thermoplastic pavement marking materials:

- Retroreflectivity.
 - ♦ The initial retroreflectivity values of the lead-free thermoplastic application were above the minimum level specified by TxDOT at test deck 2. At test deck 3, the initial retroreflectivity values of the leaded and lead-free thermoplastic with Type II beads were slightly below the minimum initial retroreflectivity level, but the lead-free material with a double drop of Type II and IV beads exceeded the minimum level. The quality of the marking installation and the beads used seem to be a more significant factor in initial marking retroreflectivity than whether the marking had lead in it or not. The lead-free thermoplastic appears to be able to provide initial retroreflectivity levels similar to that of leaded material, if not better.
 - ♦ The retroreflectivity of the lead-free thermoplastic over the study period thus far indicates that material behaves similar to that of leaded thermoplastic. The two-year retroreflectivity at the test decks 2 and 3 were still acceptable. The two-year retroreflectivity of the lead-free material appears to compare acceptably to the leaded material. The 2-year old extruded lead-free thermoplastic on test deck 3 appears to be performing as well, if not better, than the adjacent section of leaded thermoplastic. The test deck 3 single drop application that was slightly below the minimum initial retroreflectivity value is now well above this value after 2 years of service.
 - ♦ Extruded applications experienced an increase in retroreflectivity over the course of the study, while the retroreflectivity of sprayed applications decreased over time.
 - ♦ Retroreflectivity values can vary significantly from one location to another. A few of the factors that can cause variation in measured retroreflectivity include: marking pigment; difference in pavement surface smoothness; type, density, and embedment of the beads; marking thickness; and the accumulation of dirt

on the marking. Differences in retroreflectivity between the leaded and lead-free marking samples may be due to factors other than the pigment.

- 30 Meter Nighttime Color.
 - ♦ All of the average measurements from each data collection period on both the leaded and lead-free markings are within the FHWA color box. At test deck 2 all the measurements were also within the NCHRP color box. The third test deck resulted in measurements that were right on the edge of the NCHRP color box.
 - ♦ The initial 30 meter nighttime color of the lead-free thermoplastic marking material appears to be acceptable. It appears from all test decks that as the markings age (both the leaded and the lead-free) they are trending toward the white area of the color box. The leaded marking at test deck 3 was both more saturated in color initially and over time than were the lead-free markings. The 30 meter nighttime color of the lead-free thermoplastic marking material appears to compare acceptably to the leaded material.
- 45/0 Color.
 - ♦ The standard color measurements using illuminants D65 and A of the leaded and lead-free material were initially found to be within the FHWA and TxDOT color boxes for yellow markings. The initial 45/0 color of the lead-free marking material appears to be acceptable.
 - ♦ The 45/0 illuminant D65 color of the lead-free marking over the two-year study period at the SH 21 extruded test deck 3 has resulted in similar D65 color changes between the leaded and lead-free materials. At test deck 2 the 2° standard observer measurements remained within the FHWA box, but were near the edge. The 10° standard observer measurements on the leaded material were not within the old TxDOT color box, but for the most part have remained within the new larger color box. At test deck 2 the 10° standard observer measurements were outside the old TxDOT box, but were within the new color box but on the edge. The 1-year 45/0 color of the lead-free thermoplastic marking material appears to be closer to white than the leaded material.

- ♦ The 45/0 illuminant A color of the lead-free thermoplastic over the 2-year study period indicates that the lead-free material behaves similarly to that of the leaded material. All readings remained within the color box, which is acceptable for the lead-free material.

SUMMARY

Initial measurements of the lead-free yellow thermoplastic pavement marking material at the test deck locations compared favorably to the leaded material placed adjacent to test deck 3.

The 2-year-long evaluation of the lead-free material at the test deck 2 indicates that the lead-free material is able to retain its retroreflectivity as expected, maintain nighttime color at 30 meters and 45/0 but is near the edge of the 45/0 illuminant D65 daytime color box. The near 2-year evaluation at the third test deck indicated that the extruded lead-free thermoplastic compared favorably with the leaded spray applied thermoplastic. The biggest difference was that the addition of larger beads on the lead-free material provided better retroreflectivity and that the leaded material provided a more saturated yellow than the lead-free marking.

The nearly 2-year-long evaluation period at test deck 3 indicates the lead-free material appears to perform in a manner that is consistent with the standard TxDOT leaded material with respect to retroreflectivity and D65 daytime color readings. The nighttime 30 meter color measurements differ slightly in that the leaded material provides a more saturated yellow than the lead free material.

Further evaluation will be conducted to assess the long-term (greater than 2 years) implications of using ribbon-extruded lead-free yellow thermoplastic material on test deck 3. The results of test decks 4 and 5 will be provided in next year's report.

CHAPTER 6: LED SIGN TECHNOLOGIES

BACKGROUND

There are several emerging technologies that are being incorporated into traffic control devices. Light emitting diodes (LEDs) are one of these emerging technologies. While they are commonly used in traffic signals, their application to static signing and raised pavement markers is still evolving. This activity was initially established to identify different applications of LEDs in traffic signs. This activity began prior to the release of the 2009 MUTCD so both the 2009 and the 2003 MUTCD information will be displayed for comparison purposes.

The 2009 MUTCD says the following about LEDs in signs (38).

Section 2A.07 Retroreflectivity and Illumination

Option:

LED units may be used individually within the legend or symbol of a sign and in the border of a sign, except for changeable message signs, to improve the conspicuity, increase the legibility of sign legends and borders, or provide a changeable message.

Standard:

Except as provided in Paragraphs 11 and 12 (*the option below*), neither individual LEDs nor groups of LEDs shall be placed within the background area of a sign.

If used, the LEDs shall have a maximum diameter of ¼ inch and shall be the following colors based on the type of sign:

- A. White or red, if used with STOP or YIELD signs.**
- B. White, if used with regulatory signs other than STOP or YIELD signs.**
- C. White or yellow, if used with warning signs.**
- D. White, if used with guide signs.**
- E. White, yellow, or orange, if used with temporary traffic control signs.**
- F. White or yellow, if used with school area signs.**

If flashed, all LED units shall flash simultaneously at a rate of more than 50 and less than 60 times per minute.

The uniformity of the sign design shall be maintained without any decrease in visibility, legibility, or driver comprehension during either daytime or nighttime conditions.

Option:

For STOP and YIELD signs, LEDs may be placed within the border or within one border width within the background of the sign.

For STOP/SLOW paddles (see Section 6E.03) used by flaggers and the STOP paddles (see Section 7D.05) used by adult crossing guards, individual LEDs or groups of LEDs may be used.

The 2003 MUTCD says the following about LEDs in signs (39).

Section 2A.08 Retroreflectivity and Illumination

Option:

LED units may be used individually within the face of a sign and in the border of a sign, except for Changeable Message Signs, to improve the conspicuity, increase the legibility of sign legends and borders, or provide a changeable message. Individual LED pixels may be used in the border of a sign.

Standard:

If used, the LEDs shall be the same color as the sign legend, border, or background. If flashed, all LED units shall flash simultaneously at a rate of more than 50 and less than 60 times per minute. The uniformity of the sign design shall be maintained without any decrease in visibility, legibility, or driver comprehension during either daytime or nighttime conditions.

A module of multiple LED units used as a closely-spaced, single light source shall only be used within the sign face for legends or symbols.

The MUTCD wording changed slightly from the 2003 to the 2009 version. The 2009 version clarified placing LEDs in the background area of a sign as well as the size and color requirements of the LEDs. A maximum size of ¼ inch is given, but there is no information concerning the size of reflector/diffuser in front of or behind the LEDs.

It was discovered that there are many different uses of LEDs in traffic signs. The researchers obtained examples of as many different signs as possible and performed a daytime and nighttime LED sign demonstration at the Texas A&M University Riverside campus in

March 2010. The goals of the demonstration were to view new LED sign technologies and to evaluate potential applications and concerns of the signs.

DEMONSTRATION PROCEDURE

Each of the acquired signs was set up on a sign pole and spaced out around the Texas A&M University Riverside Campus on the right side of the travel route. The signs were spaced out by at least 1100 ft, except for the chevrons as they were placed in a single curve. TxDOT and TTI vehicles were used to drive through the course to view the signs. The course was driven once during the day and twice at night. During the second night drive through, the TxDOT and TTI representatives stopped at several of the signs for a closer inspection and to discuss the signs.

SIGNS DISPLAYED

The demonstration used a number of different sign types and LED configurations. The types of signs that were demonstrated included stop, chevron, speed limit, school zone speed limit, pedestrian crossing, arrow, and no right turn blank-out signs. Each sign used for the demonstration is described and shown in the following sections. The additional notes in the tables indicate the capabilities of the signs actually tested. Many of the signs can be built to similar standards, including variable light intensity and variable flash rates. Most, if not all, of the signs have the ability to be solar powered as well. Comments about the signs are summarized at the end of the chapter.

Stop Signs

Eight different LED stop sign configurations were displayed during the demonstration. Descriptions of each LED configuration and additional notes can be found in [Table 5](#). [Figure 18](#) through [Figure 25](#) are daytime and nighttime photographs of each stop sign type used.

Table 5. Stop Sign Descriptions.

