STATE OF CALIFORNIA DEPARTMENT OF TRANSPORTATION
TECHNICAL REPORT DOCUMENTATION PAGE
TR0003 (REV. 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA07-0529		

4. TITLE AND SUBTITLE	5. REPORT DATE
Lane Marking/Striping to Improve Image Processing Lane Departure Warning Systems	May 2007
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
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9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NUMBER
California Department of Transportation Division of Research and Innovation, MS-83 1227 O Street Sacramento CA 95814	
	11. CONTRACT OR GRANT NUMBER
	65A0170

12. SPONSORING AGENCY AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
California Department of Transportation Sacramento, CA 95819	Final Report
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES

16. ABSTRACT

Vision-based Lane Departure Warning Systems (LDWS) depend on pavement marking tracking to determine that vehicles perform unintended drifts out of the travel lanes. Thus, it is expected that the performances of these LDWS be influenced by the visibility of the pavement markings. This research investigates the effects of the colors of pavement and lane marking on the performance of a lane departure warning system. The performance of the system was tested on highway sections of different facility types and with pavement and marking of varying types and attributes. The results obtained from the project activities should help improving the performance of lane departure warning systems and providing guidelines regarding the effects of pavement marking practices and standards on the performance of these systems.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Lane Departure Warning Systems, Intelligent Vehicles, Integrated Vehicle Based Safety Systems, Pavement Markings	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. SECURITY CLASSIFICATION (of this report)	20. NUMBER OF PAGES	21. PRICE
Unclassified	131	

Reproduction of completed page authorized

Lane Marking/Striping to Improve Image Processing Lane Departure Warning Systems

Final Report

Prepared for

**The Cooperative Vehicle Highway Automation
Systems (CVHAS) Program**

Prepared by

**The Florida Turnpike Enterprise
PBS&J, Inc.
Florida International University**

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Executive Summary

Lane departure warning systems (LDWS) can be used to provide an effective countermeasure against road departure crashes, many of which occur due to driver's drowsiness, distraction, or inattention. A number of technologies have been used as a basis for LDWS. Some of these technologies include active wire guidance, laser, magnetic sensing, and image recognition technologies. A large proportion of the commercial development of LDWS has concentrated on image recognition-based systems. These systems are currently commercially available as either vehicle factory-installed or aftermarket systems.

Image-based LDWS use image recognition software that analyzes the images collected by a small camera to track the pavement markings and to predict when a vehicle unintentionally drifts out of the travel lane. For example, if the vehicle begins to deviate from the lane unintentionally (i.e., without a turn signal), then the lane departure warning system alerts drivers using an audible, visual, and/or tactile warning signal. The main advantage of LDWS that use image recognition compared to other technologies is that they use existing infrastructure (i.e., pavement markings) without the need for additional modifications that may be required by the other technologies. Because these systems depend on pavement marking tracking, however, it is logical to hypothesize that the visibility of these markings under different weather and lighting conditions could affect the performance of the systems.

The objectives of this study are:

- To investigate the effects of environmental conditions such as rain and lighting conditions on LDWS performance for typical lane marking installations.

- To investigate the effects of lane marking and pavement quality and attributes on LDWS performance under different environmental conditions.

- To investigate the effects of the use of improved pavement marking technologies and practices on LDWS performance.

- To determine the benefit-cost effectiveness of the improved pavement markings with consideration of LDWS performance.

- To survey existing users of the system to identify the user acceptance and performance issues of LDWS.

The research team for this study conducted field and laboratory (simulated rain facility) tests to determine the LDWS performance under different environmental conditions and different types of pavement marking installations. The main performance measure used in the evaluation was the Efficacy Rate (ER), which is defined as the proportion of the number of instances the LDWS is able to provide lane crossing alarms to all the instances in which a LDWS-equipped vehicle crosses the pavement markings.

The results of the field tests indicated that, The ER under dry and light rain conditions is expected to be 100%, except when a roadway segment has poor contrast between the pavement and the markings. One important observation was that heavy rain conditions during daylight hours have little or no effect on the performance of LDWS. However, the results showed that the performance of LDWS is affected significantly by moderate to heavy rain conditions at night for typical pavement marking installations. Relationships were developed between ER during rain conditions at night and pavement marking retroreflectivity for conventional marking materials such as thermoplastic. The relationships show that LDWS perform significantly better with conventional markings that have higher retroreflectivity values. Since the retroreflectivity values decrease with age due to the loss of beads, it is expected that LDWS performance during night rainy conditions deteriorates with marking age.

Detailed investigation was performed during the course of this study to investigate the effect of the contrast between asphalt and concrete pavements and pavement markings on the LDWS performance during day light conditions. This contrast is a function of the pavement and marking colors. Based on the results presented in this chapter, it can be concluded that the tested lane departure warning system device was able to detect the pavement markings in a large proportion of the tested sections during daylight conditions. However, for a few highway segments having light concrete and asphalt pavement colors, the device was not able to detect the yellow markings. Based on analysis of the digital images taken of the pavement markings and background pavements, it can be concluded that the inability to detect the yellow markings can be related to attributes of the pavement marking color and pavement color, as measured by the three dominant colors (the red, green, and blue colors).

Testing of improved pavement markings at a simulated rain facility confirmed that the pavement marking retroreflectivity has a significant effect on LDWS performance under medium to high rain intensities (0.52 to 0.87 inch/hour) at night light. The ER value was particularly low with the conventional marking that had a low retroreflectivity value. In addition, the results of this study indicated that using wet-reflective tapes (that use special optics to improve marking visibility at night rainy conditions) or frequent replacement of existing conventional pavement markings to maintain high retroreflectivity will have positive effects on LDWS performance during rain at night conditions.

The benefit-cost analysis performed in this study indicates that some of the marking improvements can be justified from a benefit-cost analysis point of view for specific traffic operations (AADT level and truck percentage), horizontal alignment, and LDWS market penetration levels. Under these conditions, it is expected that installing wet-reflective tapes with long service life (longer than 6 years) is the most effective alternative followed by more frequent replacement of thermoplastic markings (every 2 years).

For a general segment of a typical freeway, it was found that marking improvements start to be cost-effective at 50% LDWS market penetration for freeways with 80,000 to 100,000 vehicles per day (vpd) or above and at 25% market penetration for freeways with very high AADT (160,000 vpd or above). Improving markings on highway sections with horizontal curvature, particularly those with sharp curvatures will result in higher cost-benefit ratios compared to those

on general highway segments. Improving the markings on these segments can be justified from a benefit-cost point of view at a lower AADT and/or LDWS market penetration levels compared to general highway segments.

Additional sensitivity analysis can show that the benefit-cost ratio is also a function of truck percentage, shoulder widths, related crash rates on the highway segment under consideration and the proportions of these crashes in night rainy conditions.   Furthermore, the costs of wet-reflective tapes may drop in the future due to advancements in technologies and increasing competition.   This reduction in tape costs combined with an increase in their service lives will increase their cost-effectiveness compared to other alternatives.

This study confirmed the generally high level of acceptance and satisfaction with the LDWS by truck drivers in the United States. The level of satisfaction was relatively low among the drivers of one of the companies surveyed. The low level of satisfaction of some drivers indicates the need for additional driver education of the system benefits.

1. Introduction

1.1 Background

The Strategic Highway Safety Plan produced by the American Association of State Highway and Transportation Officials' (AASHTO's) identified 22 goals (1) to significantly reduce highway crash fatalities. Two of these goals are "Keeping Vehicles on the Roadway" and "Minimizing the Consequences of Leaving the Road". Emphasis has been placed on the reduction of run-off-road (ROR) crashes and head-on crashes, to achieve the above two goals. These crashes can be avoided by keeping the vehicles in their travel lanes to prevent roadway departures and by faster notifications to drivers that they have left their lanes such that they can perform the required corrective actions.

Lane departure warning systems (LDWS) provide an effective countermeasure against road departure crashes, many of which occur due to driver drowsiness or distraction. These systems are particularly useful for commercial vehicle drivers that drive long hours that often result in a higher number of crashes that occur due to driver fatigue or distraction in the case of commercial vehicles compared to passenger cars.

A number of technologies have been used as the basis for LDWS including active wire guidance, laser, magnetic sensing technologies, differential global positioning systems (DGPS), and image processing technologies. A large proportion of the commercial development has concentrated on image processing based systems. However, for low visibility conditions, other technologies have been used. As an example, the Minnesota Department of Transportation has equipped a fleet of snowplows with both magnetic and DGPS-based lane tracking for low visibility operations.

Image recognition-based LDWS use image recognition software that analyze the images collected by a small camera to track the pavement markings and to predict when a vehicle performs an unintended drift out of the travel lane. If the car begins to deviate from the lane unintentionally (i.e., without a turn signal), the lane departure warning system alerts drivers using an audible, visual, and/or tactile warning signal. The main advantage of LDWS that use image recognition compared to other technologies is that they use existing infrastructure (lane markings) without the need for additional modifications that may be required by the other technologies. These systems are wholly dependent on lane marking tracking. It is logical to hypothesize that the visibility of these markings under different weather and lighting conditions could affect the performance of LDWS.

This document is the final report of a project that investigated the effect of lane marking qualities and improvements to these markings on the performance of LDWS. The project, entitled "Lane Marking/Striping to Improve Image Processing Lane Departure Warning Systems," was funded by the Cooperative Vehicle-Highway Automation Systems (CVHAS) program, which is a federal pooled-fund program that uses resources from public and private sector partners. The

CVHAS program has eleven state department of transportation members and is managed by the California Department of Transportation (Caltrans) Division of Research and Innovation.

1.2   Project Objectives

The objectives of this study are:

- To investigate the effects of environmental conditions such as rain and lighting conditions on LDWS performance for typical lane marking installations.

- To investigate the effect of lane marking and pavement quality and attributes on LDWS performance under different environmental conditions.

- To investigate the effect of the use of improved pavement marking technologies and practices on LDWS performance.

- To determine the benefit-cost effectiveness of the improved pavement markings with consideration of LDWS performance.

- To survey existing users of the system to identify the user acceptance and performance issues of LDWS.

1.3   Report Organization

This report has been structured into nine chapters as follows:

- Chapter 1 describes the background and objectives of the project

- Chapter 2 provides a review of lane departure warning systems and previous projects that investigated these systems.

- Chapter 3 provides a review of pavement marking literature and standards.

- Chapter 4 reports on the results of a survey conducted in this study to determine the level of acceptance and satisfaction with the LDWS by truck drivers in the United States.

- Chapter 5 presents the results of the field tests performed to investigate the effect of environmental conditions and marking quality on LDWS performance.

- Chapter 6 presents an investigation of pavement color and pavement marking colors on LDWS performance in daylight.

- Chapter 7 presents the results of a test performed at a simulated rain facility to investigate the impacts of improved pavement markings on LDWS performance during rain at night.

- Chapter 8 presents the results of a benefit-cost analysis to determine if improving the pavement markings can be justified from a benefit-cost point of view.

- Chapter 9 presents the final conclusions and recommendations of the study.

2.   Lane Departure Warning System Review and Selection

2.1   Background

Lane-keeping systems have been classified into three categories (*2*)

- *Warning systems:* These systems do not alter the vehicle trajectory and requires driver action in response to warnings to affect the vehicle trajectory.

- *Intervention systems:* These systems have the ability to affect vehicle trajectory but they are meant to augment driver commands, not replace them.

- *Control system:* These systems have the ability for full automatic control of steering the vehicle.

In the United States, the commercially available lane keeping systems can all be categorized as lane departure warning systems (LDWS). LDWS provide warnings to drivers but do not intervene or control vehicle trajectory.   Therefore, drivers remain in full control of the vehicle.

As stated in Chapter 1 of this report. A number of technologies have been used as basis for lane departure warning systems.   These include active wire guidance, laser, magnetic sensing technologies, differential global positioning systems (DGPS), and image processing technologies. Zhang et al (*3*) listed several disadvantages with the use of active wiring technology including the requirement for high wire placement accuracy and the influence of pavement movement and lighting on system operation. In addition, wire malfunctions can impact the system operation on an extended length of road.

The development of lane departure systems based on magnetic technologies has focused on magnetic markings and tapes. The California Path Program has tested the use of a system based on magnetic markings. The test demonstrated the effectiveness of the system and found that in general 2-4 meter marking spacing provided satisfactory results. Noticeable degradation was observed when increasing the marking spacing from 4 to 6 meters (*4*).   The Minnesota Department of Transportation (DOT) developed automated driver-assistance systems for heavy-duty vehicles (e.g., snowplows) (*5*). This system used magnetic pavement marking tape that can take the place of the regular lane striping.

A large proportion of the commercial development of LDWS has concentrated on image processing based systems.   These systems use image recognition software that analyze the images collected by a small camera to track the pavement markings and predict when a vehicle performs an unintended drift out of the travel lane, typically due to driver drowsiness, distraction or inattention. If the car begins to deviate from the lane unintentionally (i.e., without a turn signal), then the LDWS automatically warns drivers using an audible, visual, and/or tactile

warning signal.. The main advantage of image processing based systems is that they are designed to use the existing infrastructure without expensive modifications.

2.2   LDWS Issues and Requirements

This section presents a review of issues and requirements of LDWS that are related to the subject of this project, as reported in previous studies.

Ran and Liu (*6*) listed the following issues with image recognition-based lane warning systems:

- Shadows (projected by trees, buildings, bridges, or other vehicles) may produce artifacts onto the road surface, and thus alter the road texture.
- The system has to be robust enough to cope with the situations where lane markings are worn and partly missing.
- The system should be flexible enough to adapt to different road environments.

Bertozzi et al. (*7*) listed the following problems that have to be faced when developing LDWS:

- The detection should not be affected by shadows from trees, buildings, large vehicles, etc.
- LDWS should be capable of processing marked or unmarked roads. It has to detect painted lines of road markings and road boundaries of unpainted roads correctly.
- LDWS should be capable of handling a curved road rather than assuming a straight road.

Pomerleau et. al. (*8*), in a report produced for the United States Department of Transportation, presented guidelines for LDWS development. The followings are a subset of these guidelines that are related to LDWS performance under different geometry, lane marking and environmental conditions:

- An LDWS should be capable of determining the vehicle's position and orientation relative to the lane in all reasonable environmental conditions. This should include both day and night operation. It should also include operation in rain, snow, sleet and fog.
- An LDWS should attempt to minimize false alarms.
- The LDWS availability due to degraded environmental conditions should not fall below a certain percent of the total time the vehicle is operating on roads.
- If the LDWS is unable to accurately estimate the vehicle position and orientation relative to the road due to degraded environmental conditions, the system should discontinue operation and inform the driver of its status.
- It is recommended that a LDWS be capable of operating on the range of typical US road types, including those where visible lane markings are worn or in some other way degraded.
- The LDWS should be capable of handling:

    o   Roads made of asphalt or concrete
    o Lanes delineated by white or yellow visible markings

- o   Lanes delineated by visible markings made from paint or tape
- o   Lanes delineated by intermittent raised pavement
- o   Lanes delineated by visible markings on only one side of the lane
- o   Lanes delineated by skipped lane markings
- o   Lanes delineated by visible markings composed of a single stripe or a double stripe (two single stripes separated by approximately 10cm).

- An LDWS should be capable of operating on curves with a radius of curvature as small as 125m. It shall disable warnings and inform the driver when the road curvature is determined to be smaller than what it can accommodate.

A report produced by the Federal Motor Carrier Safety Administration (FMCSA's) (*10*) provided the concept of operations and voluntary requirements for LDWS for large trucks greater than 10,000 pounds gross vehicle weight rating (GVWR). The following are requirements presented that are related to the subject of this study:

- LDWS should detect vehicle position relative to the following types of visible lane boundaries:

  - o   Solid and dashed painted lines
  - o   Single and double painted lines
  - o   Yellow and white painted lines
  - o   Raised pavement markers
  - o   Lines with and without reflectors/reflective material

- LDWS should issue warnings, detect vehicle position relative to visible lane boundaries, and track lane boundaries where lane markings are clearly visible in daylight (sunny/cloudy), nighttime (with and without streetlight illumination), and twilight (sunrise/sunset) lighting conditions.
- LDWS should be able to track the lane towards 95% of the time on dry straight roads when lane boundary markings types listed above are present.
- The LDWS should function properly when windshield wipers are operating.
- LDWS should also issue warnings on the roadway curvature test conditions for the following conditions:
  - o   For vehicle speed of less than 45 mph and more than 38 mph and curve length longer than 820 ft.
  - o   For vehicle speed of more than 45 mph and curve length longer than 820 ft.

2.3   Previous Evaluation Studies of LDWS

Because image-based lane departure warning systems depend on the visibility of lane markings, it is logical to assume that the quality of lane markings and environmental conditions could have a significant effect on marking visibility and possibly on the performance of LDWS. However, no significant research has been performed to investigate the effects of environmental conditions on LDWS performance.

A study performed by Pomerleau et al. (*8*) reported that image-based LDWS availability in the 95-99% range can be achieved with existing technology across a broad range of road types, weather and lighting conditions. However, the study did not specifically investigate the combinations of conditions that cause the deteriorations in LDWS performance.

A field operational test (FOT) project conducted in the Netherlands equipped a number of commercial vehicles with image-processing-based LDWS to examine the effects of the use of LDWS in these vehicles (*10*). Although the main objective of the FOT was not to examine the effects of lane marking quality and environmental conditions on LDWS performance, the project concluded that, under normal conditions, the LDWS functions properly on the freeway infrastructure as well as on the secondary roads in the Netherlands (*10*). Even on the roads in the worst marking conditions, the markings were still good enough for the systems to identify them.

The project report stated that the introduction of LDWS in the Netherlands will not have significant impacts on existing roadway standards and maintenance activities. The project also concluded that different weather conditions occurring in the Netherlands did not cause any problems with LDWS performance but cautioned that snow is not a regularly occurring weather condition in the Netherlands and that in countries where snow is a recurring situation the effect of snow should be evaluated (*10*).

Motoyama et al. (*11*) reported on an image recognition-based lane departure system developed in Japan. A survey of seven drivers that used the system showed that the detection rate was about 88%. This was considered sufficiently high considering that the test drive included some adverse conditions such as rainy driving and night driving.

The U.S. Department of Transportation (USDOT) Mack Intelligent Vehicle Initiative (IVI) FOT focused on an evaluation of LDWS implementation for large trucks. The test included 22 trucks and 31 drivers based in ten terminals throughout the southeastern United States. The following were some of the conclusions of the test (*12*):

- The frequency of drift alerts provided by LDWS was directly proportional to the frequency of the recorded lane excursions, indicating that the LDWS drift alert was strongly related to lane excursions.

- Drivers using the LDWS were found to have a lower rate of drift alerts and a lower probability of being out of their lane.

- The use of the LDWS could reduce driving conflicts associated with run-off-road and rollover crashes from a rate of 20.9 to 14.3 conflicts per 10,000 vehicle miles traveled (VMT), which is a 31 percent decrease.

- The FOT examined the proportion of time that the LDWS did not give warning due to various reasons. Warnings were enabled about 86 percent of the time, with a range of about 78 to 91 percent.

- The FOT concluded that LDWS could reduce crashes, injuries, and fatalities in crashes involving large trucks due to improved driver lane-keeping behavior and the reduction in the frequency where the driver is exposed to driving conflicts. From an economic point of view, the system was economically justified for tractors pulling tanker trailers and for tractors pulling HAZMAT tanker trailers.

2.4   User Acceptance of LDWS

The Netherlands Field Operational Test

In a field operational test (FOT) conducted in the Netherlands, three different image processing-based LDWS products were installed in different trucks, as part of the FOT (*10*).   A total of forty truck drivers participated in the LDWS FOT.

Behavioral study, user acceptance survey and a simulator study revealed that the truck drivers seemed to appreciate the system and use the system to assist in their driving. 75% of the drivers in the FOT gave the systems a positive rating. Only 10% of the drivers rated the system negatively. 50% of the drivers said that they prefer to drive with LDWS. 21% of the drivers said that they prefer to drive without the LDWS. The remaining group of those surveyed was uncommitted. The number of received warnings was perceived as higher than necessary and the circumstances under which the warnings were given were not always perceived as critical to the driver. This was particularly true for driving on secondary roads, which are in general narrower than freeways. Thus, drivers, in many cases, deactivated the system on these types of roads.

Mitsubishi System Study

An image-based LDWS (*11*) was developed as the main component of a Driver Support System introduced in February 2000 in Japan. Seven experienced drivers evaluated the LDWS on an inter-city freeway. The result indicated that about 68% of the total warnings were "useful" or "a little useful". Drivers estimated that the detection rate was 88%. This was considered sufficiently high considering that the test drive included some adverse conditions such as rainy weather and nighttime driving. No false warnings were observed during the test.

LDWS Vendor Survey

One of the vendors of LDWS conducted a survey of 132 drivers in the United States and reported the results in presentations made by the vendor representatives. Based on the results reported by the vendor, we calculated the following percentages relating to these test results:

- 95.2% of the drivers believe that LDWS can prevent accidents.
- 80% of the drivers stated that they drive with the system enabled.

- When asked if they feel the warning came at the right time, 75.39% said this is true most of the time, 23.01% said this is true only some of the time, and 1.58% said this is rarely true.
- 89.39% of the drivers reported that the system is valuable.
- Among respondents, 52 drivers were very satisfied, 29 drivers were somewhat satisfied, 34 drivers were neutral, and 8 drivers stated they were dissatisfied with the system. The rest of the drivers did not respond to this question.

The MACK FOT Test

As part of the MACK FOT described above *(12)*, an assessment of driver acceptance and human factors was conducted based on an initial driver survey at the beginning of the evaluation period before drivers had experience using the LDWS, and a second survey after the drivers had experience using this system. The final report of the FOT mentioned that "Since a small number of drivers responded to the surveys, the results were mixed and unlikely to be representative of all truck drivers' opinions about the LDWS. However, the surveys provided a range of reactions to driving with the LDWS in the FOT."

The results of the survey indicated that, in general, the drivers felt that using the LDWS improved their lane-keeping ability and reduced their workload, but it did not change other aspects of their safety-related driving. Some of the stated benefits include that the LDWS helped drivers to drive in a straighter path, maintain alertness (especially in late night driving), and improve concentration on the driving task. Some of the attributes disliked by the drivers included that the location of the LDWS on the dash obscured the view; the alert tones were annoying, and sometimes difficult to distinguish from tones generated by other systems in the truck; and that the LDWS contributed to "information overload."

On average, these respondents said that using the LDWS was most helpful at night, in heavy rain or snow conditions, in fog, and on open highway with light to moderate traffic, in that order.

2.5   LDWS Product Review and Selection

Lane departure warning system products based on image processing are currently commercially available in the United States. Additional systems have been introduced to the market in Europe and Japan.   This chapter reports on the comparison and selection of the lane departure warning system product subtask. First, an overview of available products is presented. Then, a detailed comparison is presented of the two commercially available products in the United States at the time the selection was made. Then, this chapter identifies the product attributes used to select a product for use in the study. Finally, a recommendation is given regarding the product selection.

2.5.1   Available Products

Two systems were commercially available in the United States, at the time that this project started. These systems are:

- AutoVue™ by Iteris
- SafeTRAC™ by AssistWare Technology

. Figure 2-1 depicts the typical architecture for these systems.
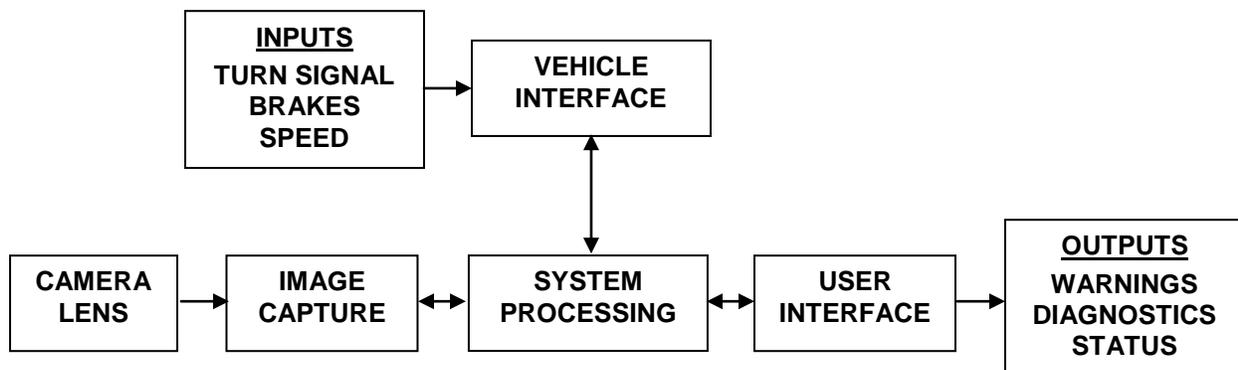
Figure 2-1: Typical Lane Departure Warning System Architecture

Below is a description of the two systems identified;

***AutoVue*™** – this lane departure warning system is available from Iteris, Inc. The system was developed in cooperation with DaimlerChrysler and consists of a camera, processor, and

software. The camera can be attached to the windshield, dashboard, or ceiling. AutoVue™ is programmed to recognize the difference between the road and lane markings. The unit's camera tracks the lane markings (both solid and skip) and feeds the information directly into the unit's computer, which combines this data with the vehicle's speed. Using image recognition software, the system predicts when a vehicle drifts towards an unintended lane change (without a turn signal). When this occurs, the unit automatically emits a distinctive rumble strip sound, alerting the driver to make a correction. The system is available for light vehicles and heavy trucks. It is typically installed by a vehicle manufacturer and calibrated at the factory for each vehicle model, but can also be installed as an aftermarket system.

SafeTRAC™ – this lane departure warning system product was developed by AssistWare Technology, Inc. It uses a small camera mounted to the windshield and computer software to analyze the scene ahead of the car, detect the lane edges, and then assess the position of the car within the lane. If the car begins to deviate from the lane unintentionally (i.e., without a turn signal), an audible, visual, and/or tactile warning is given. The system is composed of a windshield mounted camera and a driver interface that attaches to the dashboard. SafeTRAC™ development started as part of a research project at Carnegie Mellon University and was then commercialized by AssistWare, which was founded in 1995. The system detects visual lane markings and can estimate some lane boundaries when visual lane markings are not present. The system is available as either a factory-installed or an aftermarket system.

In addition to the above systems, a third image recognition lane departure warning system became available at a later stage of the project and thus was not considered for use in this study. This system is described below:

The Delphi Forewarn® Lane Departure Warning system by Delphi Electronics and Safety – this is a lane tracking system that helps alert drivers when they unintentionally drift out of their intended lane. Using a camera and image processing to detect painted lane markers up to 80 feet ahead of the equipped vehicle, the system determines the vehicle's heading and lateral position in the lane to provide the appropriate warning. The camera can be shared with Delphi Active Night Vision system. The device can be installed by Original Equipment Manufacturers (OEMs) or aftermarket consumers on passenger cars and large commercial vehicles. The warning threshold can be calibrated (i.e., customized) to satisfy a fleet company's requirement.

A number of lane keeping systems are available or being developed in other parts of the World. These include:

- Mobileye Lane Departure Warning System By Mobileye – This system is to become available in 2007 as an option on automobile models from three car manufacturers in the United States and Europe. The system includes a camera and a processing unit mounted to the center of the windshield and a cell phone-sized alphanumeric/graphic driver display on the dashboard. The lane detection technology detects road markings and provides the system with various measurements related to them. The technology utilizes a sophisticated filtering technique combined with detection and classification algorithms to detect a variety of lane

markings Mobileye's Lane Detection algorithms can measure the distance from the wheel to the lane markings, as well as providing a more detailed description of the lane marking – for example, the width. The Lane Detection technology is based upon a three-parameter lane marking model that accounts for lateral position, slope and curvature and has been tested using various sensors and validated by thousands of hours of driving in many countries and conditions. The warning mechanism can be tuned for sensitivity. For example, the system can warn only when the vehicle is actually crossing the lane marking or it can give an early warning. The warning can be adapted to the type of road – for example it could provide the driver with more slack in case of narrow roads or allow the driver to "cut" curves.

- In England, a lane-keeping system is being developed by TRW Automotive and will be available in the next few years. The system will include a lane departure warning system combined with active control of the vehicle to automatically maintain an acceptable lane trajectory through interaction with the steering system.

- In Japan, an image processing lane departure system called Hino ASV-2 is being produced. The position and angle of the vehicle in the lane is calculated. The system warns the driver of the possibility of lane departure using audible and visual alerts. If the driver does not react appropriately, the system applies torque to the steering wheel and performs the steer.

- Volvo has developed a lane keeping system that can be categorized as an "Intervention System", since the driver perceives a torque feeling in the steering wheel that mediates the correct lane position[1].

The last three systems in the above list differ from LDWS like AutoVue™ and SafeTRAC™ in that they can be classified as intervention or control systems. AutoVue™ and SafeTRAC™ are warning systems.

2.5.2 Product Attribute Comparison

As stated above, the two systems that were available in the United States at the beginning of this research project were AutoVue™ and SafeTRAC™. Table 2-1 presents a detailed comparison of various attributes of the AutoVue™ and SafeTRAC™ products. The information presented in Table 2-1 is derived from product information available on the Internet, telephone interviews with product provider representatives, and documents obtained from these representatives.

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[1] Ibid.

**Table 2-1: Comparison of AutoVue^{TM} and SafeTRAC^{TM}
Product Attributes (As of January 2005)**

SYSTEM ATTRIBUTES	AutoVue^{TM}	SafeTRAC^{TM}
Manufacturer	Iteris, Inc.	AssistWare, Inc.
Components	Integrated unit that consists of a camera, on-board computer and software. The camera can be attached to the windshield, dashboard or overhead console behind rearview mirror. The used camera is CMOS black and white camera.	A CCD camera mounted to the windshield and on-board computer that can be mounted on the dashboard or headliner.
Operation	Image recognition software tracks lane markers and predicts when a vehicle drifts towards an unattended lane change.	Image recognition software measures the vehicle's position in the lane. If the vehicle begins to weave excessively or drift a warning alarm is given.
Features	Unsignaled lane departure	Unsignaled lane departure Alertness feedback and indicator (adjustable)
Warning Types	<u>Audible:</u> The unit automatically emits the commonly known rumble strip sound, alerting the driver to make a correction. The sound is directional using 3.5 inch left or right speakers that are provided with the equipment. <u>Visual:</u> No <u>Tactile:</u> Seat or steering wheel <u>Warning Threshold Control</u>: During calibration, it is possible to set how much of the lane marking is crossed before drivers are warned.	<u>Audible:</u> Unit automatically emits a sound whenever the vehicle drifts. <u>Visual:</u> The unit provides visual warnings <u>Tactile:</u> No. Although digital output from the machine can be used to create this type of warning. <u>Warning Threshold Control:</u> Unit can be adjusted to trigger before or after lane crossing.

SYSTEM ATTRIBUTES	AutoVue™	SafeTRAC™
Disabling Device	The system does not sound an alarm at speeds under 35 mph. Dashboard indicator to alert driver when system is not able to track lanes.	When road is not visible, an audible indication is given. The system is disabled when the speed is below 25 mph.
Alertness Warning	Feature not available.	The system calculates a numeric Alertness Index Score based on the driver's ability to stay centered in the lane and gives a warning to the driver to take a rest if it exceeds a threshold.
Calibration	See the information provided for "Installation" above. The device does not need to be recalibrated after initial calibration.	Unit is self-calibrating. Calibration takes 30 seconds. The device does not need to be recalibrated after initial calibration.
Installation Requirements	Installation Kit: After market package comes with an installation kit that consists of a wiring harness, speaker, switch, connectors, and pre-made cables. Installation Time: For trucks that have J-1939, the installation and calibration takes about three hours and can be done by the users. For other car types, Iteris recommends using an Iteris technician that performs the installation. The estimated labor time is 1.5 days. Interfaces: Turn signals (required only if the warning is not to be given when the signal is used).	Installation Kit: The installation primarily consists of mounting the camera and optionally connecting the turn signal wires. The used vehicle type can be specified during installation. Installation Time: Easy to install by the user. This takes ten minutes according to AssistWare and requires no special training or tools. Interfaces: Turn signals and brakes (required only if the warning is not to be given when the signal or brake is used).
Commercially Available	Yes	Yes

SYSTEM ATTRIBUTES	AutoVue™	SafeTRAC™
Original Equipment Manufacturer (OEM)	Yes. Domestically it is an available option on Freightliner Century, Argosy, and Columbia trucks and also in International (R) models 8600, 9200i, 9400i, 9900i, and 9900ix. In Europe, it is an available option on Mercedes Actros and MAN trucks.	Can be done, but has not been offered as an OEM yet.
After Market Solution	Yes	Yes
Device Price	The kit can be purchased for $1,000 and can be installed relatively easily on any class 8 truck with a J-1939 data bus. On other types of vehicles, the device costs $4,000-$5,000. This includes $1,000 for the device purchase and about $3,000 - $4,000 for the installation. The customized installation needs to be done on-site by Iteris.	Standard commercial unit is sold for about $2,000 and research version is available for around $15,000. Additional analysis software can be purchased with the research version for $1,500. The installation can be done locally.
Commercial Vehicle Implementation/ Market Penetration	Currently installed in over 8,700 commercial trucks in the United States and Europe. 700 of these trucks are in the United States. Over 30 different carriers have either installed or are experimenting with the device. Cargo Transporters is specifying the device on new truck purchases with 150 total units in use and 300 on order. 160 units installed on Praxair, Inc. trucks. Logex has purchased 75 units with 65 more units were planned for installation in	McKenzie Tank Lines has installed 36 units on their trucks as part of Mack Trucks IVI operation test. 25 units were installed on Pitt Ohio trucks in 1999 for testing purposes. A total of 150 units sold for testing and research purposes.

SYSTEM ATTRIBUTES	AutoVue™	SafeTRAC™
	2004. Other US fleets include Robert Transport, BOC Gases, Air Liquide, Piedmont Express, and Stagecoach Cartage. Being tested on 22 more fleets.	
Passenger Car	Beginning fall 2004, the device was offered as an option on 2005 Nissan Infinity and FX crossover sport utility vehicle	The user can use the after market product with any type of vehicle by specifying the vehicle type/parameters during installation.
Test Results	A survey of commercial truck drivers by Iteris indicates that these drivers consider the system to be a valuable safety feature in the vehicle. Cargo Transporters has reported that they are seeing improved safety and driver satisfaction due to the use of the device.	AssistWare brochures indicate that test results found that the system is able to track lanes 90%-97% of the time. However, the system providers did not provide official test result documents since these documents are not publicly available.
Planned Departure Detection	Recognized based on turn signal on J-1939 data bus.	Recognized based on turn signal and braking.
Manual Disable	Allow manual disable switch to eliminate nuisance alarms in confusing situations (e.g., construction zones).	Allow manual disable of the device. The system can be configured so that the driver cannot turn it off.
Other Features	None	Alertness Indicator warns driver of decreased performance. Fleet Management option generates report summarizing driver performance. Black-box recorder provides video log and performance data timeline prior to an incident. "Windshield may be dirty warning"

SYSTEM ATTRIBUTES	AutoVue™	SafeTRAC™
		"Black box" 10-second video and data logging.
Operational Environment	Both day and night conditions where the lane markings are visible. The main problem faced is with glare from concrete pavement. Not maintained lane markings can affect the operation. This is particularly true for confusing situations in work zones. Roadway curvature, guardrail, traffic volume should not be a problem.	All weather and lighting conditions but the performance is negatively affected by nighttime rainy conditions or heavy snow. The main problem is glare from concrete pavement. Not maintained lane markings can affect the operation. Roadway curvature, guardrail, traffic volume should not be a problem.
Save Historical Performance Record	Can be done by collecting discrete data from device output and reducing the data. This requires writing software for this purpose.	The research version can be used in conjunction with the SafeMON software produced by AssistWare. This software allows overlaying various device performance, vehicle operation, and geometry data that are collected by the system over recorded video images. Serial communication is only available with the research version, allowing the collection of discrete data from device output and reducing the data. This requires writing software for this purpose. An option provided with the standard version allows logging of driving performance including the number and type of warnings given.

2.6   Camera Type

As previously stated, digital video cameras are used to capture the images in image-based LDWS.   Both CCD (charge-coupled device) and CMOS (complimentary metal-oxide semiconductor) image sensors have been used.   In general, CMOS sensors are much less expensive to manufacture than CCD sensors. AutoVue uses CMOS cameras while SafeTrack uses CCD cameras.   Both technologies convert light into electrons using censor cells.   The accumulated value (accumulated charge) of each cell in the image is read in both devices. In a CCD device, the charge is transported across the chip and read at one corner of the array. An analog-to-digital converter turns each pixel's value into a digital value. In most CMOS devices, there are several transistors at each pixel that amplify and move the charge using more traditional wires.   CCD sensors create higher-quality, lower-noise images compared to CMOS sensors. CMOS consumes significantly less power than CCD cameras (*13*).

2.7   Selection Criteria

The following are the criteria used in this study to decide whether to use the SafeTRAC[TM] or the AutoVue[TM] lane departure systems for the project. These criteria are presented in order of their importance.

Ease of Installation: This criterion is evaluated based on the wiring/mounting requirement, flexibility of use on different types of vehicles, time required for installation, flexibility in moving the device between vehicles, and the expertise required to install the equipment.

Cost: This includes device and installation costs. This project had a limited budget and the cost of the purchased device was one of the considerations.

Store/Analyze Historical Performance Data: Ability of the device to record the historical data for further analysis.

Market Penetration: This criterion is evaluated using two measures: 1) The number of existing users of the system in the U.S.; and 2) The number of OEM that have committed to provide the system as an option in their cars. Market penetration is an important factor to consider since the higher number of users of a system will allow the gathering of more information about driver's perception of the system performance and how this performance changes with lane marking improvements.

2.8   Selection Recommendation

Table 2-2 presents a comparison of the ability of SafeTRAC[TM] and AutoVue[TM] to meet the selection criteria. As indicated in this table, AutoVue[TM] had achieved a higher market penetration compared to the SafeTRAC[TM] product at the time of the comparison. AutoVue[TM]

had a significant number of fleets using it or experimenting with it, as well as it being offered as an option on Freightliner trucks and on Nissan Infinity and FX crossover sport utility vehicles. Unfortunately, AutoVue ™ is difficult to install on vehicles that do not have the J-1939 data bus. In addition, it is both difficult and costly to move the device to another vehicle, once it is installed.

Additional optional performance analysis capabilities are available with the SafeTRAC™ research version. In particular, this version provides serial data outputs and inputs and allows the use of the SafeMON software to analyze the serial data and to display the captured video images. The cost of this version is much higher than the standard version.

Based on the above analysis and after careful consideration by all research team participants including Caltrans and Florida's Turnpike management and the research team, it was decided to use the Autovue™ produce. Although the effort required to install and move Autovue™ between vehicles and the restrictions on the vehicle types that can be used with this product created difficulties for the research team, project stakeholders indicated that the higher market penetration of the Autovue™ product is the most important critical success factor for the project.

Table 2-2: Comparison of the Ability of AutoVue^{TM} and SafeTRAC^{TM} to Meet Selection Criteria

SELECTION CRITERIA	AutoVue^{TM}	SafeTRAC^{TM}
Ease of Installation	For vehicles that do not have J-1939 data bus, it requires an Iteris representative to travel to the location where the device is installed to perform the installation that will take about 1.5 days. Once the device is installed on a vehicle, it will not be easy or economical to move it to another vehicle. To remove and reinstall the device in another vehicle will require an Iteris representative. The manufacturer provided a list of vehicle types that the product should be installed on including F-150 truck, GM trucks, and equivalent SUVs.	Non-experienced users can do the installation in minutes. No wiring is required except for connecting the device to the vehicle lighter. The device can be moved easily from one vehicle to another and recalibrated by specifying parameters such as height of camera off the ground, width of car, and pitch of camera relative to the car.
Cost	$1,000 for the device purchase and about $3,000 - $4,000 for the installation. The installation needs to be done by Iteris.	Standard commercial unit is sold for about $2,000 and research version is available for around $15,000.
Store/Analyze Historical Performance Data	Can be done by collecting discrete data from device output and reducing the data. This requires writing software for this purpose. Not all desired information elements are available using this interface.	The research version (the DDO option) can be used in conjunction with the SafeMON software developed by AssistWare. This software allows overlaying various device performance, vehicle operation, and geometry data that are collected by the system over recorded video images. Serial communication is only available with the research version, allowing the collection of discrete data from device output and reducing the data.

SELECTION CRITERIA	AutoVue^{TM}	SafeTRAC^{TM}
Store/Analyze Historical Performance Data (Continued)		An option provided with the standard version allows logging of driving performance including the number and type of warnings given.
Market Penetration	Made significant market penetration including its installation on 8,700 trucks in the U.S. and Europe and offering it as an option on Freightliner trucks and on Nissan Infinity and FX crossover sport utility vehicle.	Has been used mainly in tests and evaluation purposes. AssistWare mentioned that it is close to signing agreements regarding product sales.

3.   Lane Marking Technologies

3.1   Background

Pavement lane markings are required for effective and safe use of roadways. Lane markings define the edges of the traveled way, the boundaries between lanes in the same direction, and the boundaries between lanes in opposite directions. They are especially important during nighttime driving when other visual guides might be of limited value.

Various types of lane marking materials with varying visibilities and service lives have been used on roadways. In order to investigate the effect of lane marking attributes on the performance of lane departure warning systems, information is needed regarding the marking types, visibility, standards, and testing procedures.

This chapter discusses the various types of available marking materials, their associated standards and testing procedures. Both national and Florida procedures will be reviewed since the performance of lane departure warning systems will be tested in Florida. Special consideration is given to discussing lane marking visibility under different conditions and service life performance of different marking materials and types. This chapter also identifies high performance lane marking products and technologies that produce good visibility under night and wet conditions. These products and technologies will be analyzed for possible inclusion in this project to determine their effect on the performance of lane departure warning systems.

3.2   Marking Materials

As stated above, transportation agencies have used various types of materials for pavement markings. The most widely used among these are traffic paints and thermoplastic markings. Other used types of marking materials include tapes, epoxy, polyester, and methyl methacrylate *(14, 15)*.

Highway agencies have also used raised pavement markers (RPMs), placed along the side or both sides of longitudinal lane markings, to enhance the visibility of other types of lane markings. This chapter presents a review of the most-widely used types of lane markings.

3.2.1   Traffic Paint

The three main components of traffic paints are the binder, base material pigment (for color and retroreflectivity) and solvent (alkyd, modified alkyd, or water). When applied to pavement, the solvent evaporates leaving a hard film that constitutes the pavement markings.

Traditionally, the alkyd and modified alkyd traffic paints were the most widely used type of paint markings. However, the water-based latex markings have experienced increased usage due to environmental considerations (*14, 15*).

Traffic paint markings are the cheapest compared to other marking types but are the least durable. Most highway agencies consider a reasonable target for the service life of these materials to be six to twelve months.

3.2.2 Thermoplastic

Thermoplastic markings have been proposed as an alternative to painted markings due to its readiness for immediate use and superior durability and visibility. The initial cost of thermoplastic markings is significantly higher than painted markings. However, the longer service life of thermoplastic markings makes it a cost-effective alternative to traffic paints in many situations. Thermoplastic marking service life has been reported to range from three to six years.

Thermoplastic markings include three basic components: plastic and plasticizer (binder), pigment and filler, and glass beads (*14, 15*). The specific chemical compositions of thermoplastic marking components vary. In general, thermoplastic materials can be classified into two categories, depending on the type of the binder used:

- Alkyd-based uses synthetic alkyd resins as a binder.
- Hydrocarbon-based uses petroleum-based organic compounds as a binder.

The most widely used type of thermoplastic marking material is the hot-applied markings that consist of synthetic resins that soften when heated and harden when cooled.

3.2.3 Preformed Tapes

Preformed pavement marking tapes are generally recognized for their durability, especially abrasion resistance. Another main advantage of tapes is their ease of installation and removal procedures. They are ideal for locations where frequent replacements of the markings are more expensive and less practical. Preformed tapes are generally fabricated as rolls or sheet stocks in a factory. These tapes consist of resin binder, pigment, glass beads and fillers. The tapes are backed with an adhesive for pavement bonds (*14, 15*). Preformed tapes are generally more expensive than thermoplastic and traffic paint markings.

3.2.4 Raised Pavement Markers

Commonly used pavement markings disappear when the surface of the markings becomes wet resulting in a loss of visibility. Retroreflective Raised Pavement Markers (RPMs) have been used to replace or supplement other pavement markings to enhance marking visibility in wet conditions. Another advantage of using RPMs is that the vehicle vibration and audible tone produced by the vehicle crossing over the RPMs create a secondary warning of lane departure. The disadvantage of using RPMs is their relatively high initial cost. Thus, their application tends to be on major roadways.

The three colors for RPMs in use are white, yellow, and red. White and yellow RPMs have the same meanings as these colors in pavement markings (see Chapter 5). Red retroreflective RPMs convey the message "wrong way" (*16*).

In recent years, a number of vendors have started producing self-emitting light RPMs to provide excellent visibility under various weather conditions. These products, however, are considerably more expensive than the retroreflective RPMs.

The Manual of Uniform Traffic Control Devices (MUTCD) (*16*) addresses the patterns and spacing of RPMs for supplementing other markings. In Florida, RPMs are used to supplement lane markings on state roads and other major roads. The Florida design standards (*17*) address the details of RPM implementations. These standards are compliant with the MUTCD standards.

3.3   *Marking Visibility*

Marking visibility and its measurement are important to this research since markings need to be visible enough to be detected by lane departure warning systems. This chapter discusses visibility, its measurement, required marking visibility, and the effects of wet and night conditions on the marking visibility.

3.3.1   Measures of Visibility

The method by which markings are made visible to drivers is called retroreflection. Retroreflection occurs when light rays strike a surface and are redirected back to their source. The imperfect nature of retroreflectors cause the redirected light to be reflected in a cone around the source light (the auto headlight) rather than reflected as a line directed to the source light, as shown in Figure 3-1 (*14*). A portion of this light is therefore directed to the driver's eye and to the lane departure camera lens, if such a camera is installed, making the lane markings visible to the driver and the lane departure unit. Generally, the less retroreflective the marking is, the poorer is its nighttime visibility.
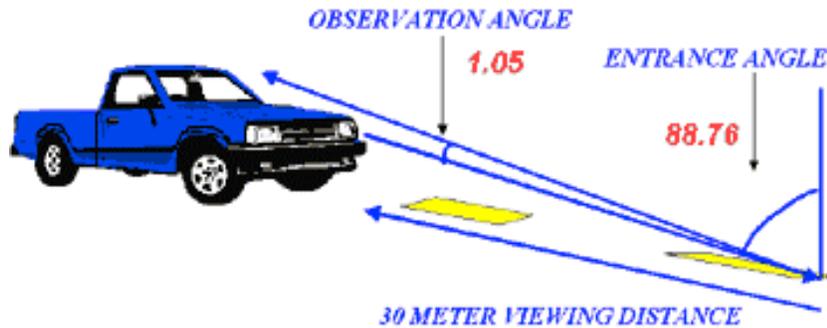
Figure 3-1: The 30-Meter Observation Geometry

Figure 3-1 shows that the driver viewing distance is approximately 30 m (*18, 19*). The geometry shown is known as the "30-meter observation geometry distance". Thus, the recent trend is to use this geometry in the measurement of pavement marking condition. In Figure 1, the entrance angle is the angle between the light source axis and the reference axis. The observation angle is the angle formed between the light source axis and the light receptor axis.

The most-widely used measure of pavement marking visibility is the "retroreflectivity" of the markings. Retroreflectivity represents the portion of incident light from a vehicle's headlight that is reflected back. Retroreflectivity is expressed using the coefficient of retroreflected luminance (R_L) as defined by the ASTM standards. R_L is defined as the ratio of the luminance of a projected surface to the normal luminance at the surface on a plane normal to the incident light and is measured in millicandelas/m2/lux (mcd/m2/lux). The average initial values of retroreflectivity have been reported as 250 and 500 mcd/m2/lux, for paint and thermoplastic markings, respectively (*20, 21*).

Pavement marking color has been reported to affect the retroreflectivity of pavement marking materials. Yellow markings are generally expected to have about 70%-80% of the retroreflectivity of white markings of the same marking material (*20, 21*).

In addition to the above mentioned retroreflectivity measurement (R_L), the Contrast Ratio (CR) has been proposed in the literature to measure the visibility of lane markings (*22*). This is the ratio of the luminance from the pavement marking to the luminance from its surrounding. CR is defined as:

$$CR = R_L \text{ (marking)} - R_L \text{ (pavement)} / R_L \text{ (pavement)} \tag{3-1}$$

3.3.2   Retroreflectivity Measurement Devices

One of the concerns with retroreflectivity measurements of pavement markings has been the lack of standardization of these measurements. There has been a poor correlation between measurements made by different units because of the use of different observation distance geometries. Some units have used the 15-meter geometry and others have used the 30-meter geometry, described previously (*18, 19*). It has been shown that the obtained retroreflectivity is dependent on the used observation distance geometry. The values obtained, using the 30-meter geometry, are normally lower than the values obtained using the 15-meter geometry. In addition, different hardware implementations and products from different manufacturers have produced different results even when using the same observation geometry.

The Federal Highway Administration (FHWA) has recommended that all retroreflectometers utilized in pavement marking testing should use the 30-meter observation distance geometry. This is the geometry initially recommended for use in testing by the European Committee for Normalization (CEN). The American Society of Testing and Materials (ASTM) has also adopted the CEN geometry recommendation. The 30-meter observation distance geometry yields an observation angle of 1.05 degrees and an entrance angle of 88.76 degrees, as indicated in Figure 3-1.

There are a number of handheld devices for measuring retroreflectivity. The Florida State Materials Office has issued "Florida Method of Test for Traffic Striping Field Test," Designation 5-541, the latest version is September 1, 2000. This document provides the statewide guidelines for testing installed pavement markings. This document also specifies that the hand held LTL 2000 retroreflectometer is the approved device for measuring retroreflectivity according to this method.

Retroreflectivity can also be measured using a vehicle mounting device referred to as LaserLux The LaserLux uses a scanning laser beam to scan the pavement marking roughly 32,000 times per hour, while traveling at highway speeds under all ambient light conditions. These values are averaged over a user-specified length (typically 30 to 150 meters) to provide an overall retroreflectivity value for the given length of markings.

The Laserlux mobile unit uses a 30-meter equivalent geometry. The observation angle and the entrance are approximately equal but are not identical to those recommended by CEN and ASTM for the 30-meter geometry (*19*). Results obtained using LaserLux retroreflectometers have been shown to be within 5-10% of the results obtained using the LTL 2000 handheld devices with 30-meter geometry (*19, 23*). The device is able to measure nighttime retroreflectivity under daylight conditions using a laser beam to simulate the vehicle headlight.

The advantages of the mobile units compared to the handheld devices are increased data collection safety (by reducing exposure to traffic), increased data collection speed, and the ability to obtain continuous data measurements along the roadway section (*18, 19*). In addition, the use of handheld units requires that the road/lane being measured be closed to traffic. Handheld device advantages are significantly lower cost and somewhat more accurate measurements.

Figure 3-2 shows a picture of the LTL 2000 handheld device. Figure 3-3 shows a picture of a Laserlux unit mounted on the side of a van. It is recommended that the LaserLux be calibrated against the LTL 2000 unit measurements.

Figure 3-2: LTL 2000 Hand-Held Retroreflectivity Measuring Device

Figure 3-3: Van-Mounted LaserLux Retroreflectivity Measuring Device

3.3.3   Required Visibility

Several studies have been performed recently to identify the minimum acceptable retroreflectivity and contrast ratio of roadway markings based on motorist reactions to these markings and/or crash experience. Below is a summary of the results obtained from these studies:

- Graham and King *(24)* reported that 90% of test subjects rated a retroreflectance of 93 mcd/m2/lux as adequate or more than adequate.

- Graham et al. (*25*) reported that 85% of test subjects aged 60 years and above rated marking retroreflectance of 100 mcd/m2/lux as adequate or more than adequate.

- Migletz et al. (*26)* found a retroreflectivity range of 80 to 130 mcd/m2/lux to be adequate under favorable dry driving conditions.

- A Minnesota DOT study recommended the use of 120 mcd/m2/lux based on data collected using a mobile retroreflectometer (*27*).

- Ethen and Woltman (*22*) found that a marking reflectance of 100 mcd/m2/lux was the minimum acceptable value under dark conditions provided that the contrast ratio (CR) was at least 3. However, the desired retroreflectance is 400 mcd/m2/lux under dark conditions and 300 mcd/m2/lux for an illuminated road.

- Aboud and Bowman (*20*) recommended a retroreflectivity threshold of 150 mcd/m2/lux for use by practitioners when traffic safety is a primary concern based on crash analysis.

- Parker and Meja (*21*) found that the threshold value of acceptable versus unacceptable retroreflectivity appears to be between 80 and 130 mcd/m2/lux for New Jersey drivers less than 55 years of age, and between 120 and 165 mcd/m2/lux for drivers greater than 55 years of age.

- Cottrell and Hanson (*28*) found that retroreflectivity readings less than 300 mcd/m2/lux were classified by drivers as acceptable 53% of the time, where as markings with retroreflectivity greater than 600 mcd/m2/lux were classified as acceptable approximately 92% of the time.

A 2000 report (*29*) suggested potential minimum threshold retroreflectivity values to define the end of service life of pavement markings. Table 3-1 shows these suggested threshold values. The Florida Department of Transportation (FDOT) specifies that 150 mcd/m2/lux is the minimum acceptable retroreflectivity of pavement markings.

Recent studies found that it might be possible to reduce the retroreflectivity of pavement markings by about 45% when appropriate RPMs are installed to supplement these markings (*30, 31*). The visibility of pavement markings is enhanced by light from street lighting systems and other ambient light sources adjacent to the roadway. Thus, lower retroreflectivity values are needed under these conditions.

**Table 3-1: Threshold Retroreflectivity Values Presented in the
All-Weather Marking Evaluation Report (29)**

Material	Non-Freeway <= 40 mph	Non-Freeway >= 45 mph	Freeway >= 55 mph
White	85	100	150
White and Lighting or RPM	30	35	70
Yellow	55	65	100
Yellow and Lighting or RPM	30	35	70

3.3.4   Visibility under Wet and Night Conditions

One major concern of highway agencies has been that pavement markings may not be sufficiently visible during inclement wet/night conditions. Under these conditions, guiding motorists along their intended paths is most needed. Driving under wet night conditions is stressful and fatiguing for all drivers, but particularly so for elderly ones, who are becoming an increasing percentage of the driving population. The concern regarding visibility under wet and night conditions is also applicable to image recognition based lane departure warning systems since the images captured by the system cameras might not be adequate for tracking lanes during wet and night conditions.

During heavy rain, lane markings may be covered by water, thus reducing the visibility of the markings. When the rainwater floods the markings, the incident light on the markings is specularly reflected rather than being retroreflected. In addition, under rainy conditions at night, headlight glare causes visibility to drop significantly (*32*). It was found that the retroreflectivity of pavement marking materials under wet conditions is 42% to 52% of the retroreflectivity for the same marking under dry conditions (*29*).

The necessary pavement marking retroreflectivity is provided using glass beads that are partially embedded in the surface of the marking materials. Glass beads are small glass spheres applied to pavement markings.   They can be dropped on or premixed in marking materials before application. The light that glass beads reflects is a function of three variables (*14*):

- Index of refraction (RI) of the beads
- Bead shape, size, and surface characteristics
- Number of beads present and exposed to light rays

Under wet conditions, the beads become covered with water and are unable to perform their retroreflective function (see Figure 3-4).

It has been found that large beads enhance marking retroreflectivity, particularly under wet conditions. To provide all-weather pavement markings, the FHWA has developed gradations of large glass beads, for use in water based paint, epoxy, polyester, and thermoplastic marking materials. Field tests show that the use of larger beads provides enhanced visibility of markings at night and during rain (*33*).