Stop Sign Type	LED Configuration	Additional Notes
1	Internally illuminated sign through the use of LEDs around internal perimeter	
2	Single LED at each corner with a reflector behind the LED	Adjustable flash rate and light intensity
3	Clusters of LEDs at each corner with no reflector behind LEDs	
4	Single LED at each corner with a reflector behind the LED	
5	Internally illuminated stop area with LED clusters at each corner	
6	Four large LED clusters surrounding STOP text	
7	Single red LEDs around border, single white LEDs within STOP text	Flash or constant on settings
8	Single white LEDs in STOP text only	



Figure 18. LED Stop Sign Type 1.



Figure 19. LED Stop Sign Type 2.



Figure 20. LED Stop Sign Type 3.



Figure 21. LED Stop Sign Type 4.



Figure 22. LED Stop Sign Type 5.



Figure 23. LED Stop Sign Type 6.



Figure 24. LED Stop Sign Type 7.



Figure 25. LED Stop Sign Type 8.

Chevron Signs

Five different LED chevron configurations were displayed during the demonstration. Descriptions of each LED configuration and additional notes can be found in [Table 6](#). [Figure 26](#) through [Figure 30](#) are daytime and nighttime photographs of each chevron sign type used.

Table 6. Chevron Sign Descriptions.

Chevron Sign Type	LED Configuration	Additional Notes
1	Internally illuminated through the use of LEDs around internal perimeter	
2	Single yellow LEDs with reflectors around border of chevron	Adjustable flash rate, light intensity, and flash patterns between sequential signs (signs can all flash at once or flash in sequence)
3	Single yellow LEDs with reflectors placed within chevron	
4	The entire chevron is covered with single yellow LEDs without reflectors	
5	Two rows of single yellow LEDs without reflectors surrounding the border of the chevron	Vehicle activation capabilities with adjustable flash rate and light intensity



Figure 26. LED Chevron Sign Type 1.



Figure 27. LED Chevron Sign Type 2.



Figure 28. LED Chevron Sign Type 3.



Figure 29. LED Chevron Sign Type 4.



Figure 30. LED Chevron Sign Type 5.

Miscellaneous Signs

Eight other types of LED sign configurations were displayed during the demonstration. Descriptions of each sign type and LED configuration and additional notes can be found in [Table 7](#). [Figure 31](#) through [Figure 38](#) are daytime and nighttime photographs of each of these signs.

Table 7. Miscellaneous Sign Descriptions.

Sign Type	LED Configuration	Additional Notes
Speed Limit – 1	Internally illuminated through the use of LEDs around internal perimeter	
Speed Limit – 2	Single white LEDs with reflectors around border and within text	Flash or constant on; some LEDs are not working in Figure 32
School Speed Limit	Single yellow LEDs with reflectors at each corner	Adjustable flash rate and light intensity
Pedestrian Crossing – 1	Large cluster LEDs at each corner of diamond sign	
Pedestrian Crossing – 2	Cluster LEDs at each corner of sign	
Arrow	Electroluminescent	
No Right Turn Blank-Out – 1	Symbol outlined with LEDs	Blank out sign, off during the daytime picture
No Right Turn Blank-Out – 2	Symbol filled with LEDs	Blank out sign, off during the daytime picture



Figure 31. LED Speed Limit Sign Type 1.



Figure 32. LED Speed Limit Sign Type 2.



Figure 33. LED School Speed Limit Sign.



Figure 34. LED Pedestrian Crossing Sign Type 1.



Figure 35. LED Pedestrian Crossing Sign Type 2.



Figure 36. LED Arrow Sign.



Figure 37. LED No Right Turn Sign Type 1.



Figure 38. LED No Right Turn Sign Type 2.

COMMENTS

The following were comments made in discussing the signs. Some of the comments may require further research to be able to completely address them, whereas others may require policy or design decisions.

- Establishing guidelines for day and night brightness of the LEDs and internal illumination may be necessary.
- The security of the signs needs to be considered due to the increased cost of the signs.
- The pattern of the LEDs needs to maintain sign shape when viewed up close and at a distance.
- Both LED clusters and single LEDs function adequately.
- Should a speed for chevrons flashing in sequence be established? Should be it based off posted speed limit, warning speeds, or a set value for any curve?
- Is putting yellow LEDs within the chevron symbol itself ok? Would it be better to fill the yellow background?
- Non-filled in no right turn sign looked better than the filled in version.
- What are the durability of the lighting systems and maintenance requirements for replacing dead LEDs? If a single LED fails, does it need to be replaced immediately, and at what cost of time and money?

RETROREFLECTIVE POWDER COATED MATERIALS

During the LED sign study, retroreflective powder coating technology was also observed on guard rails, mailbox posts, and sign posts. This is an experimental technology recently developed to improve the visibility of a traffic control device or other structures within the right-of-way. An example of a retroreflective powder coated guard rail section can be seen in [Figure 39](#).



Figure 39. Retroreflective Powder Coated Guard Rail.

CHAPTER 7: ADDITIONAL RESEARCH ACTIVITIES

UPDATES TO PAVEMENT MARKING RETROREFLECTIVITY SPECIFICATIONS

TxDOT sought assistance in updating the language in two documents that pertain to measuring the retroreflectivity of pavement marking. The first document was the Mobile Retroreflectometer Certification Guide, and the second document was Special Specification 8251: Retroreflectorized Pavement Markings with Retroreflective Requirements. The changes to these documents are indicated below.

Update to Mobile Retroreflectivity Certification Guide

The mobile retroreflectivity certification guide was updated to include annual field evaluations of certified contractors. Contractors will be required to pass these field evaluations or face losing their certification. The old language and the updated language with regard to the field evaluations are provided below.

Old Certification Guide Language

Certification Requirements. To receive certification, the operator and the mobile retroreflectometer shall meet the requirements indicated below:

- The raw data submitted by the contractor shall include all required information (0.05 mile aggregate retroreflectivity values, GPS coordinates, video with superimposed information, temperature measurements, and vehicle speed data).
- For each marking on the course, no more than one of the 0.05 mile aggregate retroreflectivity values shall be more than ± 15 percent different from the official 30 meter retroreflectivity value for the marking as determined by the Program Coordinator. Where multiple retroreflectivity measurements were made on a line, all average retroreflectivity values shall meet the ± 15 percent criteria.
- Demonstrate the ability to control the retroreflectometers temperature or to compensate for temperature changes. If software temperature compensation is used, testing results must be provided to validate proper compensation.
- Software that automatically compensates for changes in background retroreflectivity (i.e., no manually adjustable lower threshold value).

- The driver and operator or driver/operator shall possess a valid driver license from a state in the United States and make it available to the Program Coordinator for inspection.
- All data requirements of TxDOT Special Specification 6629: Mobile Retroreflectivity Data Collection for Pavement Markings must be met with the additional data that are submitted for certification.

TxDOT Mobile Retroreflectivity Data Collection Comparison Checks. Certified contractors may undergo additional evaluation during field comparison checks while collecting mobile retroreflectivity data on TxDOT jobs. These comparison checks are part of Special Specification 6629: Mobile Retroreflectivity Data Collection for Pavement Markings. These comparison checks will not cause the loss of certification, but may require that data be recollected so that the resulting data are within the accuracy that TxDOT has specified. These comparison checks, however, may extend the expiration date of the certification if the data are continuously within TxDOT's requirements.

Field comparison checks will be carried out by TTI and/or TxDOT. These comparison checks will measure the pavement markings on a road being measured under contract with portable retroreflectometers and compare the values to those measured by the contractor with the mobile retroreflectometer. The contractor will be required to provide the data from the section where the spot check occurred.

A field comparison check will consist of a minimum of 20 portable retroreflectometer readings spread out over the length of an individual mobile interval (i.e., if mobile data are being collected in 0.1-mile intervals the comparison check would be over a length of 0.1 mile). This would represent the minimum length and minimum number of readings for a field comparison check. It is recommended that the comparison checks between the mobile unit and portable unit would be conducted on a fairly flat and straight roadway when possible.

New Certification Guide Language

Certification Requirements. To receive and maintain certification, the operator and the mobile retroreflectometer shall meet the requirements indicated below:

- The raw data submitted by the contractor shall include all required information (0.05 mile aggregate retroreflectivity values, GPS coordinates, video with superimposed information, temperature measurements, and vehicle speed data).
- For each marking on the course, no more than one of the 0.05 mile aggregate retroreflectivity values shall be more than ± 15 percent different from the official 30 meter retroreflectivity value for the marking as determined by the Program Coordinator. Where multiple retroreflectivity measurements were made on a line, all average retroreflectivity values shall meet the ± 15 percent criteria.
- Demonstrate the ability to control the retroreflectometers temperature or to compensate for temperature changes. If software temperature compensation is used, testing results must be provided to validate proper compensation.
- Software that automatically compensates for changes in background retroreflectivity (i.e., no manually adjustable lower threshold value).
- The driver and operator or driver/operator shall possess a valid driver license from a state in the United States and make it available to the Program Coordinator for inspection.
- All data requirements of TxDOT Special Specification 8094: Mobile Retroreflectivity Data Collection for Pavement Markings must be met with the additional data that are submitted for certification.
- Pass annual field mobile retroreflectivity data collection comparison checks as described below.

Field Mobile Retroreflectivity Data Collection Comparison Checks. Certified contractors will undergo additional annual field comparison checks while collecting mobile retroreflectivity data on TxDOT jobs. These comparison checks are similar to what the contractor should be conducting as part of Special Specification 8094: Mobile Retroreflectivity Data Collection for Pavement Markings, Article 3, section F. If the comparison check does not result in data that are within TxDOT's requirements, the check may result in the loss of certification, and may require that data on the project be recollected so that the resulting data are within the accuracy that TxDOT has specified. These comparison checks, however, may also

extend the expiration date of the certification if the data are continuously within TxDOT's requirements. TxDOT's current accuracy requirements are within ± 15 percent.

Field comparison checks will be carried out by TTI and/or TxDOT. These comparison checks will measure the pavement markings on a road being measured under contract with portable retroreflectometers and compare the values to those measured by the contractor with the mobile retroreflectometer. The contractor will be required to provide the data from the section where the spot check occurred.

A field comparison check will consist of a minimum of 20 portable retroreflectometer readings spread out over the length of an individual mobile interval (i.e., if mobile data are being collected in 0.1-mile intervals the comparison check would be over a length of 0.1 mile). This would represent the minimum length and minimum number of readings for a field comparison check. It is recommended that the comparison checks between the mobile unit and portable unit would be conducted on a flat and straight roadway when possible.

Three comparison checks will be conducted over the course of a day, no more than one can fall outside the ± 15 percent accuracy range, and the average of all three comparison checks must be within ± 15 percent. If these criteria are not met the contractor will need to reschedule and pass certification as soon as possible (within 30 days, at no additional fee), in order to retain their certified status. If the certification trial is not passed, then certification will be rescinded. If all three checks result in data that are within ± 10 percent, certification will be extended 6 months.

Update to Special Specification 8251: Retroreflectorized Pavement Markings with Retroreflective Requirements

The language in this special specification was not very clear in how to measure yellow centerline marking situations where there was a double or broken/solid centerline marking. The specification needed to better address how to measure, record, and determine the acceptance of the retroreflectivity readings for these types of pavement markings. The old specification and the suggested changes to the specification with regards to the measurement of yellow centerlines are provided below.

E. **Retroreflectivity Measurements.** Use a mobile retroreflectometer unless otherwise shown on the plans.

1. **Mobile Reflectometer Measurements.** Provide mobile measurements averages for every 0.1 mile unless otherwise specified or approved by the Engineer. Take measurements on each section of roadway for each series of markings (i.e., edge-line, center skip line, each line of a double line, etc.) and for each direction of travel. Take all measurements in the direction of traffic flow, except on broken centerline on two-way roadways, and take measurements in both directions. Furnish measurements in compliance with Special Specification, “Mobile Retroreflectivity Data Collection for Pavement Markings,” unless otherwise approved by the Engineer. The Engineer may require an occasional field comparison check with a portable retroreflectometer meeting the requirements listed above to ensure accuracy. Use all equipment in accordance with the manufacturer’s recommendations and directions. Inform the Engineer at least 24 hours in advance of taking any measurements.

If 30 percent or more of the average measurements fail within a 1-mile segment, restripe once at the Contractor’s expense with a minimum of 0.060 in. (60 mils) of Type I marking material or 15 to 20 gallons per mile of Type II marking material. Take measurements every 0.1 mile after 3 days but before 10 days of this second application within that mile segment for that series of markings. If 30 percent or more of the average measurements fall below the minimum retroreflectivity requirements, restripe using 15 to 20 gallons per mile of Type II marking material at the Contractor’s expense. If the markings do not meet minimum retroreflectivity after this application, the Engineer may require removal of all existing markings, a new application as initially specified, and a repeat of the application process until minimum retroreflectivity requirements are met. If the Engineer does not require removal of the markings, restripe using 15 to 20 gallons per mile of Type II marking material at the Contractor’s expense until minimum retroreflectivity requirements are met.

2. **Portable Reflectometer Measurements.** When using a portable reflectometer, take a minimum of three measurements for each 1-mile section of roadway for each series of markings (i.e., edge-line, center skip line, each line of a double line, etc.) and for each

direction of travel. Take all measurements in the direction of traffic flow, except on broken centerline on two-way roadways, and take measurements in both directions. The spacing between each measurement must be at least 1000 ft. The Engineer may decrease the mileage frequency for measurements if the previous measurements provide satisfactory results. The Engineer may require the original number of measurements if concerns arise.

Suggested Changes to Special Specification 8251

E. **Retroreflectivity Measurements.** Use a mobile retroreflectometer unless otherwise shown on the plans.

1. **Mobile Reflectometer Measurements.** Provide mobile measurements averages for every 0.1 miles unless otherwise specified or approved by the Engineer. Take measurements on each section of roadway for each series of markings (i.e., edge-line, center skip line, each line of a double line, etc.) and for each direction of traffic flow. For centerlines on two-way roadways measure all lines in both directions (i.e., measure both double solid lines in both directions and measure all centerskip lines in both directions). Furnish measurements in compliance with Special Specification, “Mobile Retroreflectivity Data Collection for Pavement Markings,” unless otherwise approved by the Engineer. The Engineer may require an occasional field comparison check with a portable retroreflectometer meeting the requirements listed above to ensure accuracy. Use all equipment in accordance with the manufacturer’s recommendations and directions. Inform the Engineer at least 24 hours in advance of taking any measurements. A marking meets the retroreflectivity requirements if:

- No more than 30 percent of the values are below the minimum level within a 1-mile segment.
- No more than 20 percent of the values are below the minimum level if the average retroreflectivity of the segment is less than the minimum level.

The 1-mile segment will start from the beginning of the data collection and end after 1 mile of measurements have been taken; each subsequent mile of measurements will be a new segment. Centerlines with two stripes (either solid or broken) will result in 2 miles

of data for each mile segment. Each centerline stripe shall be tested for compliance as a stand-alone stripe.

If a marking fails these retroreflectivity requirements, restripe once at the Contractor's expense with a minimum of 0.060 in. (60 mils) of Type I marking material or 15 to 20 gallons per mile of Type II marking material. Take measurements every 0.1 mile after 3 days but before 10 days of this second application within that mile segment for that series of markings. If 30 percent or more of the average measurements fall below the minimum retroreflectivity requirements, restripe using 15 to 20 gallons per mile of Type II marking material at the Contractor's expense. If the markings do not meet minimum retroreflectivity after this application, the Engineer may require removal of all existing markings, a new application as initially specified, and a repeat of the application process until minimum retroreflectivity requirements are met. If the Engineer does not require removal of the markings, restripe using 15 to 20 gallons per mile of Type II marking material at the Contractor's expense until minimum retroreflectivity requirements are met.

2. **Portable Reflectometer Measurements.** When using a portable reflectometer, take a minimum of three measurements for each 1-mile section of roadway for each series of markings (i.e., edge-line, center skip line, each line of a double line, etc.) and for each direction of traffic flow. For centerlines on two-way roadways measure all lines in both directions (i.e., measure both double solid lines in both directions and measure all center skip lines in both directions). The spacing between each measurement must be at least 1000 ft. The Engineer may decrease the mileage frequency for measurements if the previous measurements provide satisfactory results. The Engineer may require the original number of measurements if concerns arise.

TECHNICAL SUPPORT FOR TRAFFIC OPERATIONS DIVISION

During this past year, researchers also performed three short-term activities to support the Traffic Operations Division. One of these activities was set up to develop realistic estimates for the life of thermoplastic pavement markings materials. Another activity was to determine the breadth of the pavement marking material shortage that surprised many agencies in the spring of 2010. The third activity was to investigate the feasibility of an automated flagging assistance device.

Durability of Thermoplastic Pavement Markings

After canvassing available literature for relevant pavement marking durability studies, the following service life formulas were recommended to be the best available for thermoplastic pavement markings (40-46). They are based on 30 meter geometry and include adequate statistical analysis to support their results.

$$\text{White edge line } R_L = 231 + 0.39 \times R_{L, \text{initial}} - 2.09 \times \text{months} - 0.0011 \times \text{AADT}$$

$$\text{White skip line } R_L = 188 + 0.39 \times R_{L, \text{initial}} - 2.09 \times \text{months} - 0.0011 \times \text{AADT}$$

$$\text{Yellow edge line } R_L = 188 + 0.39 \times R_{L, \text{initial}} - 2.09 \times \text{months} - 0.0011 \times \text{AADT}$$

$$\text{Yellow center line } R_L = 150 + 0.39 \times R_{L, \text{initial}} - 2.09 \times \text{months} - 0.0011 \times \text{AADT}$$

These relationships assume asphalt pavements and ribbon applied thermoplastic (with AASHTO M247 Type I beads applied at a typical rate of 7 lb per 100 sq ft). Because TxDOT uses grade 3 rock in a seal coat application on many highways, especially the lower volume highways, and apply thermoplastic with a spray rather than ribbon technique, an adjustment factor of 30 percent was introduced to the relationships shown above. With user defined typical initial retroreflectivity levels and minimum acceptable retroreflectivity levels, service life values were estimated. Table 8 shows the estimated service life values for thermoplastic markings based on initially installed markings with retroreflective levels of 350 mcd for white and 300 mcd for yellow. It is also based on minimum acceptable retroreflective levels of 150 mcd for white and 125 mcd for yellow.