Lindly, et al (*34*) performed statistical analysis to correlate the dry and wet retroreflectivity. The dry and wet retroreflectivity measurements were taken using the LaserLux mobile retroreflectivity-measuring device.   The wet test procedure was based on the ASTM E 2177 Standard (discussed in Chapter 5 below). Two regression models were developed, one for flat thermoplastic markings and one for profiled pavement markings. The obtained correlation coefficient (R^2) value was 0.2 and 0.4, respectively.
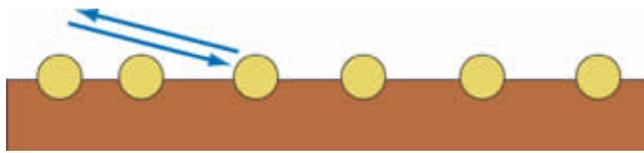
(a) Dry Conditions
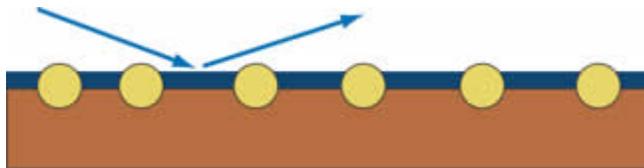
(b) Wet Conditions
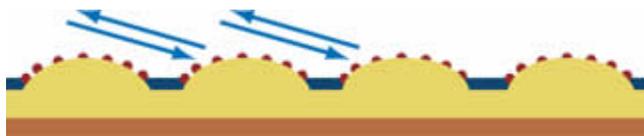
(c) Profiled Markings or Large Beads
     in Very Light Rain or Recovery
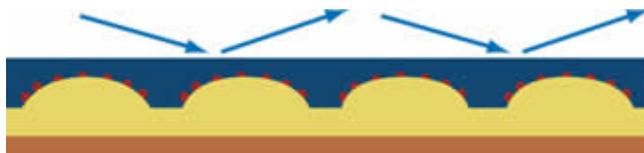
(d) Profiled Markings or Large
     Beads During Heavier Rain
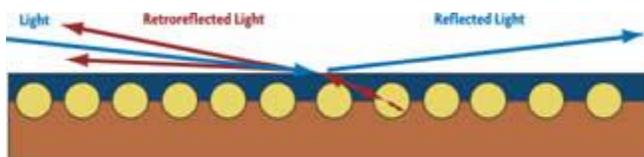
(e) All Weather Tapes

Figure 3-4: Retroreflectivity Performances Under Wet Conditions (Source: Reference 33)

The obtained equation for the flat thermoplastic markings is:

Wet Retroreflectivity = 7 + 0.12 * Dry Retroreflectivity   (3-2)

The obtained equation for the profiled pavement marking is:

Wet Retroreflectivity = 12 + 0.32 * Dry Retroreflectivity   (3-3)

3.4   Marking Service Life

Pavement markings deteriorate with time. Ultra-violet light and heat from the sun can deteriorate the binder, releasing the beads. In addition, abrasion from traffic, sand, and snowplows can wear off the beads. The rate of degradation of pavement markings and the loss of retroreflectivity due to bead loss is affected by traffic volume, heavy vehicle percentages, environmental conditions, and quality control in applying the marketing material. Furthermore, the various pavement materials have different life expectancies. For this reason, a fixed time schedule re-striping strategy has been questioned in terms of both sufficiency and economy. Rather, it has been suggested that re-striping should take into consideration the factors identified previously.

Table 3-2 presents a comparison of different pavement marking types with respect to initial retroreflectivity and service life based on a study performed in Virginia (28).

**Table 3-2: Initial Retroreflectivity, Installation Cost, and Service Life
Based on Virginia Study (28)**

Material	Initial Retroreflectivity (mcd/m2/lux	Service Life (yr)
Paint (large Contract)	250	1
Paint (VDOT)	250	1
Paint (Small Contract)	250	1
Thermoplastic	350	3
Epoxy	350	3
Polyurea	900	3
Waffle Tape	1000	6

Migltetz et al. (*35*) estimated the durability of markings using statistical regression analysis. The derived models provide estimates of the retroreflectivity of each type of marking material, marking type, and marking color as functions of cumulative traffic passages. These models allow service life estimation by determining the point in time at which retroreflectivity falls below an acceptable level using the number of cumulative vehicle passages as the independent variable. However, the regression analysis identified large variations in the derived relationships between different sites and required that the models be derived separately for each study site. Based on the statistical analysis, variation in service life was attributed to differences in roadway type, region of the country/weather conditions, manufacturer of pavement materials and glass beads, agency marking specifications, contractor installing the markings, quality control at the time of installation, and winter maintenance snow removal policy.

3.5   Marking Technology Standards

This section discusses national standards that are related to the implementation, installation, and testing of lane markings. The lane departure warning systems will be evaluated on the Florida Turnpike in this project. Thus, related Florida standards are also reviewed.

3.5.1   Manual of Uniform Traffic Control Devices (MUTCD)

The applications of standard colors, widths, patterns, and placements of pavement markings are defined in the MUTCD (16). The MUTCD is recognized as the national standard for all traffic control devices installed on any street, highway, or bicycle trail open to public travel. When a State or other federal agency manual or supplement is required, that manual or supplement shall be in substantial conformance with the national MUTCD.

The MUTCD specifies that pavement markings must be clearly visible in daylight, in darkness and under adverse weather conditions. Chapter 406(a) of the 1993 Department of Transportation Appropriations Act requires the MUTCD to specify minimum threshold retroreflectivity to be maintained by pavement markings and signs. However, the current version of the manual does not specify such thresholds.

The MUTCD specifies the following types of pavement marking lines (16):

- Continuous solid white lines are used as edge lines to define the right edge of the roadway traveled way.

- Broken (or skip) white lane lines are used to separate lanes of traffic moving in the same direction.

- Yellow centerlines are used to separate traffic moving in opposite directions of an undivided highway. Two continuous solid lines are used when passing maneuvers are prohibited for traffic in both directions of travel. A combination of a continuous solid yellow line and a broken yellow line are used where passing maneuvers are prohibited in one direction of travel but permitted in the other direction. A single broken or skip yellow line is used where passing maneuvers are permitted for traffic in both directions of travel.

- Continuous solid yellow edge lines are used to define the left or median edge of the traveled way for each roadway of a divided highway.

Markings of these types are used uniformly throughout the United States. Individual states including Florida (*17*) have developed their own standards that are compliant with the MUTCD standards.

3.5.2   *ASTM Standards*

The ASTM publishes a number of standards related to pavement markings. ASTM standards currently do not include specific minimum marking retroreflectivity values. Specific to pavement markings, ASTM standards address pavement marking materials (D1155-89, D 1214-89, D 1309-93), conduct in-service tests of these materials (D 913-88, D 713-90), and laboratory assessment of marking material properties (D 711-89, D 868-85, D 969-85) (19).

ASTM E 1710 specifies the procedure for using portable instruments to measure the retroreflectivity of pavement markings under dry conditions. In 2001, the ASTM developed two additional methods for measuring pavement marking retroreflectivity under wet and rain conditions (Standards E 2176 and E 2177, respectively).

The E 2176 standard, "Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting", is also known as the "Continuous Wetting" and the "Spray Method." This method calls for the retroreflectivity to

be measured while the marking is being sprayed with water under defined conditions. Reference 33 states that there is evidence that the performance level obtained as measured by E 2176 correlates with the visual performance experienced by drivers under both wet conditions and during rain events.

The E 2177 Standard, "Test Method for Measuring the Coefficient of Retroreflected Luminance (R$_L$) of Pavement Markings in a Standard Condition of Wetness", is also known as the "Wet-Recovery" and "Bucket Method," and is based on a test method developed by the CEN. In this test, a defined volume of water is poured over the markings, allowed to drain for a specified period before retroreflectivity is measured. The performance level obtained as measured by E 2177 predicts visual performance under wet conditions, but it may not predict visual performance during rain events, depending on the duration or intensity of the rain. (*33*).

The ASTM is developing a "Specification for Retroreflective Performance of In-Use Pavement Marking Materials When Wet". The scope of this proposed standard is the retroreflective performance requirements of pavement marking materials used for traffic control lane markings under prescribed conditions of wetness (*33*).

Pike et al. (*36*) evaluated the performance of 18 different pavement markings in wet, night conditions. Three measures were used in the evaluation: retroreflectivity, dynamic detection distance, and luminance measurements. The retroreflectivity measurements were made under a variety of conditions including dry, wet recovery (according to ASTM E 2177) standard, and 12 levels of continuous wetting ranging from 0.28 inches per hour to over 20 inches per hour. The ASTM E 2176 Continuous Wetting Standard corresponds to a large range for acceptable rainfall rates that can be used during testing (5.8 to 14.4 inches per hour with 9.3 inches per hour as the target rate) (*36*). It was found that the higher the rate of continuous wetting the lower the retroreflectivity. However, some markings degrade rather quickly while others maintain their performance longer under continuous wetting. Pike et al. concluded that continuous wetting retroreflectivity measurements using ASTM E2176 do not provide a good indication of the 30-meter luminance of a marking as measured in simulated rainfall events. The authors recommended potential enhancements to the ASTM standard.

In another paper by Pike et al (*37*), it was concluded that while the allowable rainfall rate in E 2176 ranges from 6-14 in/hr, 88 percent of rainfall events in Texas produced maximum rates of less than 0.75 in/hr. The researchers found that, for most markings, the retroreflectivity level decreases as the rainfall rate increases, but the changes in retroreflectivity were not consistent for different marking types. Based on the research findings, Pike et al (*36*) suggested that the range of conditions permitted by E 2176 "brings into questions the ability to use this procedure to make comparisons of material retroreflectivity in a standardized manner." (*37*)

3.5.3 *FDOT Standard Specifications*

The FDOT State Specifications Office publishes the Standard Specifications for Road and Bridge Construction (*38*) and the implemented modifications to the Standard Specifications.

There are also process proposed modifications to the Standard Specifications, (Special Provisions, or Supplemental Specifications) which when approved become the implemented modifications to the Standard Specifications for Road and Bridge Construction.

The 2004 Florida Department of Transportation Specifications (*38*) specifies the pavement marking construction requirements in Division II and pavement marking material in Division III of the specifications. The construction specifications denote an initial retroreflectance of 300 mcd/lux/m2 and 250 mcd/lux/m2 for white and yellow pavement markings and a final retroreflectance (i.e., minimal acceptable reflectivity) of 150 mcd/lux/m2. This applies to all types of pavement marking materials.

3.5.4   *Florida Qualified Product List*

The FDOT State Specifications Office Product Evaluation Chapter reviews and evaluates transportation related products and maintains a Qualified Products List (QPL). The QPL is a published list of products that have been evaluated against implemented FDOT specifications and standards and found to meet those standards.

The approved products for use in pavement marking listed in the QPL can be accessed on the web at www.dot.state.fl.us/specificationsoffice/QPLdefault.htm. The list includes the following types of pavement markings:

- Raised retro-reflective pavement markers and bituminous adhesive according to FDOT Specification 706.
- Two reactive component traffic markings according to FDOT Specification 709.
- Water base traffic paints according to FDOT Specification 710.
- Thermoplastic traffic stripes and markings (Alkyd thermoplastic products that meet FDOT Specification 711).
- Thermoplastic traffic stripes and markings (Hydrocarbon thermoplastic that meets FDOT Specification 711).
- Thermoplastic traffic stripes and markings (Alkyd hot-spray thermoplastic products that meet Specification 711).
- Thermoplastic traffic stripes and markings (Hydrocarbon hot-spray thermoplastic products that meet Specification 711).
- Preformed pavement stripes and markings (Permanent tape products that meet Specification 713).
- Preformed pavement stripes and markings (Permanent thermoplastic products that meet Specification 713).

3.5.5   *Existing Lane Markings on Florida's Turnpike*

In order to develop a test plan for the evaluation of existing lane marking on Florida's Turnpike, an investigation of the existing lane markings on the Turnpike was performed based on site visits

and a number of meetings conducted with Mr. Douglas Prager, the Traffic Services Manager and the Quality Control Engineer for FTE Maintenance. The objective of the meetings was to discuss the study effort, currently installed marking materials, installation dates, the lane marking installation and testing procedures used on the FTE facilities, and potential test locations.

Below is a summary of the collected existing condition information:

- The material commonly used on the Turnpike for lane marking is Alkyd-based thermoplastic.

- Traffic paint markings are only used as temporary markings on newly paved roadway segments. It is deployed for the first six months after paving the road and then replaced by thermoplastic markings to prevent the permanent markings from being blackened by the pavement materials.

- Tapes are only used on bridges on FTE facilities.

- The Florida Turnpike Enterprise uses the FDOT 5-541 procedure (that references ASTM standard E-1710) for retroreflectivity measurement. Although, in the past contractors used the 15-meter observation geometry hand-held units when measuring retroreflectivity, most of them at the present time use the 30-meter geometry hand-held units.

- It appears that there is a wide variation in the retroreflectivity of lane markings on the Turnpike, which will permit testing the lane departure system performance with different marking quality and visibility.

- In general, raised pavement markers (RPM) are used in conjunction with skip markings in accordance with the Florida Department of Transportation requirements. These requirements are applicable to all state roads.

- There are no lane markings for about 500 ft on both sides of the FTE toll plazas.

New installations of lane markings on the FTE facility use double drop beads to increase the visibility of lane markings during night conditions. Double drop beads include larger size beads that are mixed with the regular size beads used in the single drop bead markings. In addition, the quantity of the used beads is larger in the double drop bead markings compared to single drop bead markings. Table 3-3 presents a description of the lane marking installations by mile post on the Florida Turnpike mainline, the Homestead Extension of the Florida Turnpike (HEFT), and the Sawgrass Expressway. All of these facilities are managed by FTE.

Table 3-3: Existing Marking Installations on the Turnpike

Roadway	Mile Marker	Marking Type	Marking Age (as of the beginning of 2005)	Comments
Florida's Turnpike	MP 0 – 26	Thermoplastic (single bead)	Over the last 4 years	
	MP 26 – 32	Thermoplastic (double drop bead)	Within last 6 months	
	MP 32 – 39	2 part polyester hi night visibility system (Glass and ceramic beads)	Applied in 2003	
	MP 39 – 47	Paint and or thermoplastic (double drop bead)	Within the next 6 months	
	MP 0X – 4X	Paint and or Thermoplasticr (double drop bead)	Within the next 6 months	
	MP 47 – 50	Thermoplastic (single bead)	Within the last 2 years	
	MP 54 – 63	Thermoplastic (single bead)	Within the last year	
	MP 63 – 75	Thermoplastic (single bead)	Over the Last 4 years	
	SB Direction adjacent to the Sample Road	Thermoplastic (single bead)	Within the last year	
	MP 75 – 81	Thermoplastic (single bead)	Within last 1.5 years	
	MP 81 – 88			Under construction, paint and thermo in bad shape.
	Mp 88 – 309	Thermoplastic (double drop bead)		Resurfacing projects, the markings are in numerous different levels but all should be new thermoplastic with double drop beads within the next 18 months.
Sawgrass	MP 0 – 9			Thermoplastic (double drop bead) recently installed
	Mp 9 – 21	Thermoplastic (single beads)	Over the last two years	

3.6   High-Performance Marking Technologies

This section presents a discussion of past experience with high performance marking technologies that can produce higher retroreflectivity values and longer service lives compared to other more commonly used lane markings. It also presents a review of products currently available in the market that produce such performance.

3.6.1   Technology Evaluation

Marking manufacturers have produced high performance lane marking materials that have higher retroreflectivity, longer service lives and better performance in night and rainy conditions compared to commonly used lane marking technologies. To provide retroreflection at night, conventional pavement markings use exposed glass beads. These glass beads become flooded with water under wet conditions, thus reducing the visibility of lane markings.

In recent years a number of technologies have been developed in an attempt to overcome this problem (*33*). These include the use of larger beads that may overcome some of the effect of flooding of the markings, and may be effective under lighter rain conditions. Patterned tapes also known as structured or waffle tapes ensure higher visibility by elevating entire portions of the markings above their base, in the form of "waffles," or ridges of extruded material. Another method is to use wet weather (all-weather) tapes that utilize enclosed lens optics, which are not substantially affected by the presence of water, and may be most effective in heavy rain.

Cottrell and Hanson (*28*) reported that a waffle tape initial retroreflectivity was 1000 mcd/lux/m2 and its service life was 6 years. The thermoplastic markings retroreflectivity and service life measured in the same study were 350 mcd/lux/m2 and 3 years, respectively. The traffic paint marking retroreflectivity and service life were 250 mcd/lux/m2 and 1 year, respectively (see Table 3-3).

As stated above, Lindly et al. (*34*) performed statistical analysis to determine wet retroreflectivity as a function of dry retroreflectivity for flat thermoplastic markings and patterned tape markings. The derived equations (Equations 2 and 3 above) show that the proportion of dry retroreflectivity retained during wet conditions is much higher in the case of patterned tape markings compared to thermoplastic markings.

The Operator Performance Laboratory (OPL) at the University of Iowa performed two studies to evaluate different types of pavement markings under dry, wet, and simulated rainy conditions. The first study was sponsored by the FHWA (*39*) and the second study by 3M (one of the largest manufacturers of pavement materials) (*40*). The evaluation was based on measuring retroreflectivity, driver detection distances (using a test track), and eye movement behavior under dry, wet, and simulated rainy conditions. Three hand-held retroreflectometers (ART MX-30, Delta LTL-2000, and Delta LTL-X) were used in the study under the three ASTM test methods: dry (ASTM E-1710), wet recovery (ASTM E-2177), and continuous wetting (ASTM E-2176). In addition to these devices, lux meters and a CCD photometer were used in the FHWA sponsored study.

In the two studies, five types of marking materials were tested. These were:

- Flat tape: This is a commercially available polymer preformed flat marking tape incorporating 1.5 index beads. This tape provides a wet/dry performance similar to that of conventional paint and beads or flat thermoplastic products. In wet or rainy conditions, water may cover all of the pavement marking and the glass beads, reducing the marking visibility significantly.

- Paint and large beads: This material incorporates large size beads to promote visibility and water drainage. The beads were 0.85-1.4 mm in diameter, and were applied at a rate of 12 lbs per gallon.

- Patterned tape with mixed high index beads: This is a preformed patterned (structured) tape incorporating 1.75 index ceramic beads. The tape has raised profile chapters with glass beads along the vertical walls. The profiled chapters are intended to reduce bead flooding and promote water drainage.

- Patterned tape with high index beads: This product is similar to the patterned tape with mixed high index beads but it differs in its optical properties.

- Wet weather (all weather) pavement marking tape: This tape has special optics to give a high level of dry and wet reflective performance. This product has a wet retroreflectance similar to its dry retroreflectance.

The wet weather tape performed best among all five materials under all weather conditions, especially under the simulated rain conditions. Under the dry conditions, all materials provided acceptable detection distances. The wet weather tape yielded the longest detection distances.

The patterned tape with high-index beads performed better than the flat materials but worse than both the wet-weather tape and the patterned tape with mixed index beads. Under wet conditions, the flat tape performed significantly worse compared to the other four materials. The wet weather tape performed the best followed by the patterned tape with mixed index beads, and then by the patterned tape with high index beads.

Under the simulated rain conditions, the wet tape performed the best. The patterned tape with mixed index tape beads performed second best. Paint and large bead pavement markings performed well following the tape with mixed index beads. Under simulated rain conditions, the performance of the flat tape was similar to the performance of the patterned tape with high index beads used in this study.

3.6.2   Available Products

This chapter presents a discussion of existing high performance lane marking products that are currently included or being considered for inclusion in the Florida QPL.   Table 3-4 presents a summary of the reviewed products.

Table 3-4: High Performance Lane Marking Products

Vendor	Product	Description	QPL Listed
3M	Stamark™ High Performance Tape Series 380I	Patterned tape	Yes
	Stamark™ Wet Reflective Tape Series 820	All-weather (rain/wet) tape (Use special Optics)	3M is not marketing this product any more
	All-weather paint	All-weather (rain/wet) paint (Use special Optics)	Not yet
	Stamark™ Wet Reflective Tape Series 380 WR	All-weather (rain/wet) tape (Use special Optics)	Not yet
Advance Traffic Markings	ATM 300	Flat tape	Yes
Flint Trading, Inc.	PREMARK^R	Flat tape that uses larger size beads mixed with small beads	Yes
The RainLine Corporation	RainLine System℠	All weather traffic striping system that places inverted profiles into the traffic stripe.	Under Consideration
SWARCO	Director 60 Series	Durable, highly reflective, pliant polymer pavement markings.	Yes

3.6.2.1 3M

3M is a diversified technology company that owns companies in 60 countries and provides various technologies and services. The 3M Safety Division produces the following high performance lane marking products:

- 3M^{TM} Stamark^{TM} High Performance Tape Series 380I and 381I: This is a highly reflective pavement marking tape that is designed to combine technologies in beads, topcoats, and adhesive. The tape provides high initial and retained reflectivities and high durability. This tape is manufactured with a patterned surface that presents a near vertical profile to the motorists to maximize retroreflectance and a pliant polymer conformance layer for long term durability. Series 380I is used for white markings and Series 381I is used for yellow markings. A variation of this type of tape is the Series 380I-5 Contrast Marking Tape. This tape consists of a standard white marking tape with a 1-1/2 inch wide black edge to provide contrast on light colored asphalt or Portland Cement concrete surfaces.

- 3M^{TM} Stamark^{TM} Wet Reflective Tape Series 820: This is a highly reflective tape under both wet and dry conditions. This tape utilizes specially designed optics to provide dry and wet reflective performance. The tape has been reported to produce high wet retroreflectivity that is close to dry retroreflectivity. 3M appears to have stopped producing this tape series. It is currently marketing the 380WR series.

- Stamark^{TM} Wet Reflective Tape Series 380WR is an all-weather (rain/wet) tape marking that uses special optics to provide high visibility during night and rain conditions. This product has recently been introduced to the market and is said to have overcome the limited durability issue reported for the 3M Tape Series 820.

The 3M Pavement Marking Tapes Series 380I/381I Tape and 380I-5 Contrast Tape have been installed at a number of locations in Florida as indicated in Table 3-5. The 380I/381I and 380I-5 Tapes are in the FDOT QPL. Figure 5 shows a Series 380I-5 tape implementation on I -595 in Ft. Lauderdale, FL, between I-95 and the Fort Lauderdale Airport Interchanges.

Table 3-5: 3M Pavement Marking Tapes Series 380I Tape and 380I-5 Contrast Tape Installations in Florida (as of May 2005)

Location	Type	Age
Roosevelt Bridge, Stuart	380, 381 (yellow) and 380-5 tape.	Six years old
I -595 in Ft. Lauderdale between I-95 and Fort Lauderdale Airport Interchange	380-5	Three years old
West Palm Beach Airport flyover ramp	380-5	One year old 380-5
I- 4 in Orlando	380-5	Two years old
Howard Franklin Bridge in Tampa	380-5	Five years old
I-275 in St. Petersburg	380-5	Three years old
Turnpike - Sawgrass Expressway	380 and 381 on FC-5	Four years old
I-10 in North Florida (FDOT District 2)	380 and 381 on FC-5	Six years old
I-75 in Alachua County,105 miles of skip markings	380I	One year old
I-10 in Tallahassee	380 skips	Two and half years old
Orlando-Orange County Expressway Authority	Series 380I-5 contrast tape and 381 yellow	Standard on all new surfaces for over 7 years

Note: FC-5 is the "open grade or popcorn mix" that is used by FDOT for resurfacing projects. The use of FC-5 has reduced lane marking visibility due to the lack of contrast between the lane markings and pavement.

**Figure 3-5: The 3M Series 380I-5 Tape Implementation on
I -595 in Ft. Lauderdale**

3.6.2.2   Advance Traffic Markings

Advance Traffic Markings (ATM) produces the ATM 300 and ATM 400 tapes that provide high durability and retroreflectivity. A discussion with an ATM representative indicated that ATM 300 is a flat tape with good retroreflectivity in dry conditions. However, during wet and night conditions, the tape retroreflectivity drops significantly as long as water covers the markings. The representative recommends the use of the tape, in conjunction with RPMs to deliver the required visibility. The ATM 400 tape is similar to ATM 300 tape in its visibility performance but has a higher durability. The ATM 400 tape costs about $3.00 per square foot ($1.50 per linear foot for 6 inch width marking). ATM 300 costs about $2.50 per square foot.

3.6.2.3   Flint Trading, Inc.

Flint Trading, Inc. produces the PREMARK^R marking tape that provides enhanced visibility, durability, and flexibility. The factory applied beads combine the visibility benefits of bigger beads with the durability of smaller beads. The tape also contains 30% glass beads by weight to produce retroreflectivity through all its service life.   The product representative indicated that

the tape is flat tape that produces high retroreflectivity during dry conditions but is affected by wet conditions. A 60 foot roll of a 6 inch white tape costs 81 dollars. ($2.70 per linear foot).

3.6.2.4   The RainLine Corporation

The RainLine System℠ is a wet traffic striping system that places inverted profiles into the traffic stripe. The profiles form small ridges which drain rain water so that the glass beads do not become covered with water. This allows the beads to continue to reflect light, making the traffic stripe visible during wet conditions. The system is comprised of a hot applied thermoplastic stripe that receives a double coating of glass beads. The glass beads are imprinted or embossed by a specially designed embossing wheel that is rolled over the thermoplastic and beads while they are still hot. This product is not yet on the Florida QPL.

3.6.2.5 SWARCO

SWARCO produces profiled wet-night high performance thermoplastic formulation. It also produces the Director 60 Series tapes. This tape manufacturer reported that it produces high durability and visibility in adverse weather conditions.

3.7   Conclusions

Transportation agencies have used various types of materials for pavement markings. The most widely used among these are traffic paints and thermoplastic markings. During heavy rain, commonly-used lane markings are normally covered by water, thus reducing the visibility of the markings. In addition, under rainy conditions at night, headlight glare causes visibility to drop significantly.

Marking manufacturers have produced high performance lane marking materials that have higher retroreflectivity, longer service lives and better performances under night and wet/rainy conditions, compared to commonly-used lane marking technologies.   These include:

- Markings that use large size beads (double beads) to promote visibility and water drainage.
- Profiled tape or profiled thermoplastic that has raised profile sections with glass beads along the vertical walls to reduce bead flooding and promote water drainage.   These markings are expected to work well under night wet conditions (rain recovery) but not heavy rain conditions. Examples of these are 3M Stamark^{TM} 380I profiled tape and the Rainline System inverted thermoplastic.
- All weather pavement marking paint and tape use special optics to give a high level of dry and wet reflective performance. These markings are expected to work well in dry, wet, and rain conditions.

4. Survey of Commercial Vehicle Driver Acceptance

4.1 Background

A survey was conducted of truck drivers that have used existing lane departure systems in real-world conditions to determine their experience and satisfaction levels with the two commercially available systems in the U.S. A questionnaire was developed and distributed to drivers of motor carriers that have installed these systems. The following four carriers were contacted for potential inclusion in the survey:

- Logex (uses Iteris AutoVue)
- McKenzie Tank Lines (uses SafeTRAC)
- Praxair (uses Iteris AutoVue)
- Cargo Transponders (uses Iteris AutoVue)

These four carriers have the largest number of LDWS installed on their trucks in the United States. Copies of the survey questionnaire forms were sent to a contact person at each of the above carriers, who distributed and collected the forms from drivers who use LDWS within their companies. The research team conducted telephone discussions with the contact persons before and after sending the survey forms to ensure proper distribution and collection of the forms. 20-40 copies (in paper form) of the survey were sent to each company, based on discussions with the contact persons of the companies. A copy of the survey questionnaire is included in Appendix A

A total of 40 responses were received from three carriers. These carriers are Logex (30 responses), Praxair (7 responses), and McKenzie Tank Lines (3 responses). No response was received from Cargo Transponders. Most of the drivers that responded to the survey had at least 5 years of truck driving experience with more than half having 15 years experience or more. In addition, most of the drivers had been driving with the devices for more than nine months. The characteristics of the respondents are presented in Table 4-1. We were hoping to get a higher level of participation from Praxair, McKenzie Tank Lines, and Cargo Transponders and we tried our best with these companies to get a higher level of participation. Nevertheless, we feel that, overall, the received responses provide a good indication of the commercial driver perception of LDWS and various issues associated with these systems.

Table 4-1: Characteristics of the Respondents

Attribute	Company Name		
	Logex	**Mckenzie**	**Praxair**
Number of responding drivers	30	3	7
LDWS Product Name	Iteris	SafeTrac	Iteris
No. of years driving	More then 15 years: 15 drivers 11-15 years: 5 drivers 6-10 years: 8 drivers 0-5 years: 2 drivers	More than 15 years: 2 drivers 11-15 years: 0 driver 6-10 years: 1 driver 0-5 years: 0 driver	More then 15 years: 5 drivers 11-15 years: 1 driver 6-10 years: 1 driver 0-5 years: 0 driver
No. of years driving with LDWS	More than 1 year: 14 drivers 9-12 months: 10 drivers 5-8 months: 5 drivers 0-4 months: 1 drivers	More than 1 year: 3 drivers	More than 1 year: 5 drivers 9-12 months: 1 drivers 5-8 months: 1 drivers 0-4 months: 0 drivers

4.2   System Acceptance

As indicated in Table 4-2, a large proportion of the drivers (93%) believe that the use of LDWS decreases accident potential. Only three of 40 surveyed drivers think that it does not. When asked about the confidence level in the LDWS reliability, Logex and Mckenzie drivers indicated that they have medium to high confidence in the system, while the seven responding Praxair drivers stated that they have low to medium confidence in the system (see Table 4-2).