Table 8. Estimated Thermoplastic Service Life (yrs)

AADT (×1000)	10	25	50
White Edge Line	5.8	5.3	4.5
White Lane Line	4.6	4.1	3.3
Yellow Edge Line	4.7	4.3	3.5
Yellow Center Line	3.7	3.2	2.4

This effort was meant to be a quick assessment of the existing literature with the research team’s autonomy to make adjustments based on their expertise. The effort did not include the collection of new data and was carried out in less than a week.

Pavement Marking Material Shortage Support

At the beginning of the 2010 striping season, many agencies including TxDOT were surprised to hear from the pavement marking industry concerning a shortage of raw materials used to make many of the pavement marking binder systems that are used on TxDOT highways, including thermoplastic. As the news of this shortage was initially learned, the researchers were asked to determine the breadth of the shortage and provide recommendations to alleviate the possible concerns.

The researchers used their contacts within the pavement marking industry and at various state Departments of Transportation to assess the issue. They learned that there were indeed shortages. There was a shortage of the resins used to make thermoplastic and titanium dioxide used to increase retroreflectivity of white markings by making them more opaque. The manufacturers of the pavement marking binders were not able to receive these critical raw materials in the quantities they desired and therefore were forced to limit production to a fraction of the need. These shortages were not exclusive to Texas or even the U.S. A May 2010 report from the United Kingdom demonstrated that the shortages were global (47). The good news is that the shortages were predicted to be temporary and full capacity would be achieved by the end of the 2010 striping season.

TxDOT determined that they were scheduled to stripe approximately 171 million linear feet of 4-inch stripe during the 2010 pavement marking season. This total did not include markings wider than 4-inches, temporary markings, or other specialty markings. The researchers

recommended a set of temporary guidelines be implemented until the production problem was resolved. First and foremost was to suspend all retracing work so that the limited amount of materials could be used on new seal coat surfaces and other overlays. Second, if materials allowed, prioritize the retracing work to roadways with high volumes and/or crash rates.

Prototype Automated Flagging Assistance Device

An area engineer had developed an idea for a proposed traffic control device utilizing flashing yellow directional arrows to allow driveway access on non-manned, two-way, one-lane traffic control operations. A private company had sponsored a prototype automated flagging assistance device (AFAD), which is shown in [Figure 40](#).



Figure 40. Prototype AFAD Devices.

The researchers set up a demonstration of the device at the Riverside Campus. After the demonstration, FHWA was contacted as a screening effort to determine the feasibility of going through the official process to request to experiment with a new device (as defined in the

MUTCD (38)). FHWA returned a list of concerns related to the current MUTCD and the prototype's compatibility. The researchers developed a supplemental list of concerns based on their expertise related to human factors and conducting studies of driver comprehension. After sharing and describing the concerns with TxDOT, this research activity concluded.

UPDATE ON CONTRAST PAVEMENT MARKINGS (ON-GOING)

Contrast markings are used to improve the visibility of the white pavement marking by having a contrasting black marking surrounding or near the white marking. In this study researchers will evaluate the potential benefits of different measurements for the contrast markings where the contrasting black is applied to the left and right sides of a white skip marking (Figure 41).



Figure 41. Contrast Marking Example.

Treatments

Researchers began their determination of possible treatments for this study by identifying what marking dimensions have previously been used by TxDOT. The information gathered from this effort is included in Table 9 where the *T* represents the treatments that TxDOT has used.

Based on this information researchers decided that each blue cell in the table represents a treatment that will be evaluated in this study. Researchers based the decision of including contrast borders of dimensions from 1 inch to 3 inches in this study on the information from

TxDOT, which indicated these dimensions were within the practicable range of what practitioners would desire to use. Additionally, researchers will include an evaluation of traditional (or white only) markings in each of the three white marking dimensions (4, 6, and 8 inches) as a comparison to the contrast markings.

Table 9. Study Treatments.

White Marking Dimension	Black Contrast Dimensions (inches per side)				
	1"	1.5"	2"	2.5"	3"
4"		<i>T</i>			<i>T</i>
6"		<i>T</i>		<i>T</i>	<i>T</i>
8"					

T = previous TxDOT applications

Study Design

Researchers will be evaluating two different factors during this study:

- Visibility distance of different dimensions of contrast and traditional pavement markings.
- The ability of a driver to perceive changes in the marking widths.

To accomplish this, the following two-step study will be conducted.

Step 1: Visibility Distance

Researchers will evaluate the visibility distance of the selected treatments by having drivers approach the markings at a steady speed and identify when they see the markings. On a closed course, researchers will set up a series of skip lines at the far end of an approach. Drivers will progress along the approach and will identify when they can first see the contrast markings (see [Figure 42](#)). Drivers will make several passes along a set route to evaluate different treatments.

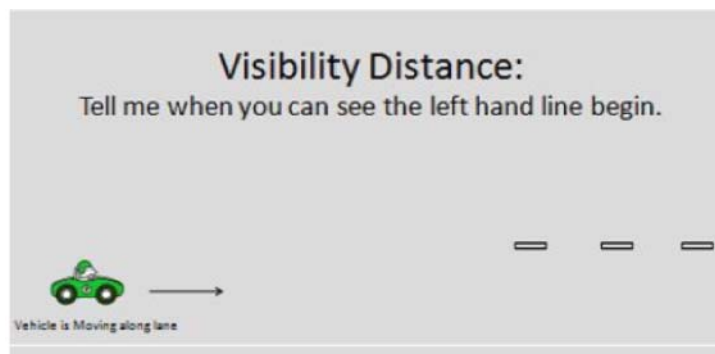


Figure 42. Visibility Study.

Step 2: Subjective Evaluation

Researchers will next set up an evaluation where a participant is in a stationary vehicle and they will view different pairs of markings. During this study the participant will be asked to identify:

- If the markings are the same or different.
- To explain the perceived difference (if any).
- To identify if they believe one of the markings is better than the other and why.

This will help researchers identify if there is a visually perceivable difference in the markings by road users and if there is a point where the contrast dimension becomes a negative based on visual perception.

Task Activities

Thus far in this task, researchers have completed the following activities:

- A preliminary study design was created.
- Treatments were selected for inclusion in the study.
- Materials were ordered and creation of the contrast marking treatments began.

The next activities for this task will be as follows:

- Complete the creation of all contrast marking treatments.
- Conduct a pilot study and revise the study design as needed based on this information.
- Conduct a full-scale study.
- Analyze data from the full study and develop contrast marking recommendations.

REFERENCES

1. Rose, E.R., H.G. Hawkins, Jr., A.J. Holick, and R.P. Bligh. *Evaluation of Traffic Control Devices: First-Year Activities*. FHWA/TX-05/0-4701-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2004.
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.
3. Hawkins Jr., H.G., M.A. Sneed, and C.L. Williams. *Evaluation of Traffic Control Devices: Third-Year Activities*. FHWA/TX-07/0-4701-3, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2006.
4. Hawkins Jr., H.G., C.L. Williams, and S. Sunkari. *Evaluation of Traffic Control Devices: Fourth-Year Activities*. FHWA/TX-08/0-4701-4, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2007.
5. Hawkins Jr., H.G., A.M. Pike, and M. Azimi. *Evaluation of Traffic Control Devices: Fifth-Year Activities*. FHWA/TX-09/0-4701-5, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2008.
6. P.J. Carlson, R.P. Bligh, A.M. Pike, J.D. Miles, W.L. Menges, and S.C. Paulus. *On Going Evaluation of Traffic Control Devices*. FHWA/TX-10/0-6384-1. Texas Transportation Institute, College Station, TX. September 2010.
7. A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials, Washington, D.C., 2004.
8. *Texas Manual on Uniform Traffic Control Devices for Streets and Highways*. Texas Department of Transportation, Austin, Texas, 2006.
http://www.txdot.gov/txdot_library/publications/TxMUTCD.htm. Accessed August 20, 2010.
9. *Traffic Control Devices Handbook*. Publication No. IR-112. Institute of Transportation Engineers, Washington, D.C., 2001.
10. Denis Leroux. Software Tools for Location of No-Passing Zones Using GPS Data.
<http://proceedings.esri.com/library/userconf/proc04/docs/pap1214.pdf>. Accessed June 23, 2010.
11. Global Positioning System Web Site. National Coordination Office for Space-Based Positioning, Navigation, and Timing Coordination Office, U.S. Coastguard Navigation Center, Alexandria VA. <http://www.gps.gov/systems/gps/index.html>. Accessed June 7, 2010.
12. The Southern California Integrated GPS Network Education Module. University of Southern California, Los Angeles, CA. <http://scign.jpl.nasa.gov/learn/gps2.htm>. Accessed June 7, 2010.
13. Department of Defense, Department of Homeland Security and Department of Transportation. *2005 Federal Radionavigation Plan*. Publication DOT-VTNSC-RITA-05-12/DoD-4650.5.
<http://www.navcen.uscg.gov/pdf/frp/frp2005/2005%20FRP%20WEB.pdf>.
14. Francois Koenig and David Wong. Real-Time Kinematics Global Positioning System (GPS) Operation and Setup Method for the Synchronous Impulse Reconstruction (SIRE) Radar. <http://www.arl.army.mil/arlreports/2010/ARL-TN-0393.pdf>.