When asked if the drivers normally drive with LDWS on, most of the Logex and McKenzie drivers responded they do. Some of these regular users mentioned that they place the system off in one or more of the following conditions:

- City streets (two drivers)
- Construction zones (two drivers)
- Two-lane highways with a lot of curves (three drivers)

Other drivers said that they turn the system off to prevent the alarms from keeping their co-drivers awake. One driver said that he turns the system on under bad weather conditions and turns it off under good weather conditions. Two out of the 7 Praxair drivers stated that they place the system off most or all of the time.

The weighted averages of the level of satisfaction with the system and the weighted average level of the potential of drivers to recommend the LDWS to other drivers was calculated based on the responses as follows:

$$Weighted\_Average = \frac{\sum_i N_i * S_i}{N}$$

(4-1)

N_i = Total number of drivers that gave a satisfaction score of S_i
S_i = System satisfaction score or the level at which a driver said that he/she would recommend the system to other drivers (Scale 1-5)
N = Total number of drivers that provided the scores

On a scale of 1 to 5, where 1 is the lowest and 5 is the highest satisfaction, it was found that the average levels of satisfaction with the LDWS were 3.8, 3.6, and 2.2 for the Logex, McKenzie Tank Lines, and Praxair carriers respectively. The average levels that the drivers would recommend the device to other drivers were 3.7, 4.0, 2.2, for the above three carriers respectively.

Table 4-2: User Acceptance and Satisfaction

Attribute	Company Name		
	Logex	**Mckenzie**	**Praxair**
No. of drivers that believe LDWS reduces potential accidents	29 out of 30	3 out of 3	5 out of 7
Confidence level in the system reliability*	High (9), Medium (11) Low (4)	Medium (3)	High (1),Medium (2) Low (3)
Weighted average level of satisfaction	3.8 (scale of 1-5)**	3.6 (scale of 1-5)**	2.2 (scale of 1-5)**
Weighted average level of the potential of drivers to recommend LDWS to other drivers	3.7 (scale of 1-5)**	4.0 (scale of 1-5) **	2.2 (scale of 1-5)**
System features appreciated by drivers*	Keeping driving alert and aware (5) Increase safety (2) Help sleepy drivers(1) Help in adverse weather conditions and very low visibility (3) Increase driver feeling of security (1)	Early warning (1) A good reminder to stay alert (1)	Early warning (1) A good reminder to stay alert (1)
System features disliked by drivers*	Alarm noise/alarm too loud (5) Keeps co-driver from sleeping (4) False alarms (5) Narrow lanes result in false alarms (1) No marking conditions (1)	Sound alarm is loud (1)	Sound alarm is loud (3) False alarms (1) Mountainous roads resulting in false alarms (1) Rain result in false alarms (1) All conditions (2)

* Number in bracket indicates number of drivers that agree with the statement
** 1 is the lowest score and 5 is the highest.

4.3   System features appreciated by drivers

The following were the system features appreciated by the drivers the most:

- Keeping driver alert and aware
- Increase safety
- Help sleepy drivers
- Help in adverse weather conditions and very low visibility
- Increase driver feeling of security
- Provide early warning
- A good reminder to stay alert

System features disliked by drivers include:

- Alarm noise/alarm too loud
- Keep co-driver from feeling asleep
- False alarms

Despite the high level of satisfaction with the system, there were a couple of drivers that had negative opinions of LDWS.

4.4   Perceived Benefits

The following were driver responses to a question about the conditions under which they believed that the device is most beneficial:

- Needed only for fatigued and sleepy drivers / keep driver awake when tired
- Countermeasure for day dreaming
- Provide driving assistance in rain and fog conditions
- Increase driver awareness
- Assist in long stretches of roads that curved slowly
- Whiteout conditions
- Ability of the system to recognize drifting before human can.

One driver mentioned that in one case the LDWS allowed him to avoid a potential accident with a car in an adjacent lane.

4.5   System Performance and Environmental Effects

As indicated in Table 4-3, most of the drivers thought that the LDWS warnings came at the right time (21 of the 23 drivers that answered the related question). 20 drivers said that false alarms occurred   seldom   to   never   and   seven   said   that   false   alarms   occurred   often.

Table 4-3: System Performance and Environmental Effects

Attribute	Company Name		
	Logex	**Mckenzie**	**Praxair**
No of drivers believing that weather affect system performance	During heavy rain (4)	During heavy rain (1)	2
No of drivers believing that night conditions affect system performance	0	0	2
Number of drivers believing that warning come at the right time	Yes (16) No (2)	Yes (3)	Yes (2) No (0)
Frequency of false alarms	Never to seldom (15) Often (4)	Seldom (3)	Never to seldom (2) Often (3)
False alarm conditions	Snow and ice Driving around corners Weather/rain (2) Narrow roads construction, detecting barrels (2)	Rain	Rain and mountainous conditions Bridges
Frequency of the system not providing alarms when it is suppose to	Never (7) Often (1) Seldom (12)	Never (3)	Never (2) Often (2 Seldom (3)
Reason for the system providing alarms when it suppose to	snow and ice construction zones under overpasses no marking lines (2)		

The remaining responding drivers had no answers to these areas. The conditions under which false alarms occurred included snow and ice, driving around corners, precipitation/rain, narrow roads, construction zones, bridges, and mountainous terrains.

Most of the drivers said that the frequency of the system not providing alarms when it should was low and this occurred mostly in snow and ice, construction zones, bridges, narrow lanes, under overpasses, rain conditions, mountainous roads, and where no markings exist.

When asked about the effects of environmental conditions, a total of 7 drivers said that heavy rain significantly affected the performance of the system. Only two drivers said that the system is adversely affected by nighttime conditions.

4.6   Conclusions

This study confirmed the generally high level of acceptance and satisfaction with the LDWS by truck drivers in the United States. The level of satisfaction was relatively low among the drivers of one of the companies surveyed. However, it should be recognized that only seven drivers responded to the survey from this company, which may not reflect the overall perception of the drivers of this company. The low level of satisfaction of some drivers indicates the need for additional driver education of the system benefits. Some drivers observed that environmental conditions can affect LDWS performance.

5.   Evaluation of LDWS Performance with Existing Marking Installations

5.1   Introduction

As stated in the previous chapters, because image-based LDWS depend on lane marking tracking, it is logical to hypothesize that the visibility of these markings under different weather and lighting conditions could affect the performance of LDWS. As stated in Chapter 1, the goal of this project is to determine the effects of environmental conditions such as rain and lighting conditions on LDWS performance and whether improvements made to roadway marking installations can enhance the performance of LDWS. This chapter presents the methodology used for field testing of the lane departure warning system with a wide variety of "typical" lane marking installations and environmental conditions.

5.2   Methodology

5.2.1   Evaluation Measures

The measures of performance used in this study for evaluating the effects of environmental conditions on LDWS performance are as follows.

- The main performance measure used in this study is the ratio of the number of instances the used lane departure warning device is able to provide lane crossing alarms to the number of all instances in which the equipped vehicle crosses the lane markings. This measure is referred to as "Efficacy Rate" or ER, in this paper.

- A second measure observed is the number of all instances per mile in which the test vehicle does not cross the lane markings and the lane departure warning system provides an alarm. This measure is referred to as the "Number of False Alarms" or FA, in this paper.

5.2.2   Test Sections

The LDWS performance, as indicated by the values of the measures of performance listed above, under different environmental conditions was evaluated on a 100 mile segment of the Florida Turnpike mainline and its Homestead extension between mile posts (MP) 16 and 116. The cross section of Florida's Turnpike between these two mile posts varies between four-lanes and six-lanes. It is a limited-access facility that passes through urban and suburban areas. The corridor includes lane markings with varying qualities and types as indicated in Table 1 with the marking age ranging between one year and more than four years and the retroreflectivity of the markings ranging between less than 100 mcd/m2/lux to higher than 500 mcd/m2/lux. A work zone between MP 81 and 88 provides an opportunity to investigate the performance of LDWS with bad markings associated with typical working zone settings. In addition to the Florida's

Turnpike mainline, on and off ramps with different horizontal curve radii were also included in the tests to determine the effects of sharp horizontal curvatures on LDWS performance. The curve radii were obtained based on Florida's Turnpike aerial photography.

5.2.3   Retroreflectivity Measurements

The retroreflectivity of the lane markings of each roadway segment was measured using the LaserLux mobile unit (*23*). Figure 5-1 shows the test section in South Florida. Figure 5-2 shows the vehicle and equipment used in the retroreflectivity measurement. The retrorefelctivity was measured by a contractor who is experienced with the use of Laserlux retroreflectometer. The measurements included the right white edge line, one skip line, and the left yellow edge line for both directions of the test highway section. LaserLux uses a scanning laser beam to scan the pavement marking roughly 32,000 times per hour, while traveling at highway speeds under all ambient light conditions. Results obtained using LaserLux retroreflectometers have been shown in previous studies to be within 5-10% of the results obtained using the LTL 2000 handheld devices with 30-meter geometry (*19, 23*). The device is able to measure nighttime retroreflectivity under daylight conditions using a laser beam to simulate the vehicle headlight.

A nation-wide search was conducted by the research team to identify qualified contractors to perform the retroreflectivity data collection using the LaserLux 30-meter mobile retroreflectometer. Four companies were identified. Each of the companies was contacted to discuss the scope of the work. Additionally, the following information was provided to these companies:

- The retroreflectivity readings should include the right white edge line, the right-lane skip line, and the left yellow edge line for each section.
- The mobile retroreflectometer should be calibrated with the manual handheld retroreflectometer.
- The data should be provided in a report format for easy reduction by the research team.
- The contractor must provide a write up explaining the procedure to be followed, data output format and cost information including the mobilization cost.
- The contractor must provide references to verify the quality of their work in previous contracts.

Based on the information provided by the contractors and the associated costs, the research team selected a contractor to perform the mobile retroreflectvity measurements for the project.

LaserLux was calibrated once per day based on the measurements of LTL 2000 30-meter geometry hand-held retroreflectometer. The data provided with the Laserlux mobile retroreflectometer was based on station intervals with average measurements recorded every 528 feet (0.1 mile). This distance was measured by a distance measurement instrument (DMI) installed on the mobile unit. As a result, there were ten readings for each one-mile test segment. The mean, standard deviation, and the 15th percentile of the retroreflectivity measurement along

the test section are shown in Tables 5-1. The standard deviation and the 15th percentile were obtained based on the 0.1 mile retroreflectivity measurements.

Figure 5-1: The Test Section of the Florida Turnpike in South Florida

Figure 5-2: Truck and Equipment Used in Retroreflectivity Measurements

Table 5-1: Characteristics of Lane Marking on the Florida Turnpike

Road	BMP	EMP	Marking Material	Marking Age (Years)	Marking Type	Northbound Retroreflectivity (mcd/m^2/lux)			Southbound Retroreflectivity (mcd/m^2/lux)		
						Mean	Std. Deviation*	15 Percentile*	Mean	Std. Deviation*	15 Percentile*
North-Bound	16	26	Thermoplastic (single drop bead)	3	Yellow	133	10	122	138	16	119
				3	White	280	47	232	287	56	242
	26	32	Thermoplastic (double drop bead)	1.5	Yellow	236	38	208	237	56	187
					White	391	87	297	426	100	339
	32	39	2 part polyester hi night visibility system (Glass and ceramics beads)	3	Yellow	314	94	202	370	56	315
					White	249	95	152	254	90	168
	39	44	Thermoplastic (single drop bead)	4.5	Yellow	96	21	81	86	27	64
					White	128	59	93	132	70	86
	44	47	Thermoplastic (double drop bead)	1	Yellow	195	53	148	269	20	249
					White	529	80	466	503	37	476
	48	50	Thermoplastic (single drop bead)	3 - 3.5	Yellow	110	17	99	115	43	89
					White	142	21	125	205	75	104
	50	54	Mixture		Yellow	92	9	84	76	9	68
					White	175	41	140	178	19	158
	54	63	Thermoplastic (single drop bead)	1 - 2	Yellow	143	28	98	128	23	100
					White	254	35	222	270	48	210
	63	75	Thermoplastic (single drop bead)	4	Yellow	129	31	110	144	17	128
					White	272	45	233	261	52	203
	75	81	Thermoplastic (single drop bead)	2	Yellow				146	26	122
					White	208	52	175	215	33	185
	81	88	Under construction, paint and thermoplastic in bad shape.	NA	Yellow	135	28	104	NA	NA	NA
					White				NA	NA	NA
	90	116	Mixture		Yellow	138	32	111	125	41	91
					White	172	44	120	180	49	125

5.2.4   LDWS Installation

As stated in Chapter 2, initially, two lane departure warning system products based on image processing were considered for use in this study. The AutoVue^{TM} lane departure warning system produced by Iteris, Inc. was selected for use in this study.   This selection was based on the higher number of commercial vehicles that were using this product or are experimenting with it at the time the decision was made. The device was installed on a pickup truck owned by the research team with the help of the LDWS manufacturer. The device was tested with the LDWS manufacturer present to ensure that it was working according to expectations.

Unfortunately, AutoVue ^{TM} is difficult to install on commonly available vehicles. In addition, it is difficult and costly to move the device to another vehicle, once it is installed.   The difficulty in installing AutoVue^{TM} made it necessary to rely on the Autovue ^{TM} manufacturer (Iteris) to provide the required installation of the device.   The manufacturer recommends using certain types of vehicles to minimize the installation and calibration times.   These include the F-150 pick-up truck, GM pick up truck, or SUV Equivalent.

One of the requirements of the selected vehicle is that it should be available to the research team during day and night and different weather conditions.   Based on the above requirements, the selected test vehicle used in this study was a 1993 F-150 Truck. An Iteris technician was paid to fly from California and install the device in the test vehicle. Figure 5-3 shows the selected test vehicle. Figure 5-4 shows the AutoVue^{TM} equipment installed in the vehicle.

5.2.5   Evaluating LDWS Performance

The test vehicle (the pickup truck with the installed LDWS) was driven on Florida's Turnpike between mile post 16 and 116 under different environmental conditions in both directions of travel, resulting in a total tested highway length of 200 miles. The right (white) and left (yellow) edge lines were intentionally crossed multiple times and the lane departure warning device performance was observed in terms of the ER and FA performance measures discussed previously. Each type of lane marking was crossed on average 10 times per mile in a given trip. Two persons were needed for the test: one for driving the vehicle and the second for recording the measurements.

The test performed in this study concentrated on the right white edge line and the left yellow edge line with some investigation of the skip line markings that separate the traveling lanes. The reason for concentrating on the edge lines is the fact that the main benefits of LDWS are the prevention of run-off-the-road accidents. The benefits from preventing sideswipe accidents due to unintentional lane change (crossing the skip lines) are very small in comparison. This is because a high percentage of sideswipe accidents occur as a result of intentional lane changing rather than unintentional lane changing maneuvers. In addition, sideswipe accidents are much less severe than run-off the road accidents. Other types of devices that can be classified as lane change/merge collision avoidance systems are effective in preventing intentional lane changing collisions.   Examples of these devices include rear and side-looking radar and vision-based cameras.

Figure 5-3: Test Vehicle Used in this Study

Figure 5-4: The AutoVue Device Installed in the Test Vehicle

The lane departure warning device was tested under different rain and lighting conditions. The rain levels in day and night rain were classified into three categories: light, moderate, and heavy as assessed by the persons conducting the test. It was not possible to quantify the amount of rainfall on a given segment of the highway during the test since the rain intensity was dynamically changing in space and time during the test. These conditions made any estimate of the rainfall from weather agencies insufficient for the purpose of this study. Further investigation of the rain intensity issue is presented in Chapter 7, which describes the testing of lane markings under a controlled environment.

5.3   Research Challenges

During the field studies conducted as part of this research, a number of difficulties were encountered. Below is a brief description of these difficulties:

- As discussed later in this paper, it was found that the main condition that affected LDWS performance were night rain. Thus, the researchers had to acquire additional detailed data for this condition. The researchers had to wait for these conditions to occur to test the device. The rainy season in Florida is the summer season. During this season, the days are long and it does not get dark until 8:30 – 9:00 PM. In addition, a high percentage of the heavy rain storms occur in the afternoon in summer, which reduces the opportunity of testing the device under rain and night conditions. Also, for safety reasons, the evaluation was not done under extremely severe weather conditions. Finally, Florida experienced a drought lasting for several months during periods of the project which affected the research progress.
- Lane markings are periodically maintained and replaced on the Turnpike. Thus, at some tested locations, the lane marking conditions were changed before the testing was completed.
- The manufacturer of the LDWS device, used in the study, specifies a limited number of test vehicle options, on which the device should be installed to work correctly. This limited the choices available to the research team resulting in the selection of a relatively old vehicle (a 1993 model) for use as the test vehicle.
- The research team had to keep track of the weather on the web and television channels to identify any adverse weather conditions that were suitable for testing the evaluated device. In many cases, the research team had to travel to the test locations, only to find out that the adverse conditions have already ended.
- The contractor that measured the marking retroreflectivity using LaserLux was not able to provide the retroreflectivity for the workzone section between MP 80 and 88. The lane markings in this section were in bad condition. It is estimated that the retroreflectivity of these markings was lower than 90 mcd/m2/lux based on the comparison of their night visibility performance compared to the visibility of other markings in the test section.

5.4   Study Results

5.4.1   Headlight Alignment

Initial tests showed that the ER of the evaluated device with respect to yellow lane markings (on the left side of the vehicle), on highway chapters with no roadway lighting, was very low during night dry conditions. However, crossing the markings on the right side of the vehicle were detected all the time (ER = 100%). After close examination, it was determined that the reason for this was that the headlights of the vehicle used in the test (a 13 year old pickup truck) were not properly aligned. The light beams were tilted to the right, thus the amount of light reaching the markings to the left of the vehicle was much lower than that to the right of the vehicle. After, correcting this problem, the ER of the markings under dry night conditions was 100% for most locations, as indicated in the following section.

5.4.2   Day Light Conditions

5.4.2.1   Dry, Light Rain, and Moderate Rain

The ER of the evaluated device was 100% during dry, light rain, and moderate rain conditions during day light for most highway sections. The exception for this was the ER for the yellow markings between mile post (MP) 39 and MP 44 and between MP 85 and 88, in both directions of travel. The efficacy rates for these two segments ranged between 0% and 40% depending on the tested sections. As seen in Table 5-1, the retroreflectivity of these markings were 102 mcd/m^2/lux or lower. The minimum acceptable retroreflectivity (the retroreflectivity at the end of the service life) of thermoplastic and paint markings according to the FDOT standards is 150 mcd/m2/lux. Thus, these installations have exceeded the marking service lives. It should be recognized that the retroreflectivity of lane marking plays a role in marking visibility only in night conditions. However, markings with very low retroreflectivity due to aging (as is the case in the two sections under consideration) are expected to score low in other physical attributes that affect day light visibility. In this case, the physical attribute that is believed to influence the LDWS performance in day conditions is the contrast between the markings and pavement. The FA values on all tested freeway mainline segments during dry, light rain, and moderate rain conditions were zero.

5.4.2.2   Heavy Rain

Except for the two highway segments with the bad lane markings previously identified, the ER of markings was 100% for heavy rain day conditions. However, in few instances when the rain was extremely heavy and the visibility dropped to unacceptable levels to human eyes, the ER with respect to yellow lane markings dropped by only 10%-15%, resulting in ER values ranging between 85% and 90%. The ER of the LDWS with respect to the white edge and skip markings was 100% for all investigated locations in heavy rain day conditions.

There were false alarms during and in the aftermath of heavy rain. In these cases, longitudinal areas of water on the pavement were confused by the evaluated device to be lane

markings, resulting in false alarms when crossed. It is estimated that during these conditions, the numbers of false alarms were between 0.5 and 1 alarm per mile.

5.4.3 Dusk Conditions

During sunrise and dusk conditions, the sun can be very bright and close to the horizon, thus affecting driver visual abilities. This study evaluated the effects of these conditions on the performance of LDWS. This evaluation was performed on two westbound segments of limited access facilities in Broward County, FL. The first segment is on I-595 and the second is on the Sawgrass Expressway. Table 5-2 indicates that the ER dropped from 100% to 82%-85% due to dusk conditions on the two segments. No false alarms were observed during these conditions.

TABLE 5-2: Efficacy Rates for Dusk Conditions

Corridor	Number of Marking Crossing	No. of Alarms	No. of missed Alarms	ER
I-595 WB	39	32	7	82%
Sawgrass Expressway WB	40	34	6	85%

5.4.4 Night Conditions

5.4.4.1 Dry and Light Rain Conditions

The ER of the LDWS during night dry and light rain conditions was 100% for both the yellow and white lane markings on all investigated segments, except the segment between MP 81 and MP 88. On this segment, which had a work zone with poor quality lane markings, the ER with respect to yellow lane markings was low, ranging between 0 and 40%. It is interesting to note that the LDWS did not have a problem detecting the yellow lane markings between MP 39 and MP 44 in both directions of travel, although it was not able to detect them during day light conditions. It appears that the low retroreflectivity of lane markings at this segment (ranging between 82 and 102 mcd/m^2/lux) was sufficient for LDWS detection of lane marking during night dry and light rain conditions, but the low contrast between the markings and the pavement prevented this detection in day light. No false alarms occurred for all highway segments during night dry and light rain conditions.

5.4.4.2 Moderate and Heavy Rain Conditions

Of all the conditions investigated, significant reductions in ER values occurred during night moderate and heavy rain conditions. Figures 5-5 and 5-6 present the relationship between the lane

marking retroreflectivity and LDWS ER for yellow and solid white lane markings, respectively, for moderate and heavy rain conditions. As seen in Figures 5-5 and 5-6, during heavy rain conditions, the ER with respect to yellow markings ranged between 0% and 60% with most of the measurements below 30%. For moderate rain, the ER values varied between 0% and 80% with most of the readings between 20% and 60%. The variation of ER for a given retroreflectivity was larger for moderate rain compared to heavy rain conditions. For moderate rain conditions, it was observed that the ER measurement was lower when the measurement was made after it had been raining long enough that the marking was covered with water, thus reducing marking visibility and the ER significantly. If the moderate rain had just started and a large proportion of the marking was not covered with water yet, then the ER could be as high as 60% to 80%. In the case of heavy rain, the rain can cover the markings quickly resulting in a significant drop in marking visibility and affecting LDWS performance.

It can be observed from Figures 5-5 and 5-6 that, in general, the ER seems to be higher on average for markings with higher retroreflectivity measurements. Regression analysis was performed to investigate the relationship between ER and lane marking retroreflectivity. A number of linear and non-linear forms were investigated for the relationships between these two variables. The best identified models based on the adjusted coefficient of correlation and t-statistic P-value is presented in Table 5-3. As can be seen from this table, the adjusted coefficient of correlation (Adjusted-R) is higher for heavy rain than for moderate rain. The R-square is 0.57 and 0.67 for yellow markings and white markings, respectively, for heavy rain indicating that there seems to be a significant relationship between LDWS performance and retroreflectivity.

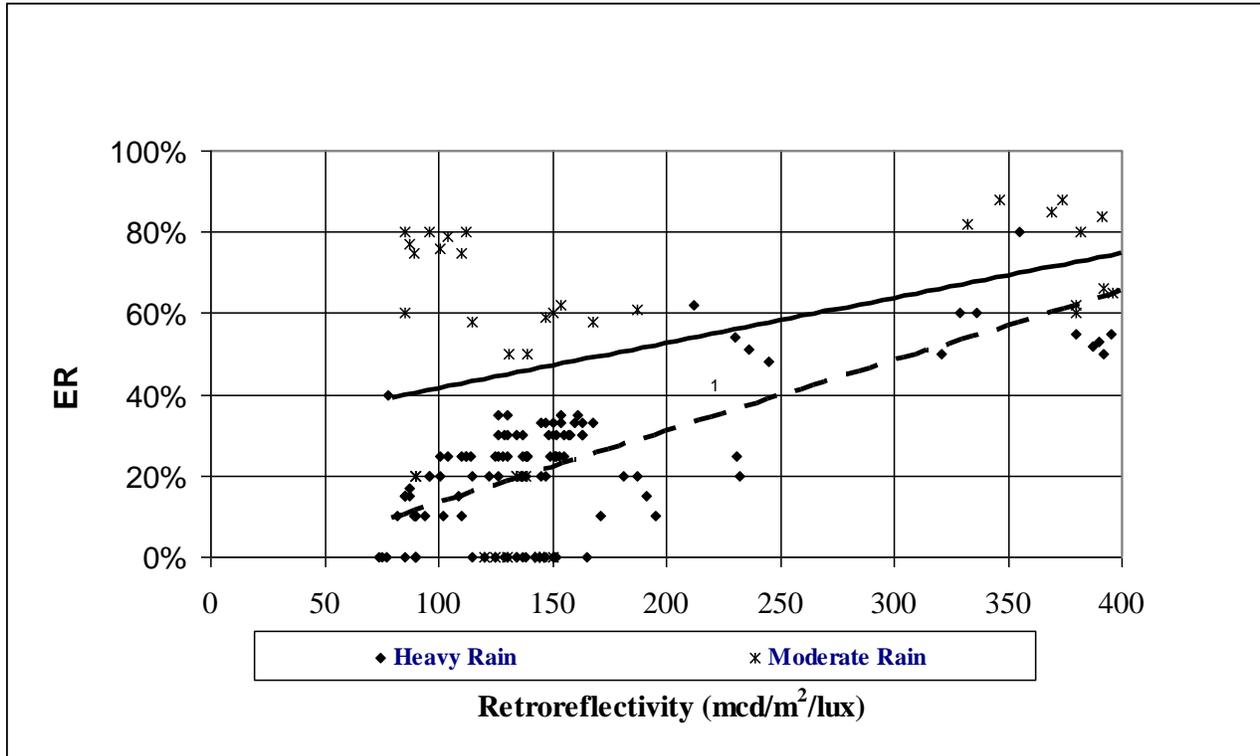**FIGURE 5-5: Relationship Between Efficacy Rate and Yellow Marking Retroreflectivity Measurement for Night Conditions.**
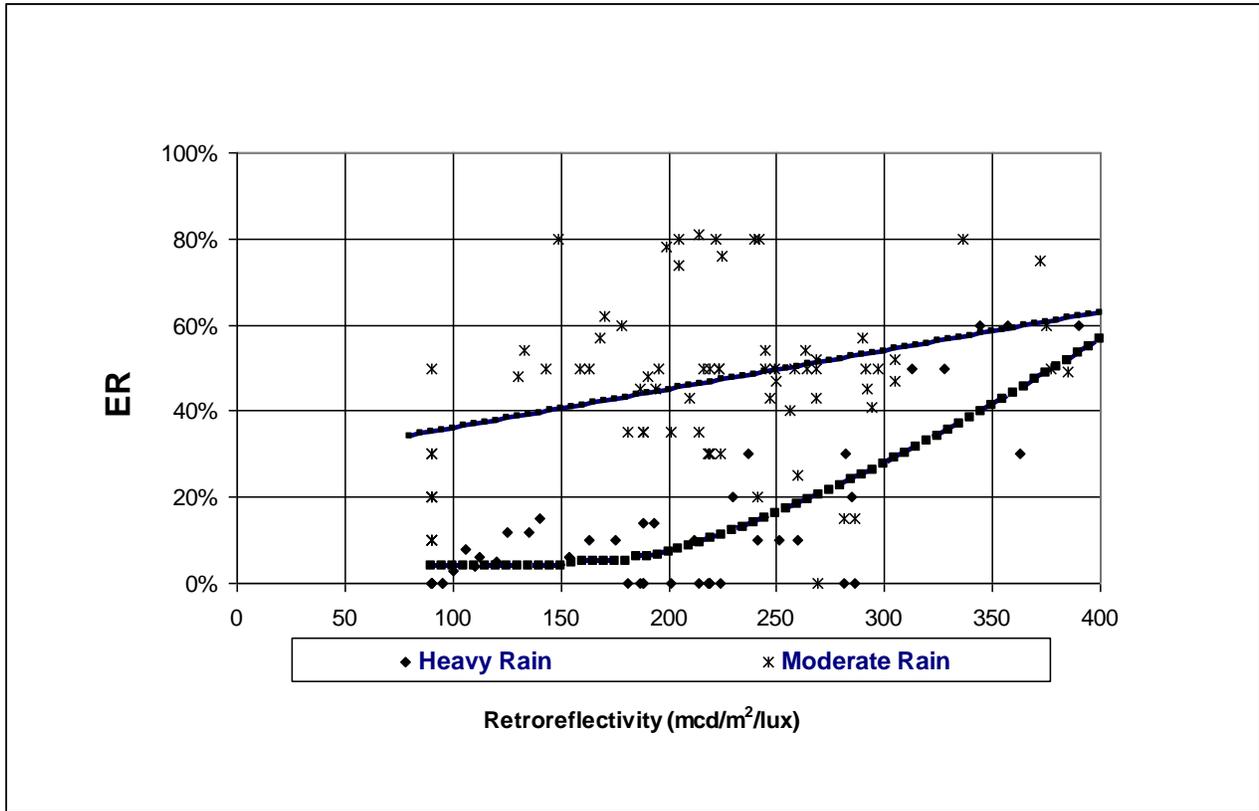
FIGURE 5-6: Relationship Between Efficacy Rate and Solid White Marking Retroreflectivity Measurement for Night Conditions.