15. The Global Positioning System for the Geosciences: Summary and Proceedings of a Workshop on Improving the GPS Reference Station Infrastructure for Earth, Oceanic, and Atmospheric Science Applications. The National Academies Press, Washington, D.C., 1997. http://www.nap.edu/openbook.php?record_id=9254&page=9. Accessed on July 12, 2010.
16. El-Rabbany, A. Introduction to GPS: *The Global Positioning System*. Artech House, Boston, 2nd Edition, 2006.
17. Hydro International Web Site. Geomares Publishing, Lemmer, The Netherlands. http://www.hydro-international.com/productsurvey/id10-RTK_DGPS_Receivers.html. Accessed on July 15, 2010.
18. George T. Schmidt. INS/GPS Technology Trends. NATO RTO. <http://www.rta.nato.int/Pubs/RDP.asp?RDP=RTO-EN-SET-116%282010%29>. Accessed June 20, 2010.
19. Sheryl H. Stovall. Basic Inertial Navigation. NAWCWPNS TM 8128, September 1997. <http://www.fas.org/spp/military/program/nav/basicnav.pdf>. Accessed June 30, 2010.
20. A.D. King, Inertial Navigation – Forty Years of Evolution, *GEC Review*, Volume 13, No. 3, 1998. http://www.imar-navigation.de/downloads/papers/inertial_navigation_introduction.pdf.
21. Defense Sciences Office Web Site. Arlington, VA. <http://www.darpa.mil/dso/thrusts/physci/newphys/pins/>. Accessed July 16, 2010.
22. USDA Forest Service, University of Washington Web Site. Seattle, WA. LIDAR Overview: What is LIDAR? http://forsys.cfr.washington.edu/JFSP06/lidar_technology.htm.
23. Amar Nayegandhi, LIDAR Technology Overview, Airborne-LIDAR Technology and Applications Workshop. http://lidar.cr.usgs.gov/downloadfile2.php?file=Nayegandhi_Lidar_Technology_Overview.pdf. Accessed on July 8, 2010
24. Coastal Services Center Website. Remote Sensing for Coastal Management. National Oceanic and Atmospheric Administration, Charleston, SC. http://www.csc.noaa.gov/crs/rs_apps/sensors/lidar.htm.
25. Rongxing Li. ABSTRACT Mobile Mapping- An Emerging Technology For Spatial Data Acquisition <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.117.3859>.
26. Ellum C., El-Sheimy N. Land-Based Mobile Mapping Systems, Photogrammetric Engineering & Remote Sensing. January 2002. <http://www.asprs.org/publications/pers/2002journal/january/georef.pdf>. Accessed June 20, 2010.
27. Development of Traffic-Speed LIDAR. <http://rip.trb.org/browse/dproject.asp?n=26472>. Accessed July 5, 2010
28. J. Talaya, E. Bosch, R. Alamus, A. Serra and A. Baron. GEOVAN: The mobile mapping system from the Cartographic Institute of Catalonia. In *Advances in Mobile Mapping Technology*, ISPRS Book Series, Vol. 4: 19-30
29. Roland Bürgmann, Paul A. Rosen, and Eric J. Fielding. Synthetic Aperture Radar Interferometry to Measure Earth's Surface Topography and Its Deformation, In *Annual Review of Earth and Planetary Sciences* Vol. 28: 169-209. <http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.earth.28.1.169>.

30. Didier Massonnet, Kurt L. Feigl. Radar Interferometry and Its Application to Changes in the Earth's Surface. In *Reviews of Geophysics*, Vol. 36, No. 4, pp. 441-500, 1998.
<http://www.agu.org/journals/rg/v036/i004/97RG03139/>.
31. Texas Department of Public Safety Emergency Evacuation Traffic Management Plan, Disaster District 3C, April 26, 2010
(http://www.txdps.state.tx.us/ftp/dem/plan_state/traffic_management_plan_district_3c.pdf, Accessed July 2010).
32. Texas Department of Transportation *I-37 Evaculane Brochure*
(ftp://ftp.dot.state.tx.us/pub/txdot-info/trv/hurricane/i37_evaculane.pdf, Accessed July 2010).
33. Texas Department of Transportation *I-37 Contraflow Brochure*
(ftp://ftp.dot.state.tx.us/pub/txdot-info/trv/hurricane/i37_contraflow.pdf, Accessed July 2010).
34. Texas Department of Transportation *I-37 Contraflow Brochure* (Spanish)
(ftp://ftp.dot.state.tx.us/pub/txdot-info/trv/hurricane/i37_contraflow_spanish.pdf, Accessed July 2010).
35. *Special Specification 8251, Reflectorized Pavement Markings with Retroreflective Requirements*. Texas Department of Transportation, Austin, Texas, March 2009.
36. *DMS-8220, Hot Applied Thermoplastic*. Texas Department of Transportation, Austin, Texas, May 2009.
37. Traffic Control Devices on Federal-Aid and Other Streets and Highways; Color Specifications for Retroreflective Traffic Signs and Pavement Marking Materials. *Federal Register*, Vol 67, No. 147, Docket FHWA-99-6190, U.S. Government Printing Office, Washington, D.C., July 31, 2002, pp. 49569-49575.
38. FHWA. *Manual on Uniform Traffic Control Devices*. 2009 Edition. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 2009.
39. FHWA. *Manual on Uniform Traffic Control Devices for Streets and Highways*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2003 Edition.
40. Migletz, J., J.L. Graham, D.W. Harwood, K.M. Bauer, and P.L. Sterner. *Evaluation of All-Weather Pavement Markings*. McLean, VA: FHWA, U.S. Department of Transportation, 2000.
41. Abboud, N., and B. L. Bowman. Cost- and Longevity-Based Scheduling of Paint and Thermoplastic Striping. Transportation Research Record No. 1794, TRB, National Research Council, Washington, D.C., 2002.
42. Craig, W.N., W.E. Sitzabee, W.J. Rasdorf, and J.E. Hummer. Statistical Validation of the Effect of Lateral Line Location on Pavement Marking Retroreflectivity Degradation. *Public Works Management & Policy*, October 2007.
43. Migletz, J., and J.L. Graham. *NCHRP Synthesis 306 - Long-Term Pavement Marking Practices*, Transportation Research Board, Washington, D.C., 2002.
44. Migletz, J., J.L. Graham, D.W. Harwood, and K.M. Bauer. Service Life of Durable Pavement Markings. *Transportation Research Record No. 1749*, TRB, National Research Council, Washington, D.C., 2001.
45. Gates, T.J., H.G. Hawkins, and E.R. Rose. Effective Pavement Marking Practices for Seal Coat and Hot-Mix Asphalt Pavements, FHWA-TX-03-4150-4, Texas Transportation

Institute, The Texas A&M University System, College Station, Texas, August 2003.
<http://tti.tamu.edu/documents/0-4150-4.pdf>

46. Sitzabee, W.E., J.E. Hummer, and W.J. Rasdorf. Pavement Marking Degradation Modeling & Analysis. *Journal of Infrastructure Systems*, American Society of Civil Engineers, September 2009.
47. Lee, G.A. Issues Surrounding Raw Material Shortages and Potential Finished Materials Shortages and Rising Material Costs in the Road Marking and High Friction Sector, Road Safety Markings Association, London, United Kingdom, May 2010.

**APPENDIX:
ALTERNATE HURRICANE EVACUATION ROUTES**

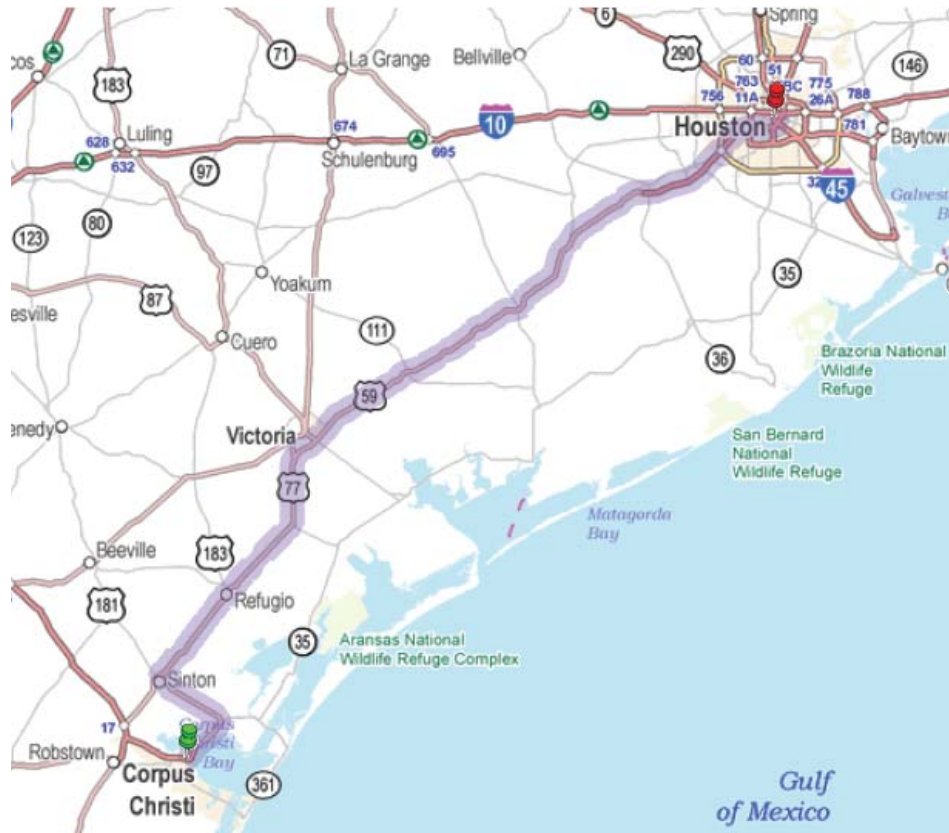


Figure 43. ALT 1 to Houston.

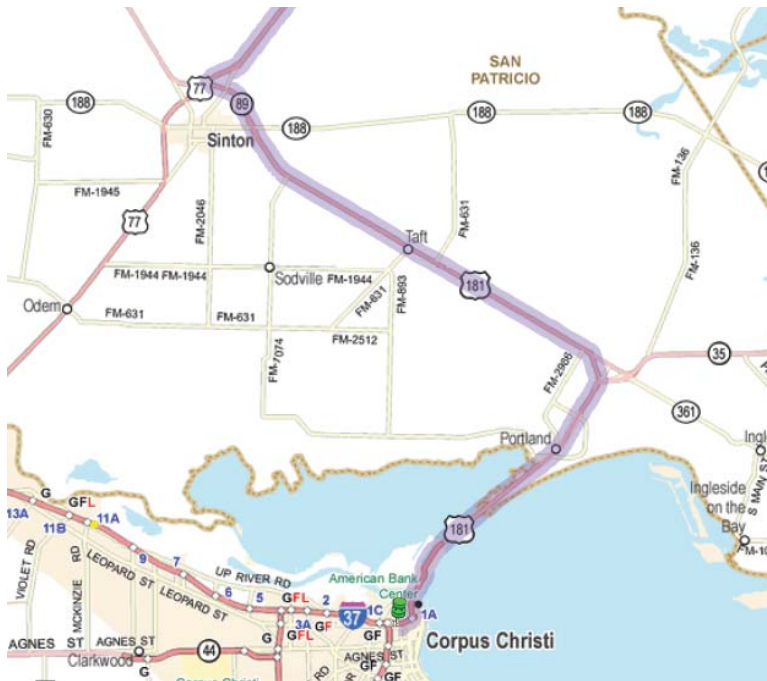


Figure 46. ALT 2a Leaving Corpus Christi via US 181.



Figure 47. ALT 2b Exit to US 183 in Refugio.

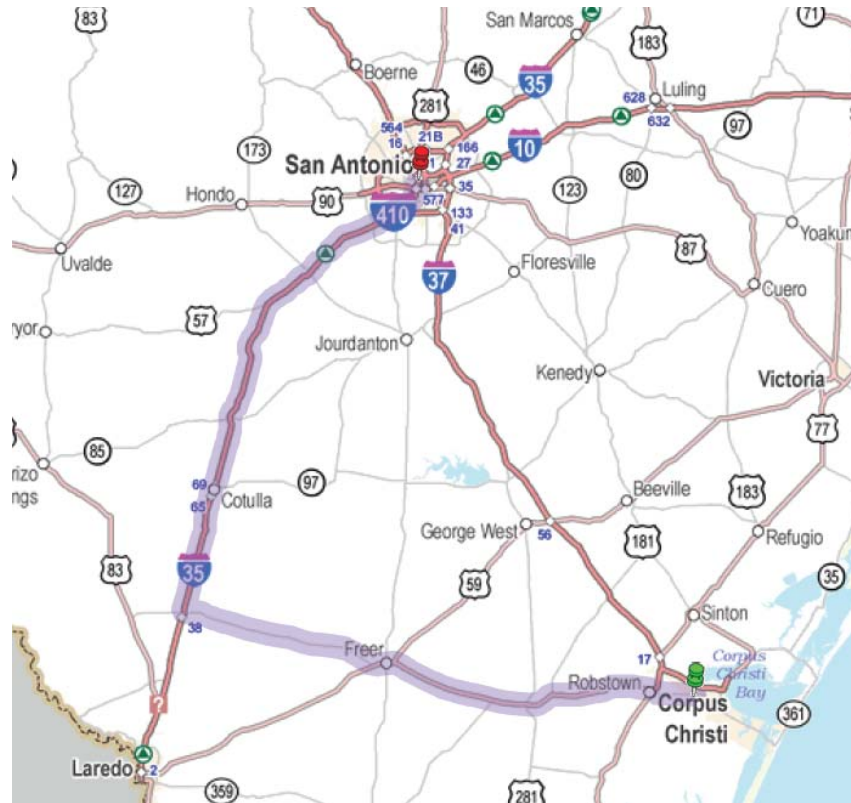


Figure 48. ALT 3 to San Antonio via I-35.

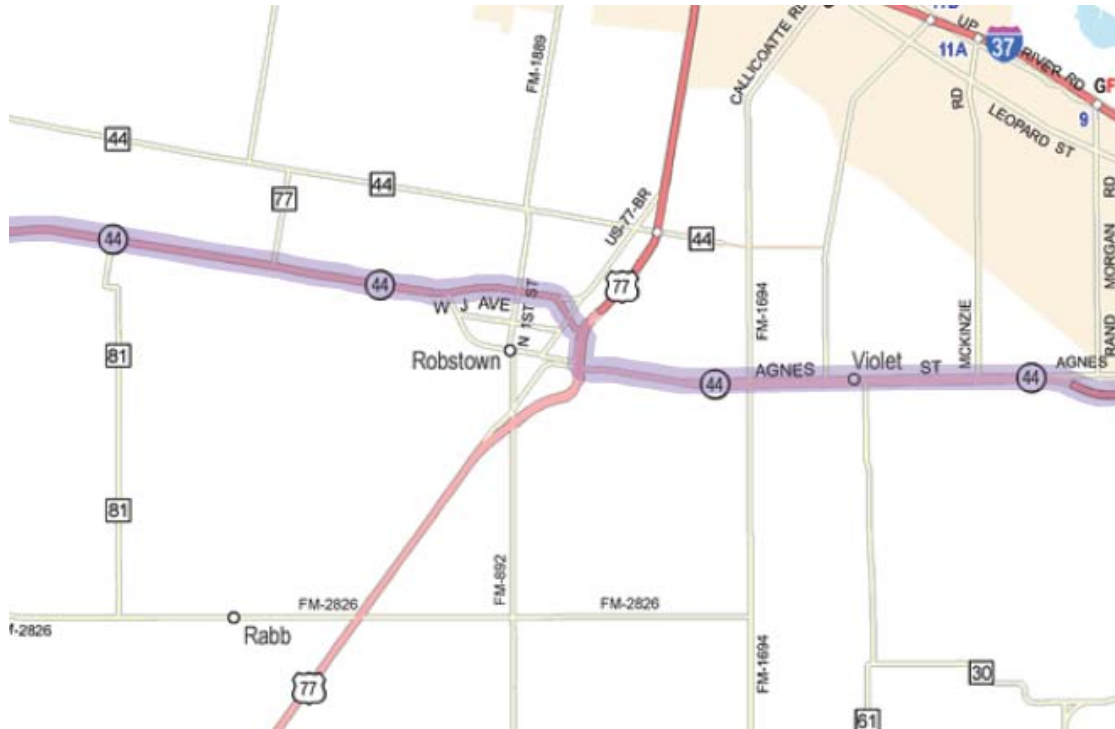


Figure 49. ALT 3a Continues on SH-44 through Robstown.



Figure 50. ALT 3b Continues on SH-44 through Alice and Freer.



Figure 51. ALT 3c Turns North on I-35 in Encinal.

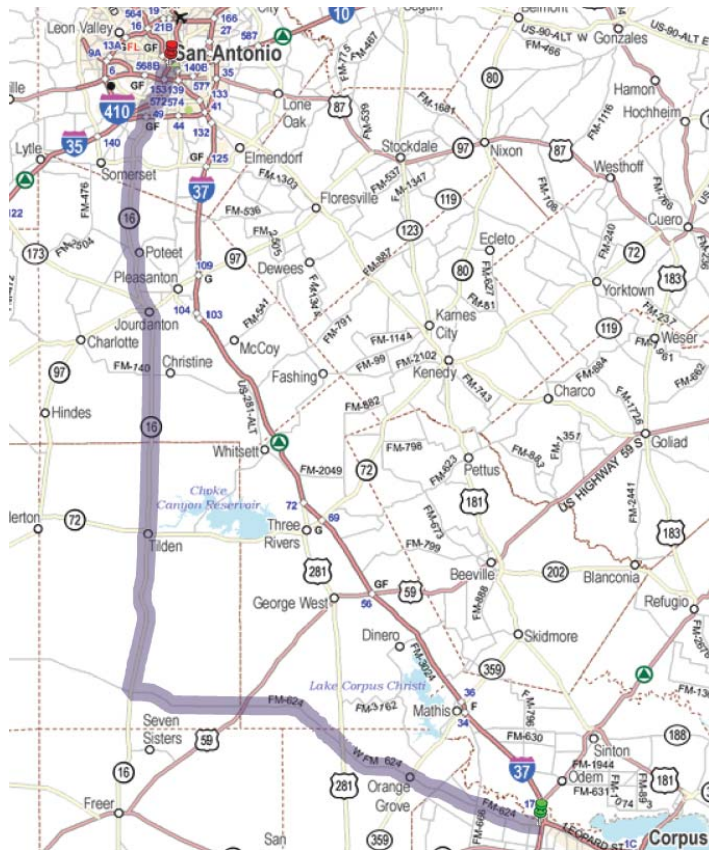


Figure 52. ALT 4 to San Antonio via FM 624 and SH 16.