TABLE 5-3: Derived Relationships between Retroreflectivity and Efficacy Rates

Condition	Marking Type	Derived Model	Adjusted-R
Heavy Rain /Night	Yellow	$EfficacyRate = 0.00342 \times R - 0.036\sqrt{R} + 0.1468$	0.57
	Solid white	$EfficacyRate = 0.00774 \times R - 0.17075\sqrt{R} + 0.9929$	0.67
Moderate Rain/Night	Yellow	$EfficacyRate = 0.00139 \times R + 0.262$	0.15
	Solid white	$EfficacyRate = 0.00089 \times R + 0.2703$	0.13

Note: In the derived models, R is the lane marking retroreflectivity. Both R and ER used in the regression analysis were recorded per mile.

5.4.5   *Effect of Roadway Lighting*

To determine if roadway lighting has an effect on the ER, the presence of roadway lighting was used as a categorical independent variable in addition to retroreflectivity in regression analyses. The results indicated that there was no significant relationship between the ER and roadway lighting, as indicated by the lack of increase in the adjusted R value of the model when this variable was installed and the low t-statistic P-value for this variable in the model. These results confirmed the general field observations that roadway lighting does not have a positive impact on LDWS performance.

5.4.6   *Horizontal Curves on Ramps*

To investigate the effect of sharp horizontal radii on LDWS performance, the device was evaluated on Florida's Turnpike on-ramps and off-ramps with radii that vary between 213 ft and 620 ft. The radii were measured electronically based on Florida's Turnpike aerials saved in AutoCad file format. The results, presented in Table 5-4, indicate that the ER ranged between 0% and 100%, depending on the ramp radius. For those ramps on which the ER was low (0% to 25%), the evaluated device gave frequent false alarms.

TABLE 5-4: Efficacy Rates on Ramp Curves

Ramp Location	Radius (ft)	ER (%)
NB I-595 to Turnpike	450	100
NB Sunrise off-ramp	213	0
NB Sunrise on-ramp	332	30
NB Commercial off-ramp	294	40
NB Sample Road On-ramp	409	75
NB I-10 off-ramp	620	100
NB I-10 on-ramp	620	100
NB Glades Road on-ramp	278	0
NB Glades Road off-ramp	450	70

5.4.7   *Pavement Contrast*

In addition to the low ER on the two highway segments mentioned above, it was observed that the ER measurements with respect to yellow lane markings on a number of bridges were also 0%. In the investigated highway sections, these bridges are short and range in length between 50 ft to 100 ft. The reason for the bad performance of the evaluated device with respect to yellow lane markings on these bridges is the low contrast between these markings and the concrete pavements that are used on the bridges. Asphalt pavements are used on other scetions of the Turnpike.   This issue is discussed further in Chapter 6.

5.4.8   *Effect of Marking and Pavement Age*

Pavement markings deteriorate with time. Ultraviolet light and heat from the sun can deteriorate the binder, releasing the beads. In addition, abrasion from traffic, sand, and snowplows can wear off the beads. The rate of degradation of pavement marking and the loss of retroreflectivity due to bead loss is affected by the type of lane marking, traffic volume, heavy vehicle percentages, environmental conditions, and quality control in applying the marketing material. For example, the service lives of pavement markings, as measured by the retroreflectivity falling below an acceptable threshold, are estimated to be one, three, and six years for paint, thermoplastic, and waffle tape markings, respectively (*28).* Migltetz et al. (*35*) estimated the durability of markings using statistical regression analysis. The derived models provide estimates of the retroreflectivity of each type of marking material, marking type, and marking color as functions of cumulative traffic passages.

As stated above, the performance of LDWS during night rainy conditions is significantly affected by lane marking retroreflectivity, which is a function of marking material, age and amount of traffic passages. In addition, as discussed above, at locations with bad contrasts between old markings

and pavements, the evaluated device did not work well in day light conditions. Thus, it is expected that LDWS performance will be affected adversely by the presence of old markings with low color contrast and low retroreflectivity.

5.5   Conclusions

The results presented in this chapter indicate that in most cases the ER of the LDWS under dry and light rain conditions is 100%. It was found that performance of LDWS of lane markings is affected significantly by heavy rain conditions at night for typical lane marking installations. With heavy rain night conditions, most of the observed ER values are between 0 and 30%. It appears that the ER at night rain conditions increases with increased lane marking retroreflectivity. Very heavy rain conditions during day light results in only a low impact on ER with a maximum drop under blinding rain conditions of about 20%. Dusk conditions were found to reduce the ER of LDWS by 15% to 18%. At few locations, with yellow lane markings that are the end of their service lives or yellow markings on concrete pavements, LDWS had difficulty detecting the markings due to the low level of contrast between the yellow markings and the pavement.

Chapter 7 presents the results of an investigation that was conducted as part of this study to compare the performances of the LDWS when using improved pavement markings under rain night conditions in a laboratory environment.

6.   Effect of Pavement and Pavement Marking Colors

6.1   Background

As discussed in the previous chapter, the field test of existing lane markings on Florida's Turnpike indicated that the ER during daylight was 100% under dry, light rain, and moderate rain for most segments of Florida's Turnpike test section. The exceptions to this were the ER values of the yellow markings between mile post (MP) 39 and MP 43, which was 0% during dry daylight conditions and between MP 85 and 87 (in both directions of travel), which was 40% (MP 85 to MP 87 were located within a work zone). It was noted that for both of these segments, the contrasts between the pavement markings and pavement appears to be less than those observed for other segments. These segments are paved with asphalt, as is the case with all other Florida's Turnpike segments that are not located on bridges.

In addition to the low ER on the two highway segments mentioned above, it was observed that the ER was zero percent with the yellow lane markings on a few short (about 100 ft long) Florida's Turnpike bridges. The pavements used for Florida's Turnpike bridges are concrete pavements. The concrete pavements of these bridges were light in color and had a low contrast with the markings compared to other roadway sections.

In the cases mentioned above, the marking visibility seemed to be acceptable from the human eye point of view. However, the tested system hardware and software appeared to have problems distinguishing between the markings and the background pavements.

The above discussion indicates that the tested LDWS device had problems on only a limited number of segments of Florida's Turnpike for both asphalt and concrete pavements. As stated above, the tested highway section had a total length of 200 miles. The total length of the sections that had low LDWS ER was about eight miles, with 4 of these miles were within a segment that is a part of a work zone. This represents only 4.0% of the total length of the tested section.

To study the extent and nature of the low daylight ER due to pavement/marking colors, it was necessary to test the LDWS performance on long highway sections of different facility types and with different pavement types and ages. This test was conducted in two states (Texas and Florida), allowing the consideration of variations in the colors of pavement and marking materials used in these two states.

6.2   Pavement Color

As described above, The LDWS performance under daylight conditions is expected to be a function of the degree of contrast between the pavement marking and background pavement. This contrast is a function of pavement and marking colors. In addition, it is expected to be a function of the LDWS hardware and image processing software.

Asphalt is the dominate type of pavement in Florida. However, in other parts of the United States, including Texas, concrete pavements are more frequently used. This chapter presents a discussion of the factors affecting the pavement color of both asphalt and concrete pavements.

It should be mentioned that a quick search of the Internet indicates that pavement color is one of the issues sited by advocates of asphalt and concrete pavements to promote these types of pavement. Asphalt pavement advocates have argued that compared to concrete pavement, "the dark color of asphalt reduces glare, helps melt ice and snow, and provides a high contrast for lane markings." On the other hand, the advocates of concrete pavements have argued that the light color of concrete compared to asphalt helps urban areas stay cooler with the ambient temperatures to be an average of 15°F lower on concrete than asphalt pavements. In addition, they argued that the light-color concrete pavements reflect more light and therefore provide better visibility in all types of weather and also require less energy to illuminate highways and roadways at night. The above discussion implies that asphalt pavements are darker than concrete pavements and thus can provide better contrasts with pavement markings. However, as indicated in the discussion below, this is not totally true, since the pavement color depends on a number of factors including age, aggregate color, cement color, and cement proportion.

6.2.1   Asphalt Pavement

Asphalt concrete pavement, also referred to as flexible pavement, consists of three components: asphalt, aggregates, and other additives that are used to improve the pavement performance (such as lime, cement, polymer, fiber, etc). The color of the asphalt pavement depends on the color of these three components.

Asphalt itself is black. The black color of asphalt comes from Asphaltens, one of the main components of asphalt. Pigments can be added to asphalt mixture to change its color but this is not widely done because of cost. When first constructed, aggregates are entirely surrounded by asphalt and the pavement's color is the asphalt color, which is black. This black color provides for a very high contrast between the pavement and pavement markings. This black pavement color remains for a short period of time that varies in length depending on the environmental conditions (sun, rain, dust, snow) and traffic characteristics (total traffic volume and axle loads). With time, the aggregates start to strip from the pavement surface and the pavement color starts to be increasingly affected by the aggregate's colors. The aggregate's color depends on the type, source, mineralogy, and percentage of silica in the aggregates. For example the color of basalt is generally dark and varies from gray to black. Granite usually has a light color that varies

widely (white, red, blue, etc.) depending on the factors mentioned above. For example in Florida, limestone (almost white in color) is widely used to produce hot mix asphalt.

The above discussion indicates that for asphalt pavements, the color of pavement as it ages change from black to a color that depends on the used aggregates. If dark aggregates are used then the pavement remains relatively dark. If light-color aggregates are used, then the pavement color changes to a light color.   Depending on traffic and environmental conditions and the color of aggregates, the asphalt pavement color can become very light after two to four years after construction. Table 6-1 shows the colors of most-widely used aggregates (*41*).

Additives that are added to change the performance or color of the pavement have different effects on colors depending on the particular additive used.   For examples, Ferrooxide a pigment additive change the pavement color to a reddish color. Sulfur based additives change the color of the asphalt to a lighter color. Antistriping agents, Polymers, and Elastomers affect the time of changing from dark to light color with age because these additives improve the bitumen properties resulting in the bitumen color remaining on the surface longer. The lime and cement additives can make the pavement surface color even lighter after surface abrasion with age.

I wrote something about that from in my mind and experience. I hope it wold be help to you. And I will be at the University on Monday. If you need any more comments, let me know I will try to write something

As mentioned in Chapter 3 of this report, FC-5 "open grade or popcorn mix" is currently used by FDOT for resurfacing projects. The use of FC-5 has reduced pavement marking visibility due to the lack of contrast between the lane markings and pavement due to the light color of pavement.

Table 6-1: Pavement Aggregate Colors (Source: References 41)

Definition of Mineralogy	Color
Limestone	Changes of color from dark wine-colored to gray
Dasit	Gray, red, black, white, yellowish, brown
Andezit	Dark color, a little bit grayish and pinkish, however usually dark color but its is color lighter than the basalt and it would be gray.
Bazalt	Usually black
Granite Group Stones	
Gabro	Black, looks like basalt, amount of the mineral with light color is little, quartz is not or is a little in it.
Diorit	*

Diyorit with quartz	*
Tonolit	*
Granodiyorit	*
Monzolit	*
Granite	*
Alkali feldspar granite	Usually dark gray, like a fresh meat color

*In the granite group stones, the color of the gabbro is the lightest and the alkaline feldspar is the darkest

6.2.2   Concrete Pavement

Portland cement concrete pavements consist of two components: cement and aggregate. The color of a concrete pavement is a function of the aggregate materials that are used in the concrete mix, the cement type, and the percentage of cement in the mixture.

The composition of the used Portland cement is what distinguishes the color of one type of cement from another. The components of Portland cements are tricalcium silicate (C3S), dicalcium silicate (C2S), tricalcium aluminate (C3A), and tetracalcium aluminoferrite (C4AF). C4AF is the component that has the main effect on cement color. If the amount of the C4AF increases, the color of the concrete gets darker. In general, the proportion of C4AF depends on the raw materials used by the cement factory. Thus, cement produced at different factories and at different time periods at the same factory have different colors, depending on the compositions of the used materials.

The second factor that affects concrete color is aggregate color. As described in the previous chapter, aggregate colors vary widely depending on the type, source, mineralogy, and percentage of the silica in the aggregate (see Table 5-1). Furthermore, fly ash and slag have been use as concrete additives to increase durability. These additives tend to make the concrete lighter in color. Unlike asphalt, the color of concrete does not change significantly after the first 28 days of installation.

6.3   *Marking Color*

Two standard colors are used for pavement lane markings (yellow and white). Black may be used in combination with other colors to increase the contrast on light-colored pavements. In December 1999, FHWA published a Notice of Proposed Rulemaking to revise its color specifications for retroreflective signing and pavement-marking materials (Docket No. FHWA 99-6190). The proposed color specifications provide requirements for daytime and nighttime color of markings. In January 2001, the American Society of Testing Materials (ASTM) issued Standard Specification D6628-01 (*42*) that addresses

the daytime and nighttime color of retroreflective pavement-marking materials. These requirements apply throughout the marking service life.

Various transportation agencies have specifications addressing the colors of yellow and white markings. Marking materials are to remain opaque and maintain their color under both daylight and artificial light. They are not to discolor under exposure to weather or traffic or show discoloration through the service life on either asphalt or concrete pavements (*43*). For example, VDOT specifies that white waterborne paint shall be equal to Federal Standard Color No. 595-17886, and yellow shall be equal to Federal Standard Color No. 595-33538 ("Paint Pavement Marking Material" 2000).

A spectrophotometer can be used to measure the marking chromaticity. Yellow can also be subjectively evaluated using a yellow color tolerance chart. The chart has seven color chips that cover the range of acceptable limits for yellow. It is placed on the yellow marking to determine if the color is within the acceptable range. Another subjective evaluation can be done using a "color visual effectiveness rating" on a scale of zero to 10, with 10 representing a new properly applied marking (*44*).

6.4   Field Test

The test vehicle equipped with the LDWS device was driven on Houston and College Station, Texas roads and the routes that connect these two cities. The driven route is presented in Figure 6-1. In addition, the test vehicle was driven in South Florida, along a variety of highway segments. The attributes of the driven highway segments in Texas and Florida and the results of driving on these segments are presented in Tables 6-1 and 6-2, respectively.

Below is a summary of the results presented in these tables:

- In general, the tested device did not have problems detecting white pavement markings even for light pavements and faded markings.

- The tested device did not have a problem detecting the yellow markings on brown, medium gray and dark gray colored asphalt and concrete pavements. In some cases, it was able to detect very bad and faded yellow markings on these pavements.

- In both Texas and Florida, the device was able to detect yellow markings on most concrete pavements. It was not able to detect the markings on a four mile section of light gray concrete pavement in Houston, Texas and a number of very short span (less than 100 ft) bridges with light color concrete.

- In Texas, the device was not able to detect the yellow markings on segments with light gray (old) asphalt pavements. These include 10 miles on Highway 6, 15 miles on Highway 105, and a short segment (about a mile) on Highway 2818.

- In South Florida, the device was not able to detect the yellow markings on segments with light gray (old) asphalt pavements. This included an eight mile segment on Florida's Turnpike (see Section 6-1 above) and short segments on secondary roads, As can be seen, the total lengths of the segments that had problems detecting yellow markings was lower in South Florida compared to Texas.
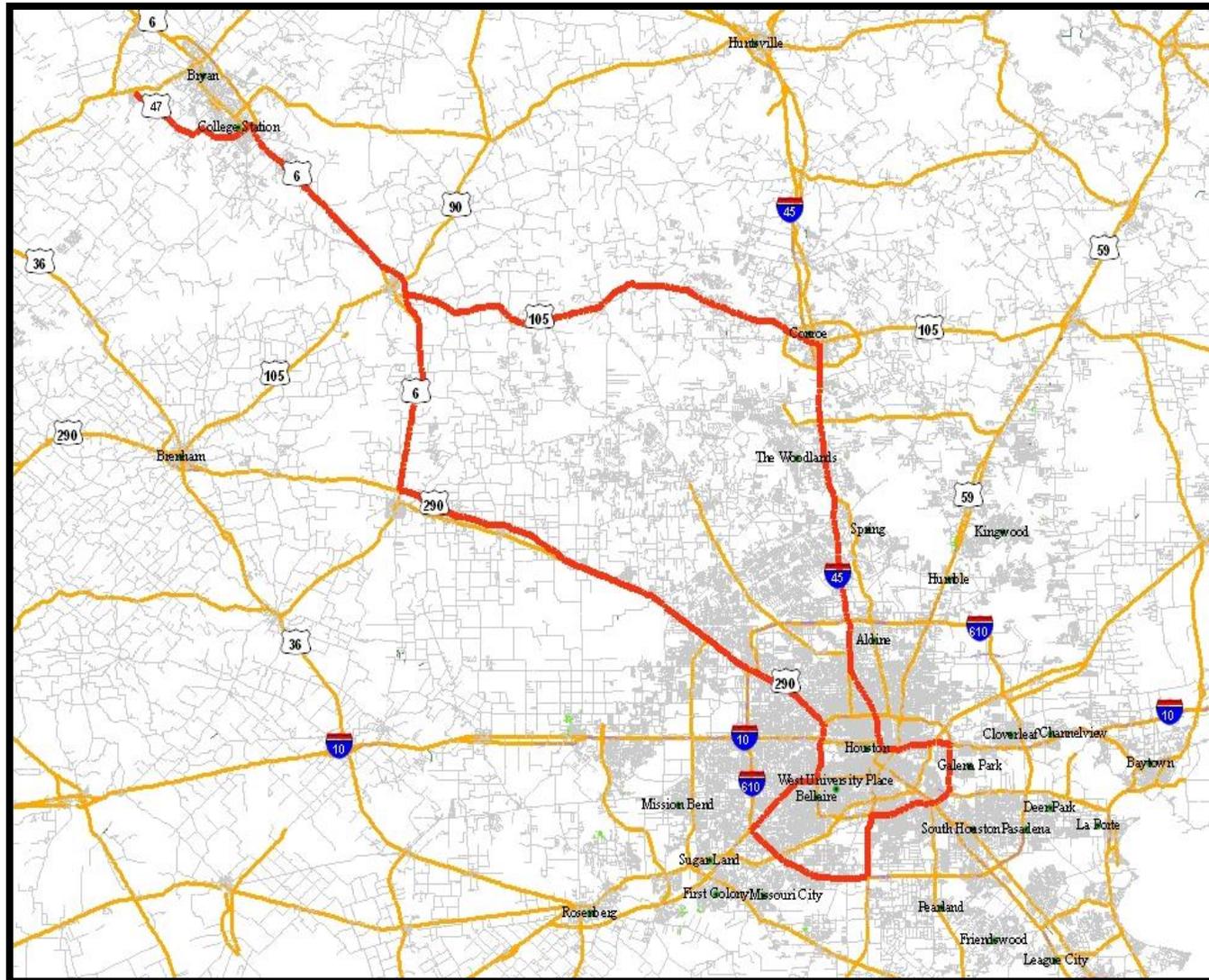
Figure 6-1: Test Route in Texas

Table 6-1: Results of the Texas Test

Area	Roadway	Highway Type	Pavement Type	Test Results
College Station	Highway 47	Four-Lane divided Rural	Asphalt on general segments. Bridges paved with brownish color concrete.	100% detection rate on both the asphalt and concrete pavements
	Highway 2818	Four-lane divided Rural	Medium to dark gray asphalt pavement in general segments. A small segment of the road (about a mile long) is light colored.	Yellow not detected on the light asphalt segment.
Route Between College Station and Texas A&M	Highway 6 (College station to just before Business 6)	Rural freeway	Medium gray asphalt pavement on roadway segments and concrete on bridges	All markings detected
	10 miles of Highway 6 from just before Business 6 junction	Rural freeway	Light asphalt pavement	Yellow not detected
	Rest of Highway 6 up to US 290	Rural freeway	Black asphalt pavement (new)	All markings detected
	US 290 in Route To Houston	Freeway (rural outside Houston changing to	Concrete pavement with most of the pavement either brownish or medium gray except a 4 mile section with light gray.	Detected all markings except the yellow on the 4 mile segment with light gray concrete pavement just south of Mueschke Road. Note that a long segment of US 290 has a black

Area	Roadway	Highway Type	Pavement Type	Test Results
		urban in greater Houston)		thick line of dark material that lies parallel to the yellow and white solid markings.
	Loop I-610	Urban Freeway	Concrete pavement with brownish color and at other locations medium gray	All markings are detected, even very bad white and yellow markings that appeared to have worn down. This indicates that the pavement color plays a major role in the contrast.
	Loop I-610	Urban Freeway	A short segment light gray concrete with good markings about one mile length	Yellow not detected.
	I-45 north from Loop I-610 to Highway 105	Urban Freeway	Concrete pavement brownish at a few chapters and medium gray at others	Detected all markings even though at several locations markings were observed to be extremely faded and narrow.
	Highway 105 from I-45 to Montgomery	Four-lane urban highway	New concrete pavement medium gray	Detected all markings.
	Highway 105 from Montgomery to Highway 6	Two-way two-lane	Asphalt with light gray color	Detected extremely light white marking even segments with highly faded pavement. Did not detect yellow.

Table 6-2: Results of the Florida Test

Area	Roadway	Highway Type	Pavement Type	Test Results
Fort Lauderdale	NE 12th Street,	Four-Lane undivided urban	Medium gray asphalt	All markings detected
	I-595	Urban Freeway	Medium gray concrete	All markings detected
	A1A	Urban two-way two lane	Medium gray asphalt	All markings detected
	Prospect Road	Urban two-way two lane	Medium gray asphalt	All markings detected
	NE 56th Avenue	Two-way two-lane urban	Medium gray except a small chapter with light gray pavement with faded markings	The device did not detect the faded yellow markings on the light pavement. The markings were yellow skip markings.
Between Miami and Fort Lauderdale	US-27	Four-lane undivided Rural	Medium gray Asphalt	All markings detected
	Florida Turnpike200 mile (100 mile per direction	General segment	Medium gray asphalt except few locations with light gray	All markings detected except at two locations with light pavements as discussed in Chapter 6.1.
	Florida Turnpike Short span bridges	Florida Turnpike Bridges	Light to medium concrete	Yellow markings not detected on bridges with light color concrete.

Area	Roadway	Highway Type	Pavement Type	Test Results
Miami	FIU main campus	Two-way two-lane	Asphalt medium gray pavement with bad markings	Marking detected
	NW 117 Avenue near FIU	Urban two-way two	Asphalt light gray with very bad markings	Skip yellow markings not detected.
	Cross Street near International Mall, Miami	Urban two-way two	Asphalt light to medium gray	Yellow detected on the medium gray but not on the light gray
	I-95	Urban freeway	Medium gray concrete	All markings detected

6.5   *Result Analysis*

As discussed in the previous chapter, it appears that the tested device had problems detecting yellow markings on light gray concrete (mainly concrete with light-color cement) and light gray asphalt (old asphalt with light aggregate). An attempt was made to associate the inability of detecting the yellow marking with a quantifiable measure of the pavement and marking colors. This section discusses the results of the analysis.

During the field tests digital pictures were taken of the pavement markings and background pavements and stored with records indicating whether the LDWS was able to detect the markings or not. Examples of the detected and undetected pavement markings for concrete and asphalt pavements are shown in Figure 6-2.

The human visual system breaks the visible spectrum into its most dominant regions of red, green, and blue. These dominant colors in different combinations and at varying levels of intensity produce the full range of color. The three dominant colors are used by computer software as the basis of composing and analyzing colors. In this study, measures of the average intensities and standard deviations of the three colors for the pavement marking and background pavement were analyzed based on the digital pictures of the markings and pavements. These measures were then related to the LDWS ability to detect the pavement markings, as explained below.

The captured digital pictures were analyzed using the Adobe Photoshop software. Both the pavement and yellow marking portions of the pictures were analyzed. For the analyzed portions, standard histograms of the three dominant colors (the red, blue, and green) were produced by the software. Figure 6-3 shows examples of the analysis of pavement and marking colors for two locations with asphalt pavements. In the first location, the LDWS was able to detect the markings. In the second, the LDWS was not able to detect the markings. The histograms illustrate how the three colors in an image region (the pavement region and the marking region) are distributed by showing the number of pixels at each color intensity level for each of the dominant colors.   In addition, the software produced statistics of the analyzed picture regions including the mean and standard deviation of each of the three colors. These statistics were used in obtaining two measures that were related to the detection ability of the LDWS. These measures were selected from a number of measures that were investigated in the study.

The first measure is the ratio between the sum of the average intensity of the green plus red colors of the pavement to the sum of the red plus green for the marking. Mathematically, this can be expressed as follows:

$$\text{YCR} = \frac{\text{R}_P + \text{G}_P}{\text{R}_m + \text{G}_m} \qquad\qquad (6\text{-}1)$$

(a) Concrete on US-290, TX (Undetected)   (b) Concrete on US-290 Texas (detected)   (c) Concrete on I-595, Florida (detected)
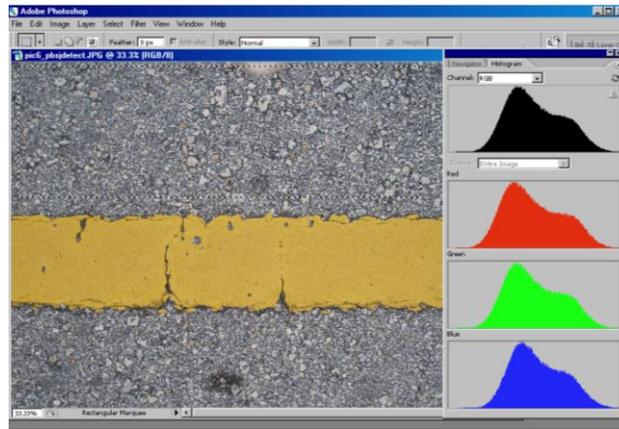

(d) Asphalt on Highway 6, TX (Undetected)   (e) Asphalt on NW 12 Av., FL (detected)

Figure 6-2: Examples of Detected and Undetected Yellow Pavement Markings on Concrete and Asphalt Pavements
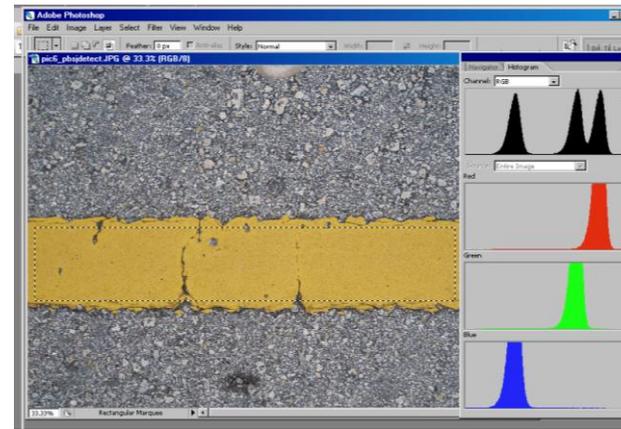
a. Pavement   b. Marker
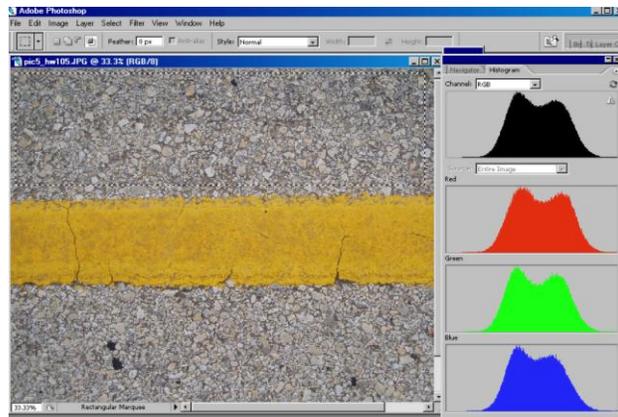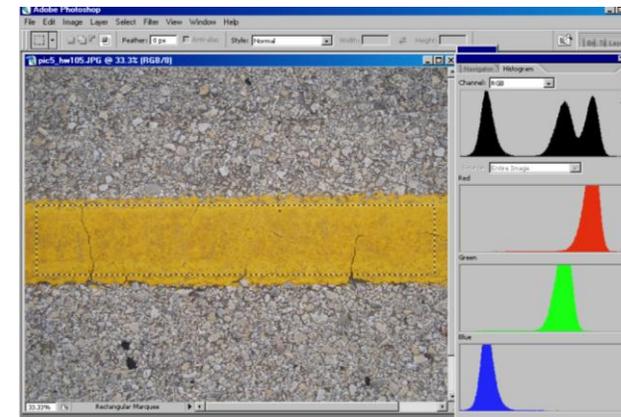
(a) Detected Markings

a. Pavement   b. Marker

(b) Undetected Markings

Figure 6-3: Example of the Picture Analysis of Pavement and Marking Colors Using Adobe Photoshop

Where:

YCR = Yellow Color Ratio,

R_p = Mean of Red Color Intensity of the Pavement,

G_p = Mean of Green Color Intensity of the Pavement,

R_m = Mean of Red Color Intensity of the Marking, and

G_m = Mean of Green Color Intensity of the Marking.

The YCR measure was selected because red and green when combined produces yellow. If the ratio of the intensity of the yellow color (sum of the intensities of red and green color) in the pavement to the intensity of the yellow color in the marking is high, it is expected that the pavement color is closer to yellow and the yellow marking is "less" yellow, resulting in low contrast between the two. This, in turn, is expected to result in a higher probability that the markings are not detected by the LDWS device with higher YCR.

A second measure that was used is the Standard Deviation Sum (SDS) that reflects the combined standard deviations of the three dominant colors in the pavement and pavement marking colors, as expressed below:

$$SDS = \sqrt{\sum_i \sigma_{ip}^2 + \sum_i \sigma_{im}^2} \tag{6-2}$$

Where:

SDS = Standard Deviation Sum

σ_{ip} = Standard deviation of color i (red, green, and blue) for the pavement

σ_{im} = Standard deviation of color i (red, green, and blue) for the marking

The reason for selecting this measure is that the standard deviations are measures of the variation in color across the pavement and also across the pavement marking surfaces. It is believed that, as pavement (particularly asphalt) and markings deteriorate in quality with age, their standard deviations increase.   This is particularly true for the asphalt pavement since old asphalt pavements have high variations in color across their surfaces reflecting the difference between the aggregate and asphalt colors, as described in Section 6.2

Figures 6-4 and 6-5 show the YCR and SDS for detected and undetected markings. As indicated in these figures, the LDWS ability to detect markings in dry day light conditions can be related to the YCR. For asphalt pavements, locations with undetected markings also had high SDS values, as indicated in Figure 6.5.
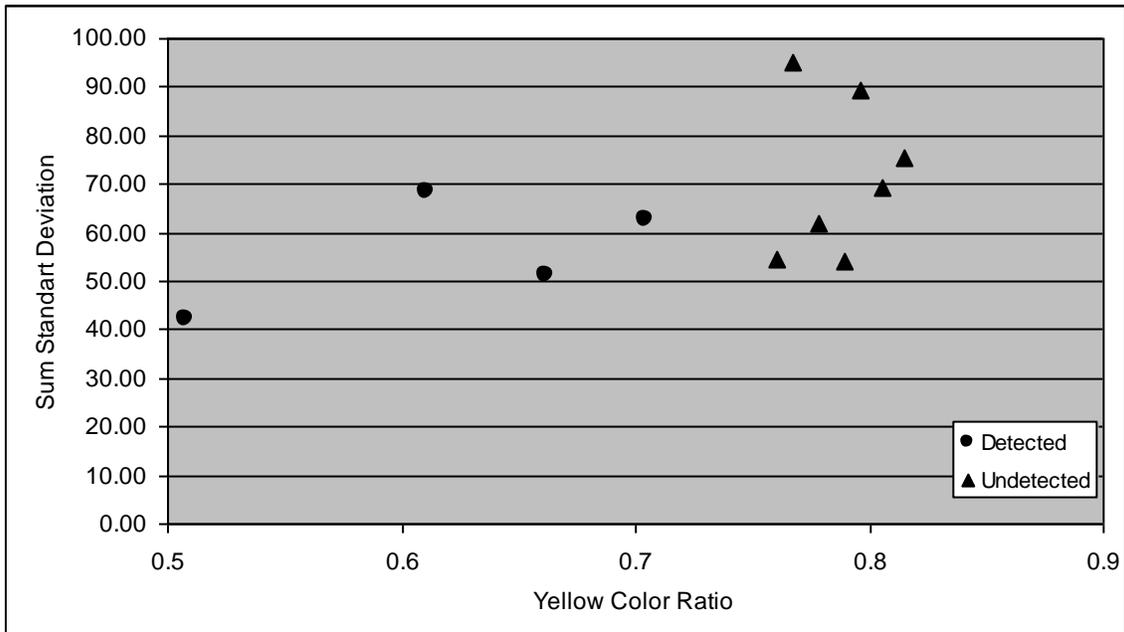
Figure 6-4: Relationship between the Measures of the Yellow Color Ratio and Standard Deviation Sum of Colors for Asphalt Pavements
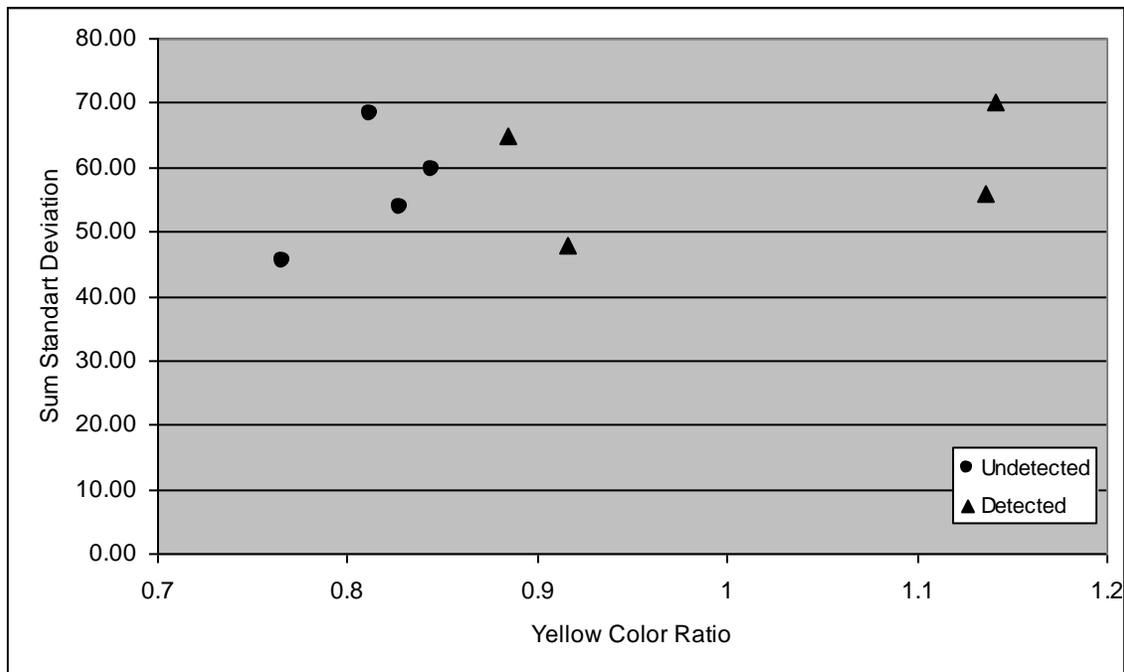
Figure 6-5: Relationship between the Measures of the Yellow Color Ratio and Standard Deviation Sum of Colors for Concrete Pavements

6.6   Conclusions

Based on the results presented in this chapter it can be concluded that the tested lane departure warning system device was able to detect the pavement markings at most tested sections during day light conditions. However, for a few highway segments with light concrete and asphalt pavement colors, the device was not able to detect the yellow markings. Based on image analysis of the digital images taken of the pavement markings and background pavements, it can be concluded that the inability to detect the yellow markings can be related to attributes of the pavement marking color and pavement color, as measured by the dominant marking colors (red, green, and blue).

7.   Evaluation of Improved Marking

7.1   Introduction

As stated in the previous chapters, the research team evaluated the lane departure warning device on a long section of Florida's Turnpike under different weather and lighting conditions. The test results showed that although the device performs well under most combinations of weather and lighting conditions, the main deterioration in its performance occurs during rainy night conditions and to a lesser extent during day light conditions at locations with low contrasts between pavements with light colors and yellow marking colors.

In the cases where the LDWS was unable to detect the markings during rainy night conditions, the markings were not visible or barely visible to human eyes because they were covered with water. Thus, it is expected that image-based LDWS that depends on marking visibility will not be able to detect the markings under these conditions, even with improvements to the existing LDWS hardware and software performance. On the other hand, relationships were found in this study between ER during night rainy conditions and pavement marking retroreflectivity for conventional marking materials such as thermoplastic, as stated in Chapter 5. The relationships show that LDWS perform significantly better with conventional markings that have higher retroreflectivity values.   This indicates that it may be possible to improve LDWS performance by using lane markings with higher visibility at night rainy conditions.

A number of technologies have been proposed to improve the visibility of lane markings under night and rainy conditions, as discussed in Chapter 3 of this report. These include:

- Markings that use large size beads (double beads) to promote visibility and water drainage.

- Profiled tape or profiled thermoplastic that has raised profile sections with glass beads along the vertical walls to reduce bead flooding and promote water drainage. These types of lane markings are referred to in this paper as "wet pavement markings" since they are expected to have higher visibility under wet (rain recovery) conditions because they allow faster drainage of water. However, under heavy rain conditions, these markings may not be able to perform adequately since they will not be able to drain the water fast enough to prevent the deterioration in the visibility of lane markings.

- Marking tapes that use special optics to give a high level of dry, wet, and rain reflective performance. These types of markings are referred to in this study as "wet-reflective" markings.

The use of the above technologies could have significant effects on LDWS performance during rain at night light. Since the main deterioration in pavement marking performance occurs during medium to heavy rain, the best performance is expected with wet-reflective markings that use special optics, particularly in the case of very heavy rain.   This chapter discusses the methodology used in this study to investigate the effects of improved pavement markings on LDWS performance and the results of the test.

7.2   Methodology

In this project, a test was conducted to determine the LDWS performance during rain conditions at night light with different types of pavement markings. This test was done in a "laboratory" (simulated rain facility) environment. The research team realized that it was difficult to perform these tests in the field for the following reasons:

- It is difficult to control and quantify the rainfall intensity in the field since the intensity of rain storms can change in a short time period and within a short driving distance. Testing different types of lane markings under fixed rain intensities is essential to produce accurate comparisons between different lane markings.

- It is difficult to convince transportation agencies to install lane markings for testing purposes.

For the above reasons, the effects of the improved lane markings were evaluated in a simulated rain facility. Initially, there was a discussion with one of the major vendors of lane markings (3M) about performing the test at the 3M rain facility in St. Paul, Minnesota. However, 3M informed the research team that due to an early winter in Minnesota, it had to shut down the facility to prevent the freeze from damaging the rain making pipes.

Later, the research team selected the Texas Transportation Institute (TTI) facility in College Station, Texas to perform the test. This facility has several advantages over the 3M facility including a longer "test track" and the capability to simulate three levels of rain intensity instead of one level, as is the case in the 3M facility. The TTI simulated rain facility was rented from TTI to perform the needed test.

7.2.1   Simulated Rain Facility Description

The TTI facility that was utilized in this study consists of a 1600 ft long paved road that is 22 ft wide. A total of 250 three quarter inch risers, each with an upward aimed nozzle at the end, are used to simulate the rain, along the westside of the road, as shown in Figure 7-1. Two sets of water risers are used to generate simulated rain with different intensities (low, medium, and heavy). The low flow line supplies water to one set of risers spaced 12 ft apart to generate the low rain level. The medium flow line supplies water to the second set of risers spaced 14 ft apart to generate the medium rain level. The heavy rain fall level can be simulated by combining the water supply from both the low and the high level risers.

The upward aimed nozzles of the risers ensure that the simulated rain can cover over half of the roadway width (one lane width) when the risers are put on. The low, medium, and heavy rain intensities represent rainfall levels of 0.28, 0.52, and 0.87 inch/hour, respectively. To ensure that the researchers drive safely within the rain tunnel area without hitting the risers on the side, one row of blue reflective raised pavement markers (RRPMs) is installed between the risers and the

roadway edge closest to it.   Figure 7-1 shows a picture of the rain tunnel facility.   More details about the facility can be found in reference 44.

Figure 7-1: TTI Rain Tunnel Assembly

7.2.2 Test Vehicle

The same LDWS-equipped vehicle that was used in the field test, as described in Chapter 5 of this report, was used in the testing at the rain facility. The vehicle was transported from Florida to Texas for the purpose of the study.

7.2.3 Tested Lane Marking Types

The performance of the LDWS in the rain tunnel was tested using a number of lane marking technologies and colors with varying visibility levels during rain at night light. Six different types of pavement markings were installed and used in the test. The details of the used markings are presented in Table 7-1. The installed marking layout at the test facility is shown in Figure 7-2. As shown in Figure 7-2, 150 ft of each of the six tested markings was installed along the rain tunnel (marking 1 being at the southern end of the tunnel and marking 6 at the north end) with a gap of 150 ft between each consecutive marking.

The installed markings represent a variety of marking types and colors including:

- Marking Number 3: This is a white pavement marking, modified to produce the expected retroreflectivity of a conventional marking close to the end of its service life by applying light coats of polyurea to reduce its retroreflectivity.

- Marking Numbers 1 and 4: These white and yellow markings represent "conventional" markings with high retroreflectivity. These markings are flat tapes that have similar visibility under rain conditions at night light, as thermoplastic markings with the same retroreflectivity. However, the retroreflectivity values of the installed tapes were higher than those normally encountered with existing thermoplastic markings. Thus, they can be considered as high retroreflectivity versions of conventional markings.

- Marking Number 6: A profiled white tape that is expected to have a high visibility under wet (rain recovery) conditions at night.

- Marking Numbers 2 and 5: Yellow and white wet-reflective tapes that use special optics to allow high visibility of pavement markings under rain conditions at night.

Figures 7-3 and 7-4 depict the six lane markings under dry and heavy rain conditions. The pictures clearly show that the wet-reflective markings have better visibility than the other markings, particularly under heavy rain conditions.

Table 7-1: Attributes of the Markings Used in the Improved Lane Marking Test

Marking Number	Marking Description	Marking Color	Modifications	Represented Type
1	Brite-Line 100 Tape	White	1 light coat of polyurea	Conventional white with high retroreflectivity
2	3M – 380 Wet Reflective	Yellow	None	Wet-Reflective Yellow
3	3M 5710 IE Tape	White	3 light coats of polyurea	Regular white close to end of life
4	Brite-Line 100	Yellow	None	Conventional yellow with high retroreflectivity
5	3M – 380 Wet Reflective Tape	White	None	Wet-Reflective Yellow
6	3M – 380 IE Tape	White	None	Wet white

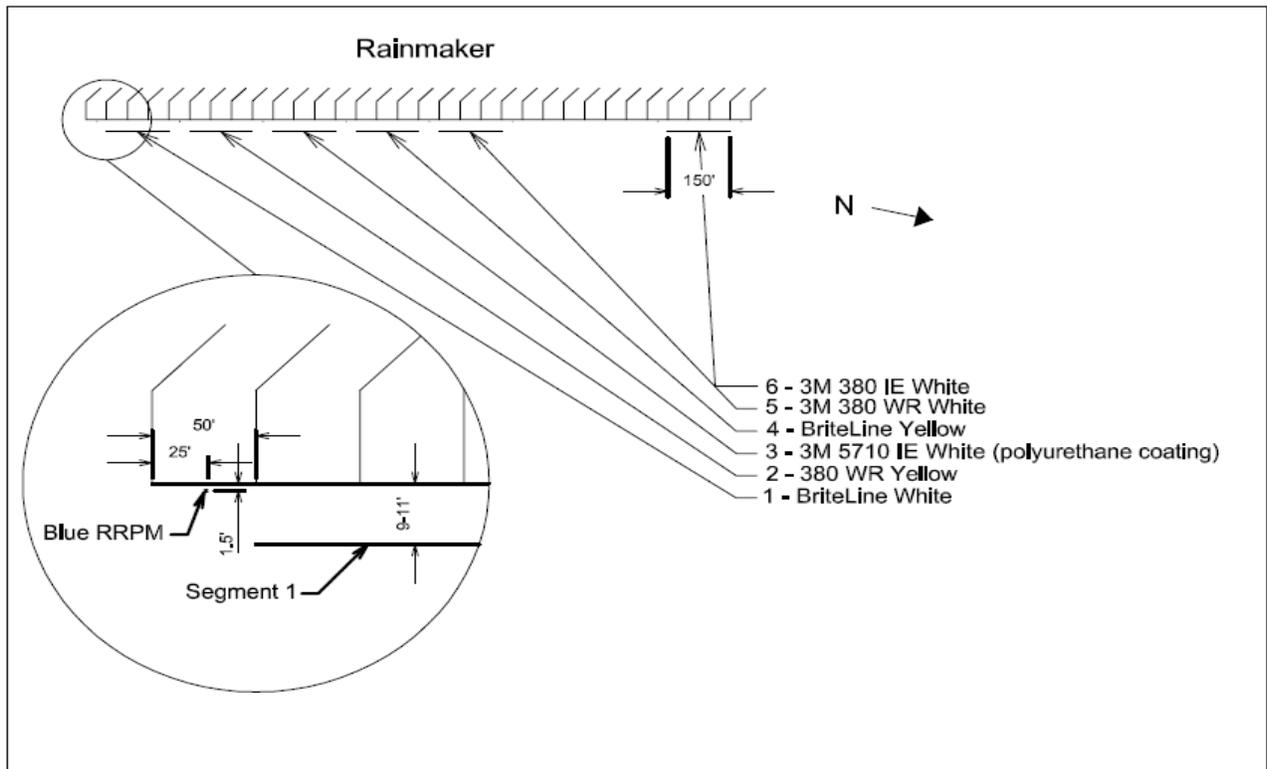**Figure 7-2: Layout of the Six Lane Marking Installed in the Test**

(a) White Regular High Retro   (b) Yellow 380WR   (b) White Regular Low Retro

(b) Yellow Regular High Retro   (b) White 380WR   (b) White 380IE

Figure 7-3: Photographs of the Tested Lane Markings in the Simulated Rain Facility During Rain Night Conditions
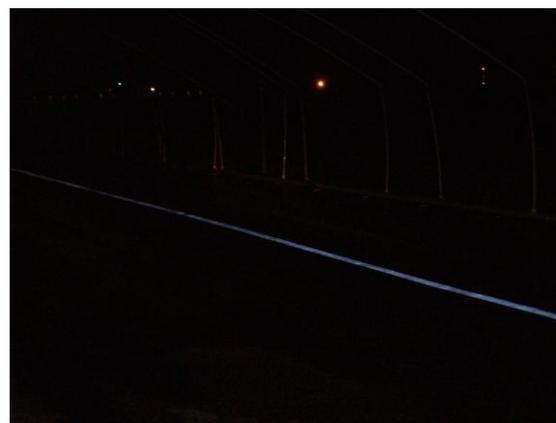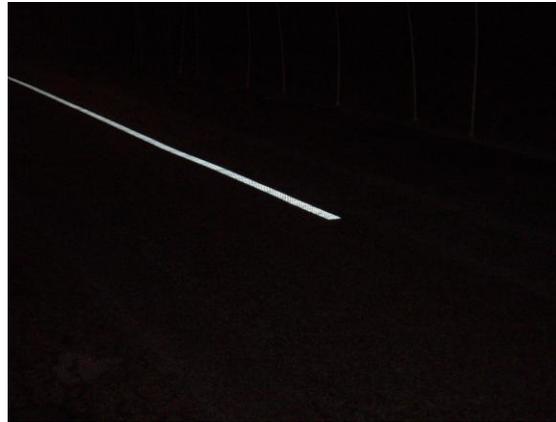
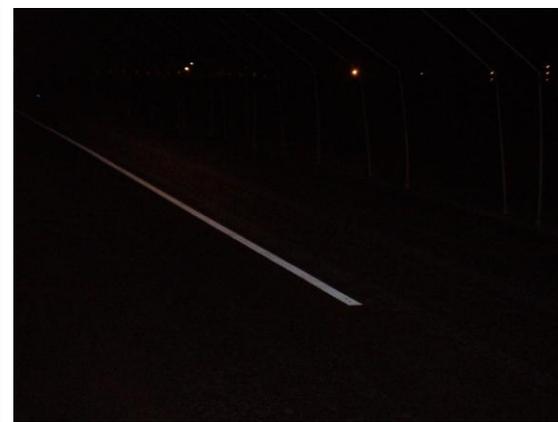(a) White Regular High Retro

(b) Yellow 380WR

(b) White Regular Low Retro

(b) Yellow Regular High Retro

(b) White 380WR

(b) White 380IE

Figure 7-4: Photographs of the Tested Lane Marking in the Simulated Rain Facility During Dry Night Conditions

7.2.4   Retroreflectivity Measurement

As described in Chapter 3, there are currently three ASTM standards for retroreflectivity measurements. ASTM E1710-05, "Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry" (45) is the standards currently used by most transportation agencies for measuring the retroreflectivity of pavement markings using a hand-held retroreflectometer. The test presented in the ASTM E1710-05 standard is conducted under dry conditions and may not reflect pavement marking visibility under wet and night conditions. Realizing this deficiency,   ASTM adopted two new procedures for measuring marking retroreflectivity of wet markings:

- ASTM E2177-01, "Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (RL) of Pavement Markings in a Standard Condition of Wetness" requires the measurement of marking retroreflectivity after water has been poured on the marking and allowed time to drain off the marking (46). This procedure is also referred to as the "recovery method".

- ASTM E2176-01, "Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (RL) of Pavement Markings in a Standard Condition of Continuous Wetting." requires that water is continuously sprayed on the marking during retroreflectivity measurement (47). The ASTM E2176-01 procedure is also referred to as the "continuous wetting" or "spray" method. It is intended to represent the retroreflectivity of a marking material during a rain conditions.

In this study, the retroreflectivity was measured based on the above three standards using the MX-30 handheld retroreflectometer.   The results are presented in Table 7-2.   As indicated in this table, the dry retroreflectivity of the tested pavement marking varied considerably, ranging from 164 mcd/m^2/lux to 1151 mcd/m^2/lux. The lowest measured retroreflectivity value was that of Marking 3. The highest measured values were those of the yellow and white wet-reflective lane markings (Markings 2 and 5)

Table 7-2: Results of Pavement Marking Retroreflectivity Measurements

Marking No.	Marking Type	Color	Retroreflectivity (mcd/m^2/lux)					
			Dry		Recovery		Continuous Wetting	
			Mean	StDev	Mean	StDev	Mean	StDev
1	Brite-Line 100	White	632	34	99	6	32	3
2	3M 380 WR	Yellow	1151	274	563	5	202	34
3	3M 5710 IE	White	164	16	23	2	8	1
4	Brite-Line 100	Yellow	458	60	100	5	26	6
5	3M 380 WR	White	1133	424	432	6	198	65
6	3M 380 IE	White	699	37	116	2	46	3
-	Road Surface		20	3	6	1	4	1

Table 7-2 indicates that the use of the ASTM recovery and continuous wetting procedures resulted in a very high drop in the measured retroreflectivity, which was in line with the expected trend of considerably lower marking visibility in wet conditions, and even more in rainy conditions. However, Table 7-2 indicates that the continuous wetting method produced very low retroreflectivity value measurement. For example, the retroreflectivity of Marking Type 1 according to this procedure was only 32 mcd/m^2/lux and that of Marking Type 2 was 8 mcd/m^2/lux. Based on the research team experience with marking visibility under various rain conditions in the field and in the lab, it appears that the ASTM continuous wetting method underestimated the retroreflectivity of lane markings under "typical" heavy rain events. The wetting used in the ASTM Continuous Wetting Standard seemed to reflect much higher intensity than that of the simulated heavy rain (0.87 inch/hour) at the TTI facility.

To confirm the above, the retroreflectivity of two of the used lane markings was measured at the TTI rain facility under the simulated heavy rain (0.87 in/hr). The rain facility measurements required the shielding of the retroreflectometer to protect the device during the measurements. Table 7-3 is a comparison between the retroreflectivity obtained using the continuous wetting method and those obtained at the TTI facility with heavy rain.
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Table 7-3: Comparison of the Retroreflectivity Measured Using the ASTM Continuous Wetting versus that Measured Under Simulated Rain

Marking No.	Marking Type	Color	Retroreflectivity (mcd/m^2/lux)				
			Different Simulated Rain Levels			Continuous Wetting	
			Low	Medium	High	Mean	StDev
5	3M 380 WR	White	887	737	631	198	65
6	3M 380 IE	White	67	44	50	46	3

Pike et al (37) estimated that the average rainfall rate associated with ASTM E 2176 standard is in the range of 5.78 to 14.39 in/hr, with an average intensity of 9.32 in/hr. To determine if such intensity is reasonable, Pike et al. analyzed twenty years of night rainfall data for the State of Texas. Approximately 79 percent of the analyzed rainfall events produced maximum rainfall rates of less than 0.50 inches per hour, and 88 percent of events produced maximum rates less than 0.75 inch/hour. While Pike et al. found that there are rain events with intensities similar to those used in E2176, these events constitute a very small percentage of the total rainfall events. The Virginia Tech Transportation Institute (VTTI) found similar results when analyzing the State of Virginia rainfall statistics (48). VTTI found that 95 percent of the rain events in Virginia had rainfall rates of 0.8 inch/hour or less.

To confirm the above, the research team evaluated five years of state of Florida rainfall data (2001 to 2006) using data obtained from the National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html.). The NCDC collects and maintains a 15-minute rain intensity data set. The 15-minute data set was analyzed to determine the rain intensity statistics during night and day light. The results show that for Florida night conditions, 77% of the analyzed rainfall events have a maximum rate of 0.8 inch/hour, 88.3% have a maximum rate of 1.2 inch/hour, and 96.36% have a maximum rate of 2.0 inch/hour. Thus, the Florida rain fall intensity is higher than those reported for Texas and Virginia. However, the analyzed data showed, as with the Texas and Virginia studies, that the ASTM E 2176 standard overestimates the effect of rain on retroreflectivity (as stated above the ASTM 2176 simulated rain intensity is in the range of 5.78 to 14.39 in/hr, with an average intensity of 9.32 in/hr).

7.2.5 LDWS Test Procedure

Before the test, trial runs were made by the research team to identify issues with the test, to define solutions to the issues, and to fine-tune the testing procedure. During these runs, the test vehicle was driven through the test course multiple times. These runs were conducted in the daylight and dry conditions and also at night conditions. For example, based on these runs, it was decided that the truck should be driven at a constant speed of 40 mph. In addition, the sequence of the marking crossing by the test vehicle was identified. The start and end points of the runs were selected to allow the truck to speed up to 40 mph before it enters the rain tunnel

area and to decelerate and turn around to perform a run in the opposing direction. Two researchers were in the test truck during the test. One of the researchers drove the truck while the other noted the test measurements.

Once the details of the test were finalized, the actual tests of the lane markings under dry and different rain intensity levels were performed during night light. The start and end time of each run were noted and the riser was switched to the tested rain level for each set of runs (low, medium, and heavy). The researchers activated the windshield wipers when the vehicle entered the simulated rain, and deactivated them when the vehicle exited the rain. During each run (vehicle trip in one direction of travel), each lane marking type was crossed one time and the researchers noted if the LDWS alarm was activated or not.

7.3   Test Results

For dry and light rain conditions (0.25 inch/hour), the ER of the LDWS was 100% for all marking types. However, rains with medium and heavy intensity affected the ER for some of the markings. Figures 7-5 and 7-6 show the change in the ER value with the time passed since the start of the simulated rain. Each report value in these figures is the average of 10 runs (10 vehicle passages).