Figure 53. ALT 4a Leaving Corpus Christi via FM 624.

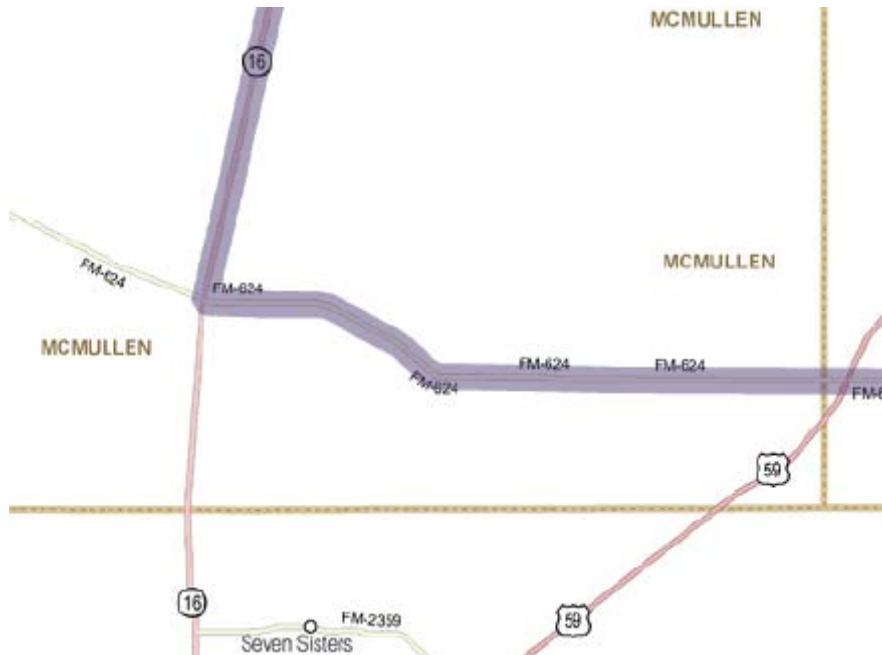


Figure 54. ALT 4b Turns North on SH 16.

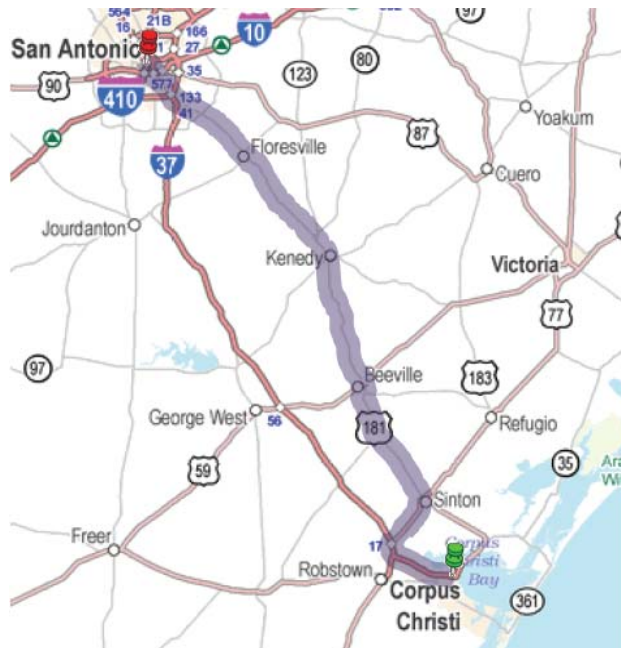


Figure 55. ALT 5 to San Antonio via US 181.



Figure 56. ALT 5a Takes US 77 to Sinton then Turns North on US 181.



Figure 57. ALT 5b Takes US 181 to Portland.

More information on hurricane preparedness and evacuating safely is available from the following:

Texas Department of Transportation
www.txdot.gov

Highway Road Conditions
800-452-9292

TxDOT Corpus Christi District
361-808-2300

TxDOT San Antonio District
210-615-1110

Radio Stations

Corpus Christi: 89.5 FM KLUX
San Antonio: WOAI 1200 AM

Texas Department of Public Safety

www.txdps.state.tx.us

Governor's Division of Emergency Management

www.txdps.state.tx.us/dem

American Red Cross
1-866-RED-CROSS

For Emergencies: Call 9-1-1

For Evacuation Routes, Shelters and Special Transportation Needs: Call 2-1-1

TxDOT's Goals

- Get people to safety
- Help in cleanup and recovery
- Get people home safely

Important Tips:

Your needs and those of your family should be the primary factors considered when evacuating from a hurricane. All citizens should prepare a plan well in advance of the evacuation.

- ✓ Assemble your disaster supplies kit with items such as flashlights, cell phones, extra batteries, battery chargers, portable radio, first aid kit, emergency water and food, medical supplies and equipment, non-electric can opener, highway map, important documents, such as insurance and medical information, etc.
- ✓ Secure your home against disaster to help reduce damages. Cover windows with shielding materials. Secure or put up any loose objects from around your home.
- ✓ If you cannot take your pets with you, make provisions for them.
- ✓ Know your area's evacuation plan/routes before you leave home (www.texasonline.com).
- ✓ Fill your vehicle with gas as early as possible.
- ✓ Take only the vehicle necessary to transport you and your family to safety. Extra vehicles create congestion.
- ✓ Bring extra cash in case banks are closed and ATMs are not working.
- ✓ Notify family and friends (especially those out of the area) of your plan and your destination.
- ✓ Develop an emergency plan in case family members are separated. Instruct all evacuating family members of the name and contact information of your designated out-of-area friend or family.
- ✓ Ensure children know how and when to call 9-1-1.
- ✓ Evacuate, traveling safely to your destination.

Expect travel times to destinations to be longer than normal.

Rev. 5/11/2010



I-37 Hurricane Shoulder Evacuation Lane

Figure 58. I-37 Hurricane Shoulder Evacuation Lane Pamphlet (Part 1 of 2).

Alternate Hurricane Evacuation Routes for Corpus Christi

The Interstate 37 Emergency Shoulder Lane Plan (Evac Lane)

This plan is comprised of two parts - an urban section and a rural section. Traffic will be shifted over to the right at the transition section north of the Nueces River Bridge on I-37.

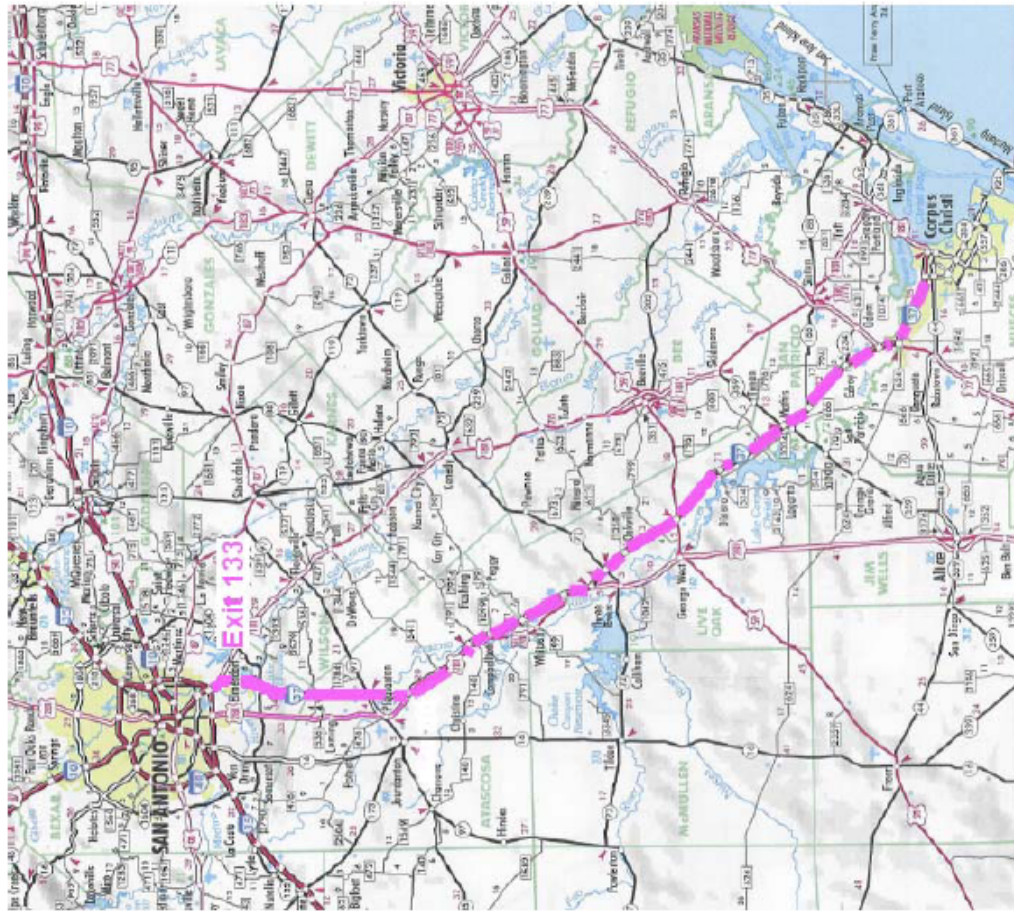
Urban Emergency Shoulder Lane Section

Uses the inside shoulder on I-37 between SH 358 (Padre Island Drive) and the north US 77 interchange (north of the Nueces River Bridge). The highway will be striped and signed to be used only for emergency evacuations.

Rural Emergency Shoulder Lane Section

Uses the outside shoulder on I-37 between the north US 77 interchange and Loop 410, Exit #133. The highway will be striped and signed for emergency use only. Traffic using the Emergency shoulder lane will have to exit at Loop 410, Exit #133 to San Antonio or other destinations of choice. **The Plum colored route is the route for the evacuees using the Emergency Shoulder lane to San Antonio.**

I-37 will not be able to handle all traffic evacuating from Corpus Christi and the surrounding areas. Evacuees should consider alternate routes if possible.



Hurricane Evacuees need to consider the travel path of the hurricane and their destination in choosing evacuation routes. Listen to local authorities and emergency broadcasts about weather and highway conditions. TxDOT will have courtesy patrols along this route to assist motorists.

Figure 59. I-37 Hurricane Shoulder Evacuation Lane Pamphlet (Part 2 of 2).

Important Tips

Your needs and those of your family should be the primary factors considered when determining the timing of your evacuation. If you must evacuate, do not delay your departure in anticipation of the opening of the contraflow lanes. Should the contraflow be activated, citizens will be advised through local radio and television stations. All citizens should prepare a plan well in advance of the evacuation.

The following steps are recommended:

- ✓ Assemble your disaster supplies kit with items such as flashlights, cell phones, extra batteries, battery chargers, portable radio, first aid kit, emergency water and food, medical supplies and equipment, non-electric can opener, highway map, important documents, such as insurance and medical information, etc.
 - ✓ Secure your home against disaster to help reduce damages. Cover windows with shielding materials. Secure or put up any loose objects from around your home.
 - ✓ If you cannot take your pets with you, make provisions for them.
 - ✓ Know your area's evacuation plan/routes before you leave home (www.texasonline.com).
 - ✓ Fill your vehicle with gas as early as possible.
 - ✓ Take only the vehicle necessary to transport you and your family to safety. Extra vehicles create congestion.
 - ✓ Bring extra cash in case banks are closed and ATMs are not working.
 - ✓ Notify family and friends (especially those out of the area) of your plan and your destination.
 - ✓ Develop an emergency plan in case family members are separated. Instruct all evacuating family members of the name and contact information of your designated out-of-area friend or family.
 - ✓ Ensure children know how and when to call 9-1-1.
 - ✓ Evacuate, traveling safely to your destination.
 - ✓ Expect travel times to destinations to be significantly longer than normal.
- After the storm, listen to local officials for the all-clear signal before returning home. Check for information at www.texasonline.com.
- Do not try to drive through standing water. Just a few inches can float a vehicle.*

Fender-Bender?

State law requires motorists to move fender-bender accidents out of the travel lanes to the shoulder of the road. To keep all travel lanes and shoulders clear, however, disabled vehicles on the shoulder will be relocated to the next exit ramp where further assistance may be available.

More information on hurricane preparedness and evacuation safety is available from the following:

Shelters and Special Needs
Call 2-1-1

Emergency Alert Station
Corpus Christi: KLUX 89.5 FM
San Antonio: WOAI 1200 AM

State of Texas
www.texasonline.com

Texas Department of Transportation
www.txdot.gov

Highway Road Conditions and Evacuation Routes
1-800-452-9292

Texas Department of Public Safety
www.txdps.state.tx.us

Governor's Division of Emergency Management
www.txdps.state.tx.us/dem

City of Corpus Christi
www.cctexas.com/eoc

American Red Cross
www.redcross.org
1-800-RED-CROSS (733-2767)

Rev. 5/11/201

CORPUS CHRISTI TO SAN ANTONIO
TEXAS



**Hurricane Evacuation
Contraflow Route**

Motorist Advisory

**Evacuation Plans May or May Not
Include Activating Contraflow Lanes**



Figure 60. I-37 Hurricane Evacuation Contraflow Route Motorist Advisory (Part 1 of 2).

CORPUS CHRISTI TO SAN ANTONIO
TEXAS



Hurricane Evacuation Route's
Potential Contraflow Plan

WHO.....This plan will affect motorists evacuating from Corpus Christi.
WHY.....To help move citizens safely and efficiently out of harm's way during large-scale evacuations.
WHAT....If this plan is activated, I-37 southbound lanes will be reversed to carry two lanes of northbound traffic. Traffic in the contraflow lanes will be able to exit I-37 at US 59 and SH 359.
WHEN...The reversal will be considered only when the Corpus Christi area is threatened by a major hurricane and mandatory evacuations are issued. A decision to reverse I-37 will be made by local authorities working with the State Operations Center based on the strength of the storm and projected landfall.
WHERE..The contraflow operations will begin at the SH 358 (SPID) interchange on I-37. Traffic also can enter contraflow from US 77, south of the Nueces River, and some traffic will cross over to the contraflow side, north of the Nueces River. The contraflow lanes will end at SH 97 and FM 3006 near Pleasanton, TX. The left contraflow lane will exit at SH 97 and the right contraflow lane will exit at FM 3006.



LEGEND

 No Traffic Zone

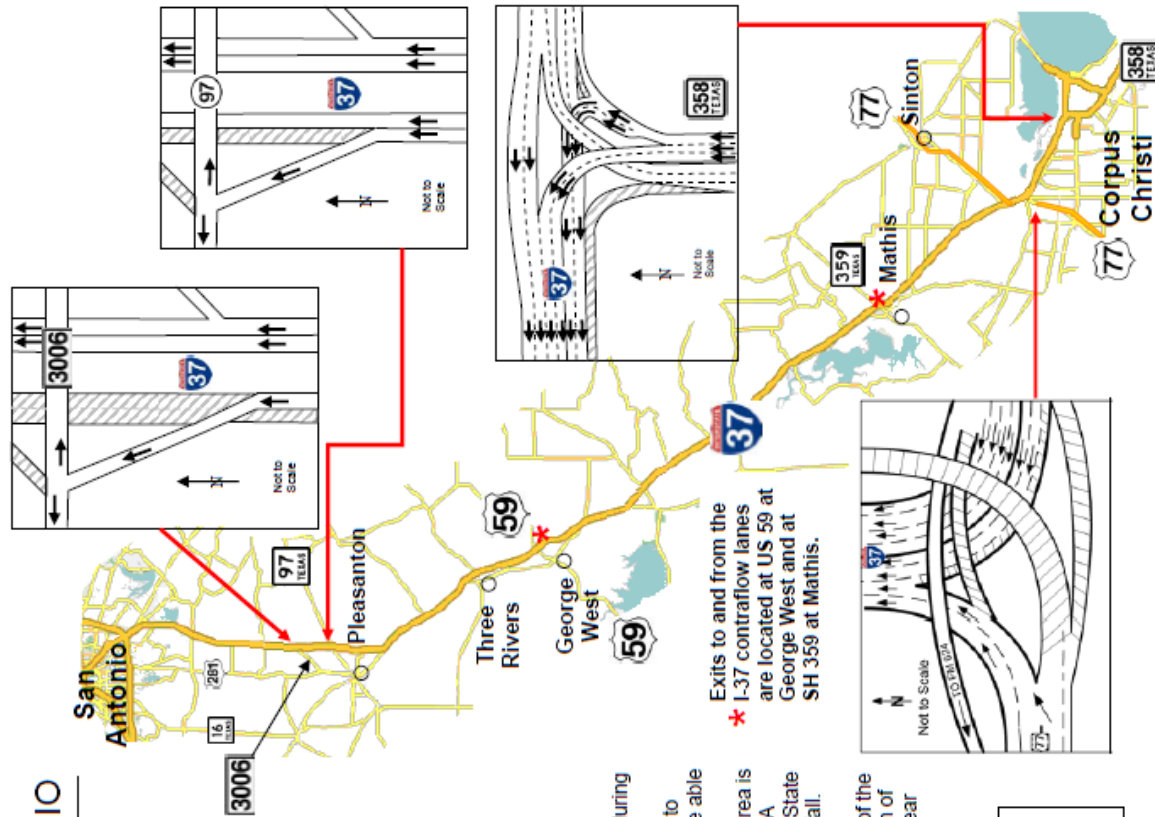


Figure 61. I-37 Hurricane Evacuation Contraflow Route Motorist Advisory (Part 2 of 2).