Figure 7-5 shows that for medium rain (0.52 inch/hour intensity), with the low-retroreflectivity conventional marking (Marking Type 3), the ER drops significantly after 30 minutes of rain, reaching an ER value of 0% after 40 minutes. An ER value of 0% indicates that the LDWS did not detect the pavement marking at all times that the marking was crossed. The retroreflectivity of all other marking types remained high (above 90%) after 30 minutes of starting the medium rain. The ER dropped to 70% after 40 minutes with markings 1 and 4 that represent white and yellow conventional markings with high retroreflectivity.   The ER for the wet-reflective markings (Marking Types 2 and 5) remained as 100% throughout the experiment. The LDWS with the profiled tape varied between 80% and 100% throughout the test.

Figure 7-6 shows that for heavy rain (0.87 inch/hour intensity), the ER varies between 0% and 20% with the low-retroreflectivity conventional marking (Marking Type 3).   For the conventional markings that have high retroreflectivity and the profiled tape, the average ER varied between 70% and 100% between different sets of test runs (see Figure 7-6). The ER for the two wet reflective markings was 100% for all test runs.
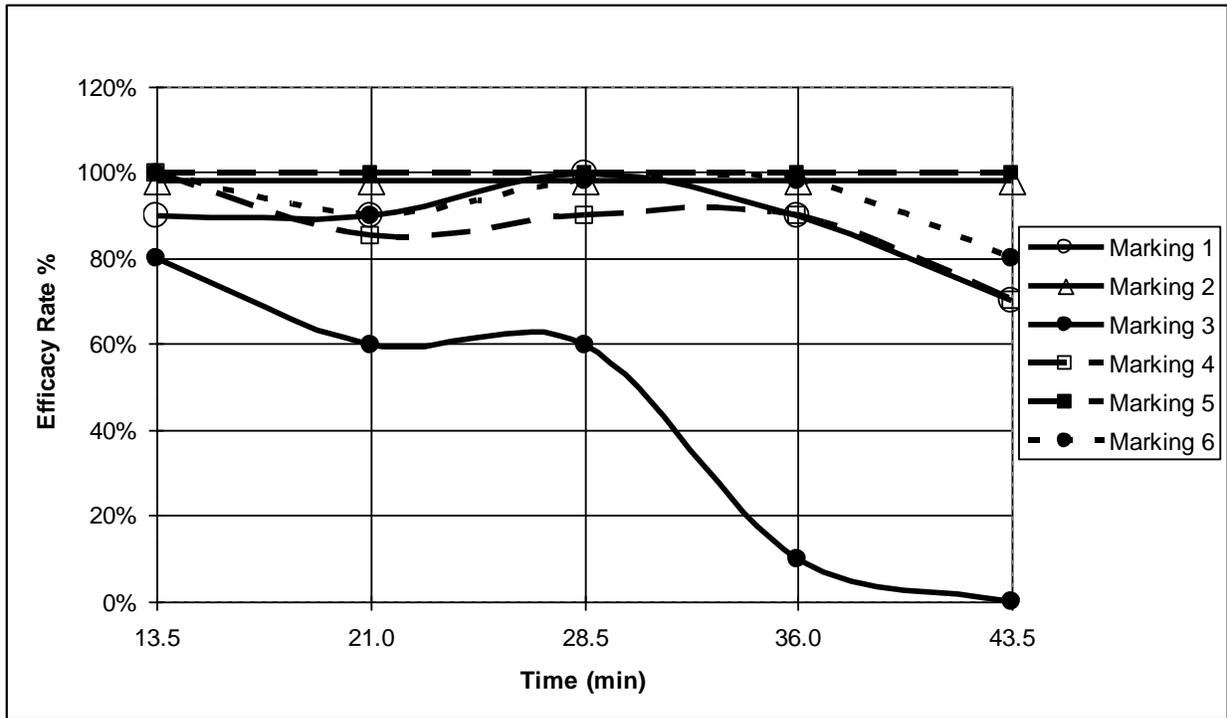
Figure 7-5: Relationship between the Time since the Start of Rain and ER for Medium Rain
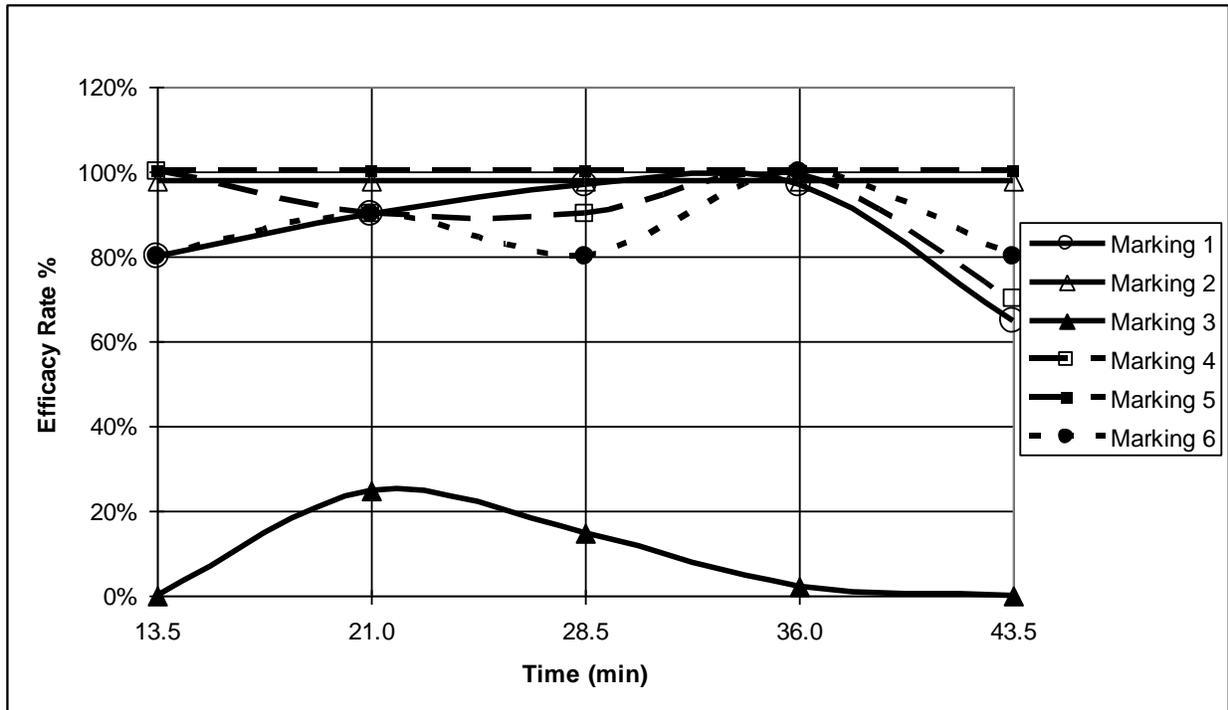
Figure 7-6 Relationship between the Time since the Start of Rain and ER for Heavy Rain

7.4   Conclusions

The results presented in this chapter confirmed that pavement marking retroreflectivity has a significant effect on LDWS performance under medium to high rain intensities (0.52 to 0.87 inch/hours). The ER value was particularly low with the conventional marking that had a low retroreflectivity value. The wet-reflective tapes performed somewhat better than conventional markings with high retroreflectivity.

It is expected that the effect of rain is even higher under heavier rain intensities that were not tested in this study. The maximum simulated rain intensity that could be achieved at the Texas rain facility was 0.87 inch/hour. As stated previously, based on the analysis of Florida rain data, 23% of the night rain events in Florida have a higher value than 0.8 inch/hour intensity and 11.7% of the events have a higher value than 1.2 inch/hour intensity. Under these events, the difference between wet-reflective tapes and other types of markings may become even higher.

The results presented in this chapter indicate that using wet-reflective tapes or frequent replacement of existing conventional pavement markings to maintain high retroreflectivity will have a positive effect on LDWS performance during night rain conditions. The benefits of these improvement alternatives are compared to their costs in Chapter 8.

8.   Benefit-Cost Analysis

8.1   Introduction

As stated previously, the research team of this study conducted field and laboratory tests to determine the LDWS performance under different environmental conditions and different types of pavement marking installations. The results of the tests indicated that, the ER under dry and light rain conditions is expected to be 100%, except for a few roadway segments with bad contrast between the pavements and markings. In addition, it was observed that heavy rain conditions during daylight have little or no effect on the performance of LDWS. However, the results showed that the performance of LDWS is affected significantly by moderate to heavy rain conditions at night for typical pavement marking installations. Relationships were developed between ER during rain conditions at night and pavement marking retroreflectivity for conventional marking materials such as thermoplastic as presented in Chapter 5. Pavement marking materials have been produced to provide very high visibility during wet and rainy conditions at night. Tests were conducted by the research team of this study to examine the performance of some of these materials at a simulated rain facility as indicated in Chapter 7. The results indicated that the ER of the LDWS can be 100% with some types of markings.

The above discussion indicates that replacing the conventional markings at more frequent intervals or the use of wet-reflective markings will result in a better performance of the LDWS during night rainy conditions. It is expected that this improvement in performance will result in a reduction in crashes of the vehicles that are equipped with LDWS. However, it is also expected to increase the cost of pavement marking installations.   This paper investigates the cost-effectiveness of the improvement in pavement marking visibility with consideration of LDWS performance.

8.2   Estimation of Benefits

8.2.1   Overview of the Methodology

An overview is presented below of the methodology used in this study to estimate the benefits of pavement marking improvements with consideration of LDWS performance. Details of the methodology are presented in the following sections.

- A review of previous studies was conducted to identify estimates of the benefits of improving the quality of pavement markings for vehicles that are not equipped with LDWS. Any estimated benefits, identified based on this review, were assessed for possible inclusion in the benefit-cost analysis.

- The frequencies of the related types of crashes (defined as those crashes that have the potential to be prevented by LDWS) were estimated per year per mile and were categorized by crash type, highway type, and severity level. The estimations were based on national crash statistics.

- Crash reduction factors were estimated for the use of LDWS. These factors are defined as the proportions of the related types of crashes that can be reduced due to the use of LDWS, taking into consideration the performance of LDWS under night rainy conditions. The reduction factors were estimated for different crash types, vehicle types (trucks and passenger cars), highway shoulder widths, and pavement marking visibility improvement alternatives.

- The reduced numbers of the related crashes per mile per year due to LDWS for passenger and commercial vehicles were then calculated for different highway types (with different crash rates), pavement marking improvement alternatives, average annual daily traffic (AADT), heavy vehicle proportions, horizontal curvature alignments, and LDWS market penetrations. The LDWS market penetration is defined as the proportion of the vehicles in the traffic stream that are equipped with LDWS. The reduced numbers of crashes due to marking improvements were calculated based on the numbers of related crashes and the crash reduction factors estimated, as described in the previous two bullets, for different marking improvement alternatives.

- The annual safety benefits estimated as described above were then converted to dollar values to allow the use of these estimates in the benefit-cost analysis performed in this study.

8.2.2   Benefits of Improved Pavement markings without LDWS

Improving the quality of pavement markings is expected to result in positive effects even without the presence of LDWS equipped vehicles. In this study, a review was conducted of previous studies that evaluated these effects to determine any identified benefits that should be included in the benefit-cost analysis conducted in this study.

Previous studies attempted to include the following expected benefits when evaluating the cost-effectiveness of improving the quality of pavement marking materials:

- Safety effects: This is the estimated reduction in the number of related crashes that could be prevented by improving the visibility of pavement markings.

- Longer service lives: Some improved pavement markings have longer service-lives than other markings.

Below is a summary of what is reported in previous studies regarding the above two benefit components.

8.2.2.1   Safety Effects

The National Cooperative Highway Research program (NCHRP) Report 500 (*49*) listed enhanced pavement markings as a counter measure of Run-off-Road (ROR) crashes and mentioned that improving pavement markings is an appropriate treatment, if it is assumed that drivers leave the roadway because they cannot see the pavement edge. The report, however,

concluded that conflicting evidence remains concerning the crash-related effectiveness of these improvements.

Previous studies attempted to quantify the safety effects of improved pavement markings. Migletze et al. (*29*) performed a safety evaluation of "all-weather" pavement marking (AWPMs). AWPMs were defined as markings that are visible at night under dry conditions and also under rainy conditions for up to 0.25 inches per hour of rainfall. The study could not demonstrate a statistically significant reduction in crash frequency for night rainy conditions, although it was able to show positive safety effects for night-time dry-pavement crashes.

Another study (*28*) evaluated the effectiveness of three types of pavement marking materials: paint, thermoplastic, and waffle tape. Waffle tape is expected to have better visibility than paint and thermoplastic markings during wet periods that follow rain events (during the rain recovery period). The tested null hypothesis was that the pavement marking material did not affect the crash rates. The study found that there was insufficient evidence to reject this null hypothesis.

Lee et al. (*50*) conducted a study of 50 locations in Michigan where the retroreflectivity of different types of markings over 3 years was measured and then compared to the number of nighttime crashes potentially associated with marking visibility. The study was unable to identify any relationships between retroreflectivity and nighttime crashes.

A recent NCHRP study *(51)* examined the safety effects of the retroreflectivity of longitudinal pavement markings and markers over time. The study found no significant difference in safety between sections with high retroreflectivity and low retroreflectivity markings, during non-daylight conditions.

Based on the above review, it was decided that the benefit-cost analysis performed in this study should not include any safety benefits of marking improvements for vehicles that are not equipped with LDWS. However, it is recognized that future studies may be able to identify safety benefits of such markings, particularly under medium and heavy rain night conditions.

8.2.2.2 Service Life

Pavement markings can reach the end of their service lives due to bead loss resulting in poor retroreflectivity, due to loss of the base material because of chipping and abrasion, or due to color change/loss of contrast of the base material of the markings. Some types of high quality pavement markings have longer service lives than conventional pavement markings. Cottrell and Hanson (*28)* estimated that the initial retroreflectivity values of paint, thermoplastic, and waffle tape are 250, 350, and 1000 mcd/m2/lux, respectively, and their service lives are one, three, and six years, respectively.

In the benefit-cost analysis performed in this study, it is assumed that, on average, the existing thermoplastic markings are replaced every three years. The assumptions made regarding the service lives of the investigated markings are further discussed later in this document.

8.2.3   Frequency of Related Crashes

The two types of crashes that are expected to be influenced by LDWS on multi-lane highways are ROR crashes and lane changing crashes. ROR is the most serious type of crash in the United States. ROR crashes have been reported to account for over 20% of all police reported crashes and over 41% of all in-vehicle fatalities (*8*). In comparison, lane change crashes represent only 4% of the total crashes in the United States and only 0.5% of the fatal crashes (*52*). This chapter presents the methodology used to estimate the number of crashes per 1 mile for each of the two types of crashes that could be prevented by LDWS, categorized by highway facility type and severity level. This estimation is based on national crash statistics. If the analysis is to be done for a specific highway segment, then the crash statistics for that segment should be used instead. Below is a description of the used methodology.

1. The crash rates (Rate$_i$) for highway type i in crashes per 1 million vehicle-miles traveled (MVM), were obtained from a study by Cirillo et al. (*53*) for three types of highway facilities (Urban Interstate, Rural Interstate, and Rural Others). These rates were calculated based on the sum of all types of crashes for a given highway type.

2. The crash rates for the two related crash types (ROR and lane changing crashes) were then estimated based on the crash rates obtained in step 1 above, by multiplying these rates by the proportions of the two types of crashes of the total crashes, as reported in the National Highway Traffic Safety Administration (NHTSA) "Traffic Safety Facts" report (*54*).

3. The crash rates calculated in step 2 above were further categorized by severity level (fatal, injury, and property damage only (PDO) crashes) by multiplying these rates by the severity level proportions for each of the two related crash types, as reported in the NHTSA report mentioned above (*54*).

The calculation of crash rates using the above procedure can be expressed as follows:

$$Rate_{ijk} = Rate_i \times f_j \times f_{jk} \qquad\qquad (8\text{-}1)$$

Where:

f_j =   proportion of related crash type j (run off the road or lane change crashes) relative to the total number of crashes;

f_{jk} =   proportion of crashes of severity level k (fatal, injury or PDO crashes

$Rate_i$ =   rate of crashes per MVM for highway facility type i considering all crash types and severity levels; and

$Rate_{ijk}$ =   rate of crashes per MVM for highway facility type.

The values of the parameters used in the calculations of Equation 8-1, are presented in Table 8-1.

Table 8-1: Values of the Parameters Used in Calculating Crash Frequency

Parameter	Category		Value
Total Crash Rate $(Rate_i)$	Urban Interstate		1.860 crash /MVM
	Rural Interstate		1.510 crash/ MVM
	Rural – Others		2.110 crash/ MVM
Proportion by Crash Type (f_j)	Run off the Road		20.0%
	Lane Change		4.0%
Proportion by Crash Severity (f_{jk}) **for Each Crash Type**	Run off the Road	Fatal Crashes	1.44%
		Injury Crashes	36.92%
		PDO Crashes	61.65%
	Lane Change	Fatal Crashes	0.2%
		Injury Crashes	13.84%
		PDO Crashes	85.96%

The crash frequencies per 1 mile could then be calculated for a given AADT level on the highway segment, based on the rates calculated in Equation 1 above, as follows:

$$Crash_{ijk} = Rate_{ijk} \times AADT \times (365/1{,}000{,}000) \qquad (8\text{-}2)$$

Where:

$AADT$ =   annual average daily traffic (vehicles per day);

$Crash_{ijk}$ =   number of crashes per 1 mile per year for a given highway facility type i, crash type j, and severity level k;

As explained previously, the main benefits of pavement marking improvements are expected to be the reduction of LDWS-equipped vehicle crashes that occur during night rainy conditions. Thus, it was necessary to estimate the frequencies of ROR and lane changing crashes that occur under these conditions. These frequencies were obtained by multiplying the number of crashes under all conditions calculated according to Equation 8-2 by the proportion of. crashes that occur during these conditions (P_{wn}). The P_{wn} value used in the sensitivity analysis performed in this study was 5% based on information presented in the NHTSA report mentioned above (*54*). However, this percentage is expected to be different for different regions and local values should be used when performing the analysis for a specific highway segment.

Equation 8-3 below presents the calculation of crashes that occur in night rainy conditions.

$$Wt\_Crash_{ijk} = Crash_{ijk} \times Pwn \qquad (8\text{-}3)$$

Where:

P_{wn} =   proportion of crashes that occur during rain at night light
Wt_Crash_{ijk} =   number of crashes per 1.6 km (1 mile) per year during night and rain conditions for a given highway facility type i, crash type j, and severity level k ;

8.2.4 *Crash Reduction Factors*

LDWS are designed to prevent crashes that are caused primarily by driver inattention and driver incapacitation. The reduction factors for ROR and lane changing crashes due to the use of LDWS are calculated, based on the percentages of these crashes, as described below.

8.2.4.1 ROR Crashes

ROR crashes that occur due to driver inattention and driver incapacitation represent about 32.8% of the total number of ROR crashes with nearly a third of these crashes involving driver intoxication (*8*). Pomerleau et al. (*8*) estimated that only 25% of intoxicated drivers would respond to a LDWS warning quickly and appropriately enough to avoid a crash. This estimation resulted in approximately 24% of all road departure crashes of passenger vehicles having the potential of being prevented due to the use of LDWS. The proportion of truck ROR crashes that could be prevented due to the use of LDWS is expected to be higher than the proportion for passenger cars due to the increased frequency of crashes due to drowsiness and the reduced frequency of crashes due to intoxication. Pomerleau et al. (*8*) estimated that approximately 53% of truck road departure crashes have the potential to benefit from a LDWS. Based on the above, the LDWS crash reduction factors used in the study were calculated to be 24% and 53%, for passenger cars and trucks, respectively. These factors need to be adjusted to take into consideration that the ability of a driver to correct the vehicle path back to the traveling lane after receiving the warning, decreases with narrow shoulder widths.

The effect of shoulder width on passenger car crashes is less than truck crashes since passenger cars are not as wide and because passenger cars are generally more maneuverable. A simulation study (*8*) estimated the effectiveness of LDWS alarms with different shoulder widths in terms of the proportion of times that the vehicle receives an LDWS alarm and was able to correct its path after leaving the road, for a given shoulder width (see Table 8-2).   This estimated effectiveness ranged from 5% for commercial vehicles and sections with 0-3 ft. shoulder width to 97% for both passenger and commercial vehicles with 12 ft. shoulder width. In the sensitivity analysis performed in this study, a 90 percent effectiveness was assumed but this number should be varied when performing the analysis for a specific highway segment with a given shoulder width.

8.2.4.2 Lane Change Crashes

Compared to ROR crashes discussed above, the number and severity of unintentional lane change/merge crashes that can be prevented by LDWS is a small percentage of the crash population. Examination of lane change crash data in the United States indicated that only 1.96-3.56% of lane changing crashes can be classified as driver inattention crashes (*55*). 85%-94% of all lane change crashes involve deliberate and controlled maneuvers initiated by the subject vehicle driver. Out-of-control crashes represent about 4.15 % of the total crashes (*55*). LDWS have the potential for addressing only the drifting type of lane changing crashes. Controlled crashes can be reduced by using other types of Integrated Vehicle-Based Safety Systems (IVBSS) that detect and warn of vehicles n adjacent lanes (including blind spots).   Based on the above discussion, the LDWS crash reduction factor used in this study for lane changing crashes is 2.5%.

8.2.5   Estimation of LDWS Safety Benefits

To be able to calculate the safety benefits of pavement marking improvements, the number of crashes reduced due to the use of LDWS with different marking improvement alternatives needs to be estimated.   The main difference between LDWS performance with different marking improvement alternatives is during rain night conditions. This is because, as explained above, the efficacy rate during these conditions (ER_w) is a function of the marking retroreflectivity during rain.   The safety benefits of LDWS during these conditions with different pavement marking improvement alternatives can be calculated as follows:

$$Av\_Cr_{ijkl} = Wt\_Crash_{ijk} \times CRF_{jl} \times MP_l \times ERw \times P_l \qquad (8\text{-}4)$$

Where:

Av_cr_{ijkl}	=	number of crashes per 1.6 km (1 mile) per year that can be avoided during rain night conditions with the use of LDWS for a given highway facility type i, crash type j, severity level k, and vehicle type l;
CRF_{jl}	=	crash reduction factor, which is the proportion of crashes that can be avoided by using LDWS for a given crash type j and vehicle type l, calculated as described in the previous chapter;
ER_w	=	LDWS efficacy rate under rain night conditions for the pavement marking type under consideration; crashes or PDO for a given crash type j;
MP_l	=	LDWS market penetration – the proportion of vehicles equipped with LDWS for vehicle type l (truck or passenger car);
P_l	=	proportion of vehicle type l in the traffic stream

The benefits from pavement marking improvements can then be calculated based on the avoidable crashes (Av_Cr_{ijkl}) with different pavement marking improvement alternatives, calculated as in Equation 8-4 above. The only difference in the calculations for different alternatives is the value of ER_w, which is higher for the improved markings compared to existing marking conditions.   The reductions in truck and passenger car crashes were calculated separately and then summed together.

Table 8-2: Effectiveness of LDWS with Different Shoulder Widths

Reduction Factor	Factor Types	Vehicle Types	Effectiveness
Shoulder Width $(SWRF_l)$	0 – 3 ft	Cars	20.00%
		Trucks	5.00%
	3 – 6 ft	Cars	60.00%
		Trucks	57.00%
	6 – 12 ft	Cars	92.00%
		Trucks	-
	12 + ft	Cars	97.00%
		Trucks	97.00%

Note: '-' indicates that data is not available.

Below are the marking installation alternatives considered in this study and the method used to estimate ER_w for these alternatives:

- *Baseline Alternative - thermoplastic markings replaced every three years:* This is the baseline alternative, to which marking improvement alternatives will be compared to, since it can be considered as representative of typical current marking installations. Immediately following thermoplastic marking installations, it has been reported that the retroreflectivity of the markings is 300-450 mcd/m^2/lux. At the end of the pavement marking service life, which is estimated to be three years on average (which varies depending on traffic and environmental conditions), retroreflectivity is expected to drop to 100-150 mcd/m2/lux.

As discussed previously, relationships have been developed between the ER_w and retroreflectivity of conventional thermoplastic pavement markings. Based on these relationships and the retroreflectivity values of the markings mentioned above, it can be estimated that the ER_w is about 80% just after the installation of the pavement markings and drops to 0% at the end of its service life. For the purpose of the benefit-cost analysis performed in this study, it is assumed that the drop in ER_w during the marking service life follows a linear relationship, as indicated in Figure 8-1. Based on this assumption, it can be estimated that the average ER_w values are 68.15, 41.50%, and 13.35%, for the first, second, and third year, respectively of a typical conventional thermoplastic pavement marking

installation. These ER_w values were used in this study to calculate the LDWS benefits, taking into consideration the drop in retroreflectivity due to aging of thermoplastic materials.
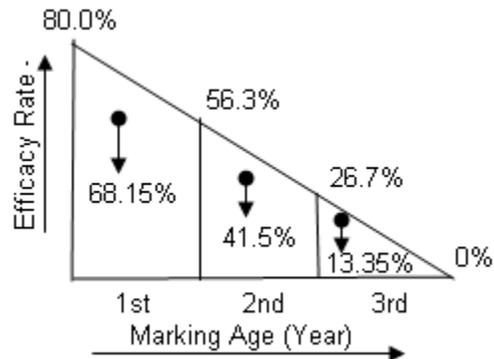

Figure 8-1: Assumed Relationship between Marking Age and ER_w for Thermoplastic Materials

- *Improvement Alternatives 1 and 2 – more frequent replacements:* Alternatives 1 and 2 represent the replacement of the conventional thermoplastic pavement markings at more frequent intervals than the typical interval of three years, as is assumed in the baseline alternative. Improvement Alternatives 1 and 2 reflect pavement marking replacement intervals of two and one year, respectively. The ER_w for these alternatives is calculated based on Figure 8-1, in a similar manner to the method used to calculate ER_w for the Baseline Alternative, as described above.

- *Improvement Alternative 3: "Wet-reflective" pavement marking tapes:* This alternative includes the use of pavement markings that are capable of producing high retroreflectivity during heavy rain conditions, resulting in ER_w equal to 100% throughout its service life. Wet-reflective markings have been introduced to the market in recent years that utilize special optics to give a high level of dry, wet, and rain reflectivity performance. As discussed above, these markings were found to be capable of producing ER_w of 100%. Previous studies have estimated that the service life of pavement marking tapes can be six years or more (4). However, the wet-reflective tapes have been introduced to the market only recently. Thus, their service-lives cannot be verified. In this study, a sensitivity analysis was conducted to determine the benefit-cost effectiveness of such tapes, assuming that they have service lives of three, four, and six years, respectively.

8.2.6   Effects of Horizontal Alignment

The numbers of related crashes per mile are expected to be significantly higher on curved segments compared to tangent segments with similar traffic and geometry attributes. It was found that ROR crashes are 1.5 to 4 times more likely to occur on curves than on tangents (56). Glennon et. al (57) derived the following relations using regression analysis:

$$\Delta R = 0.056 \times \Delta Dc \tag{8-5}$$

Where:

ΔR =   the change in crash rate per 1.6 km (1 MVM) and
ΔDc =   change in the degree of curvature.

Zegeer at al (58, 59) developed the following relationships for highway segments with horizontal curvatures and no spirals:

A = 1.552 x L x V + 0.14 x D x V   (8-6)

D   =   degree of horizontal curvature in degrees;
L   =   length of curve in 1.6 km (1 mile);
V   =   vehicle exposure in 1.6 KMVM (1 MVM) in a 5 year period;

Based on the above relationships, it is estimated that compared to general segments (segments with no significant horizontal curvatures), the crash rates are 2.5 times higher for segments with sharp horizontal curvatures and 1.5 times higher for segments with moderate curvatures. In these studies, these factors were multiplied by the crash frequencies calculated as shown in Equation 8-4 to determine the frequencies of avoidable crashes due to LDWS during rain night conditions for segments with moderate and sharp horizontal curvatures.

8.2.7   Converting Benefits to Dollar Values

The estimated safety benefits of LDWS as described in the previous sections for different pavement marking improvement alternatives were converted to dollar values to allow the use of these estimates in the benefit-cost analysis of this study. The savings in dollar values due to the reduction in crashes were estimated to be $3,200,000 per fatal crash, $74,730 per injury crash, and $3,000 per PDO crash (60).

8.3   Pavement marking Cost

The life-cycle costs of the baseline and the three pavement marking improvement alternatives were estimated based on their material and installation costs and based on their expected service lives. A number of pavement marking vendors and transportation agencies were contacted to get

the cost information. In this study, the unit costs used to estimate these life-cycle costs were 1.64 $/meter ($0.5/linear feet) for thermoplastic markings and $8.2/meter ($2.5/linear feet) for wet-reflective tapes.

8.4   Benefit-Cost Assessment

The calculated cost of installing and replacing the pavement markings and the annual safety benefits of pavement marking improvements due to better LDWS performance in dollars were converted to present worth values for the purpose of the benefit-cost analysis of this study. The interest rate that was used to calculate the present worth values was assumed to be 6%. A spreadsheet tool was developed to calculate the present worth of benefits, present worth of costs, and the benefit/cost ratios of the pavement marking improvement alternatives under different conditions. The benefit/cost ratios were calculated as follows:

$$BC = \Delta Benefit / \Delta Cost \tag{8-7}$$

Where

$\Delta Benefit$	=	the difference in the present worth of safety benefits in dollar values between a pavement marking improvement alternative and the base alternative in dollars per 1.6 km (1 mile);
$\Delta Cost$	=	the difference in the present worth cost between a pavement marking improvement alternative and the base alternative in dollars per 1 mile; and
BC	=	benefit-cost ratio of a given pavement marking improvement alternative.

The benefit-cost analysis methodology was implemented in an Excel spreadsheet that allows varying a number of influencing factors in the benefit-cost analysis including:

- Highway type with default or specified crash rates
- Segment AADT value
- Proportion of heavy vehicles in the traffic stream
- LDWS market penetrations for trucks and passenger cars
- Horizontal alignment
- Shoulder width of the highway segment
- Proportion of crashes in night rainy conditions
- Marking improvement alternative costs and service lives.

Combinations of the above variables were varied in this study to examine their effects on the benefit-cost analysis results, as described in the next section.

8.5   Results

This section discusses the application of the methodology described in the previous sections to calculate the benefit-cost ratios of pavement marking improvement alternatives under different operation scenarios and LDWS market penetrations. The analysis was performed for a freeway segment with 1.86 crashes/MVM.

Figures 8-2 to 8-4 show the derived relationship between the calculated benefit-cost ratio (BCR) and AADT for two LDWS market penetration levels (25% and 50%). The truck percentage was fixed at 4% in the analysis. Figures 8-2 to 8-4 indicate that the benefit-cost ratios of the pavement marking improvement alternatives increased with the increase in the AADT and LDWS market penetration. In general, the BCR was the highest for Improvement Alternative 3A (wet-reflective tape with 6 year service-life) followed by Improvement Alternative 1 (replacing conventional thermoplastic markings every two years). Improvement Alternative 2 (replacing conventional thermoplastic markings every year) was not found to be cost-effective compared to Alternatives 1 and 3A.

For a general highway segment (with no significant horizontal curvature), Figure 8-2 indicates that all improvement alternatives could not be justified for AADT levels below 80,000 to 100,000 vehicles/day (vpd), based on the calculated BCR values. Above these AADT levels and with 50% LDWS market penetration, Alternatives 1 and 3A could be justified based on the BCR values. The sensitivity analyses performed in this study indicated that, for general highway segments with 25% LDWS market penetrations, Alternative 1 and 3A were cost effective only for very high AADT values (above 150,000 vpd to 160,000 vpd).

Figures 8-3 and 8-4 indicate that, for highway segments with moderate and sharp curvatures, Alternatives 1 and 3A were cost-effective at AADT levels of 40,000 vpd to 60,000 vpd with 50% LDWS market penetration. For 25% LDWS market penetration, these two alternatives were found to be cost effective at AADT levels above 100,000 vpd.

Figures 8-5 to 8-7 present the relationships between the LDWS market penetration and BCR for different marking improvement alternatives. The results presented in Figures 8-5 to 8-7 are for AADT equal to 80,000 vpd and truck percentage equal to 4%. These figures indicate that with low LDWS penetration (below 20%), all improvement alternatives could not be justified, even for segments with sharp horizontal curvatures for the AADT level used in the analysis (80,000 vpd). However, they could be justified at higher AADT levels (above 100,000 to 120,000 vpd).

As stated above, uncertainty is still associated with the service lives of wet-reflective tapes. The results presented in Figures 8-5 to 8-7 include a comparison of three different wet-reflective alternatives: 3A, 3B, and 3C, representing tapes with service lives of six, four, and three years, respectively. The results indicate that wet-reflective tapes with three to four year service lives were generally not cost-effective improvement alternatives.
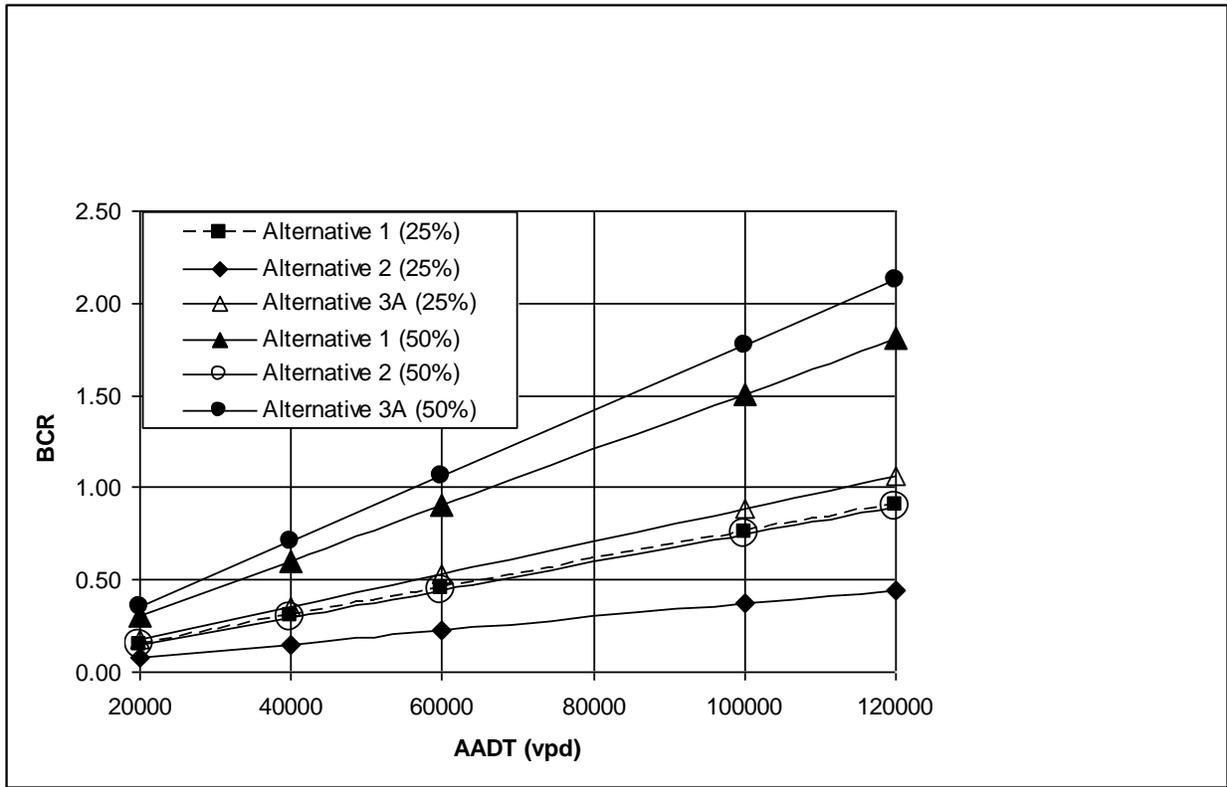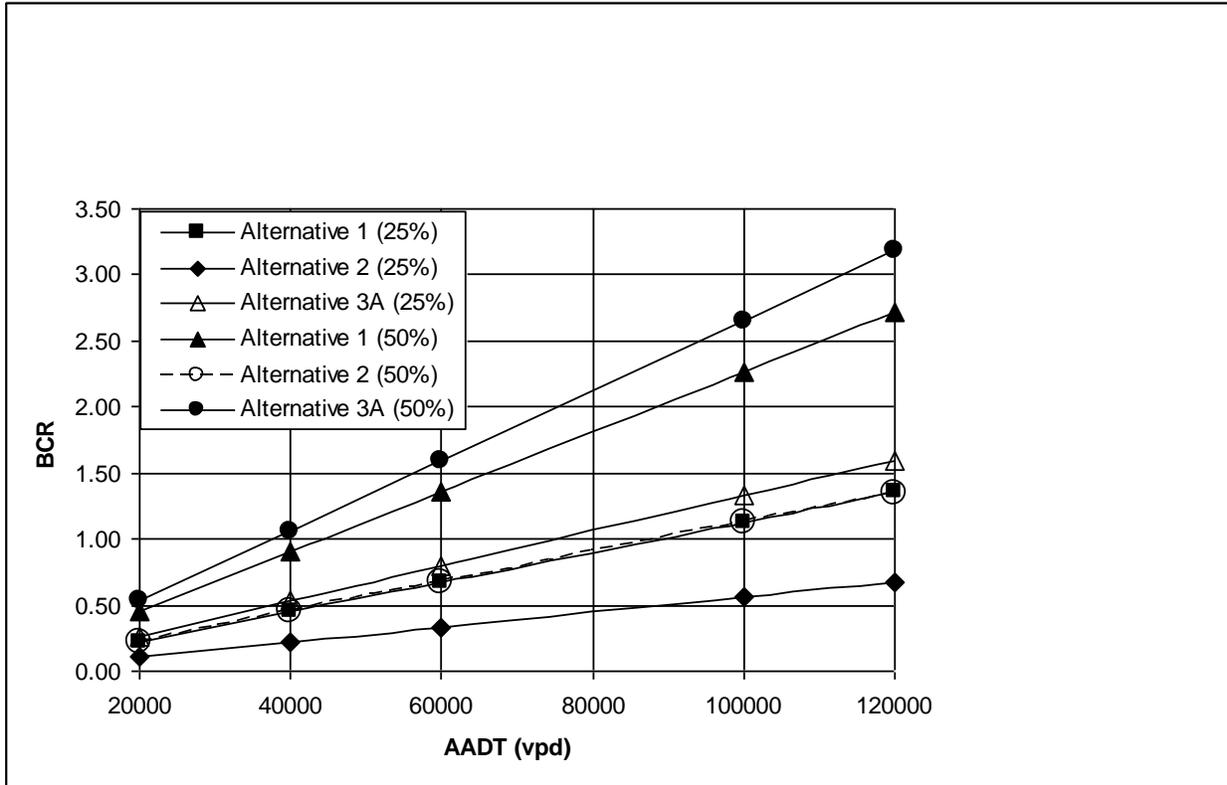
Figure 8-3: Variation of BCR with AADT for Segments with Moderate Curvatures (Percentages in brackets are LDWS market penetrations)
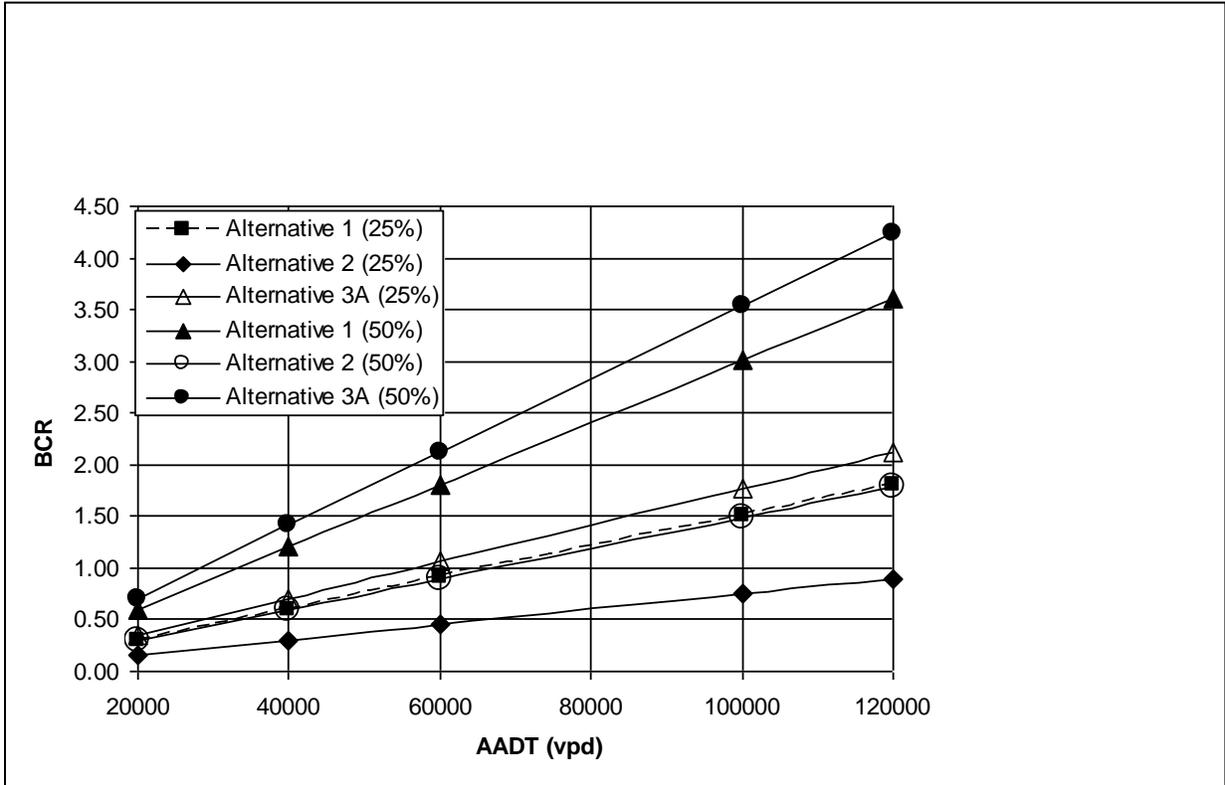
**Figure 8-4: Variation of BCR with AADT for Segments with Moderate Curvatures
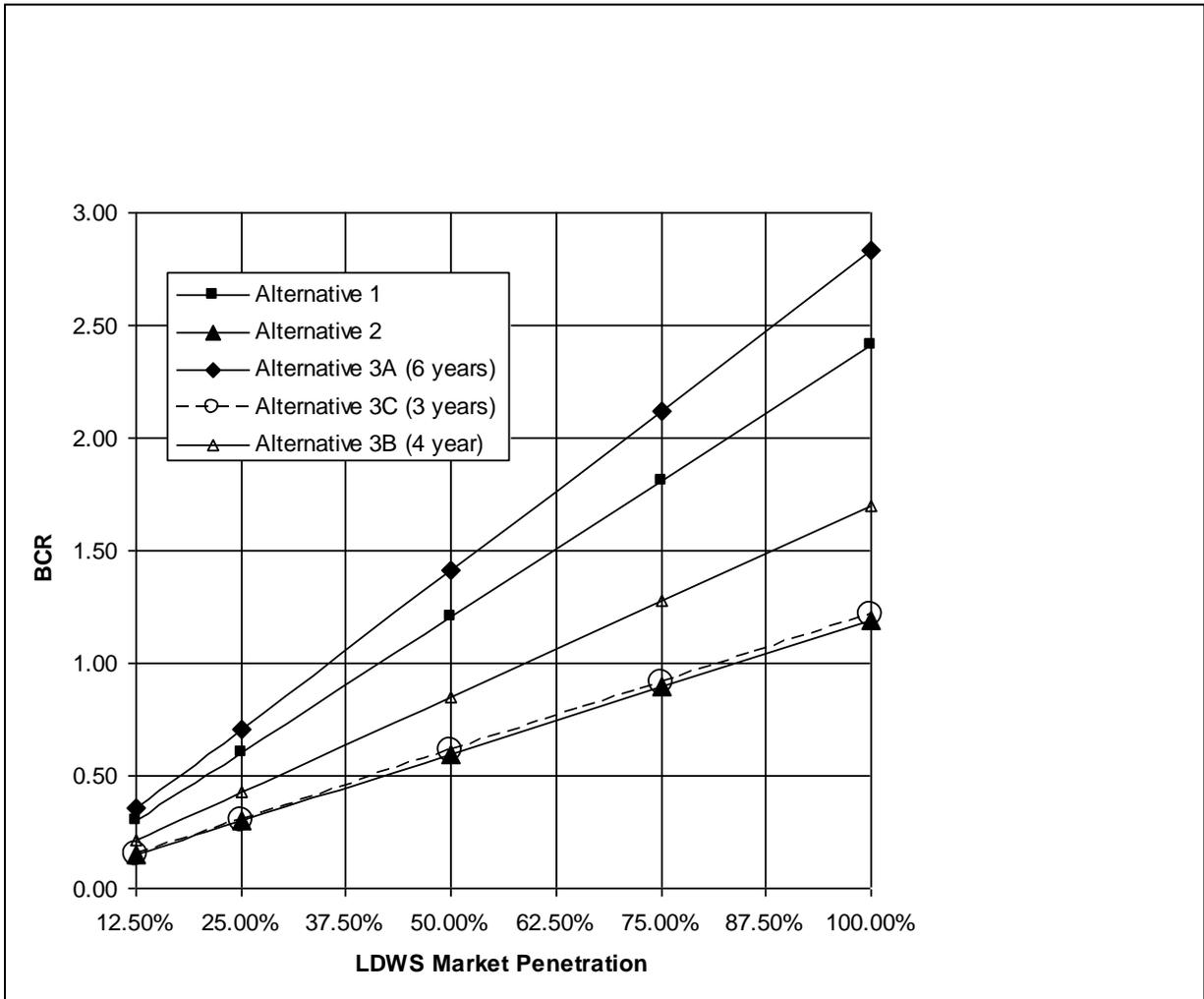(Percentages in brackets are LDWS market penetrations)**

Figure 8-5: Variation of BCR with LDWS Market Penetration for General Highway Segments. (Analysis performed for AADT = 80,000 vpd and truck percentage = 4%)
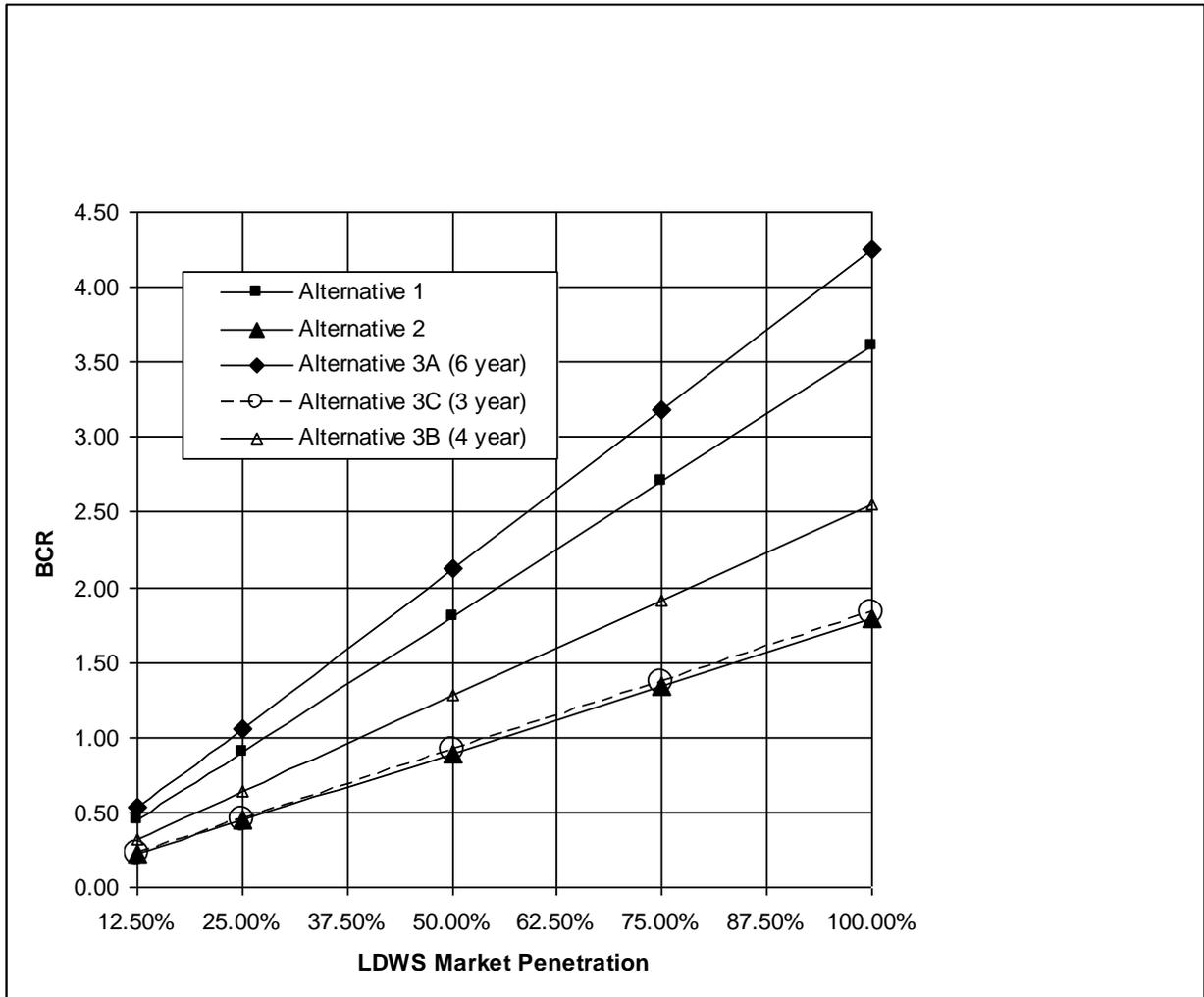
Figure 8-6: Variation of BCR with LDWS Market Penetration for Segments with Moderate Curvatures (Analysis performed for AADT = 80,000 vpd and truck percentage = 4%)
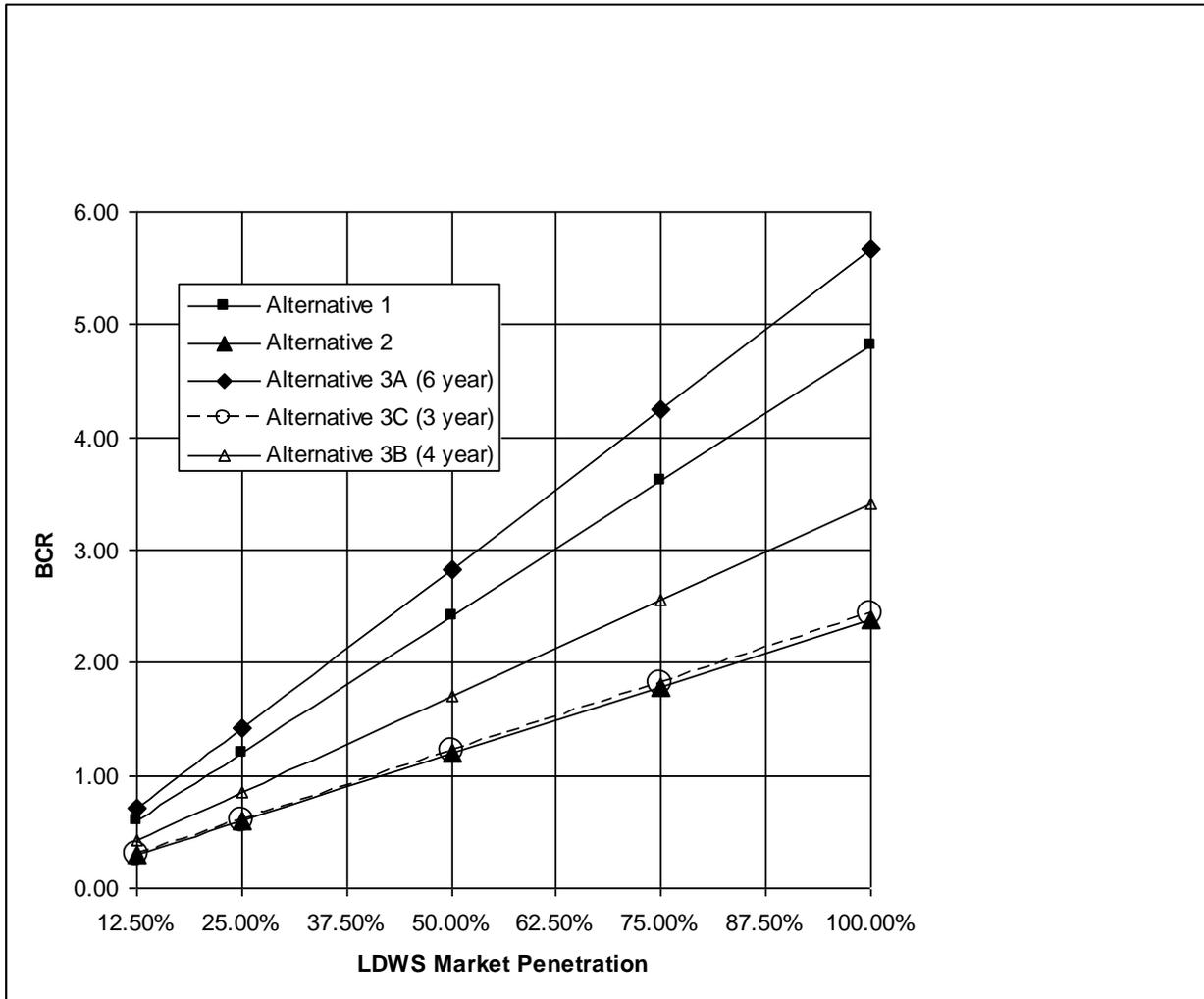
Figure 8-7: Variation of BCR with LDWS Market Penetration for Segments with Sharp Curvatures (Analysis performed for AADT = 80,000 vpd and truck percentage = 4%)

8.6   Conclusions

Pavement marking improvements, such as frequent replacement of conventional pavement markings or the installation of wet-reflective markings, can reduce the number of ROR and to a lesser degree lane changing crashes of LDWS-equipped vehicles, during night rainy conditions.

The benefit-cost analysis performed in this study indicates that some of these marking improvements can be justified from a benefit-cost analysis point of view for specific traffic operations (AADT level and truck percentage), horizontal alignment, and LDWS market penetration levels. Under these conditions, it is expected that installing wet-reflective tapes with long service life (longer than 6 years) is the most effective alternative followed by more frequent replacement of thermoplastic markings (every 2 years).

For a general segment of a typical freeway, it was found that marking improvements start to be cost-effective at 50% LDWS market penetration for freeways with 80,000 to 100,000 vpd or above and at 25% market penetration for freeways with very high AADT (160,000 vpd or above). Improving markings on highway segments with horizontal curvature, particularly those with sharp curvatures will result in higher cost-benefit ratios compared to those on general highway segments. Improving the markings on these segments can be justified from a benefit-cost point of view at a lower AADT and/or LDWS market penetration levels compared to general highway segments.

Additional sensitivity analysis can show that the BCR is also a function of truck proportions, shoulder widths, related crash rates on the highway segment under consideration and the proportions of these crashes in night rainy conditions.   Furthermore, the costs of wet-reflective tapes may drop in the future due to advancements in technologies and increasing competition. This reduction in tape costs combined with an increase in their service lives will increase their cost-effectiveness compared to other alternatives.

9.   Study Conclusions

The results of the field tests indicated that, the ER under dry and light rain conditions is expected to be 100%, except for a few roadway segments with bad contrast between the pavements and markings. In addition, it was observed that heavy rain conditions during daylight have little or no effect on the performance of LDWS. However, the results showed that the performance of LDWS is affected significantly by moderate to heavy rain conditions at night for typical pavement marking installations. Relationships were developed between ER during rain conditions at night and pavement marking retroreflectivity for conventional marking materials such as thermoplastic. The relationships show that LDWS perform significantly better with conventional markings that have higher retroreflectivity values. Since the retroreflectivity values drop with age due to the loss of beads, it is expected that LDWS performance during night rainy conditions deteriorates with marking age.

Detailed investigation was performed in this study to investigate the effect of the contrast between asphalt and concrete pavements and pavement markings on the LDWS performance during day light conditions. This contrast is a function of the pavement and marking colors. Based on the results presented in this chapter, it can be concluded that the tested lane departure warning system device was able to detect the pavement markings at a large proportion of the tested segments during day light conditions. However, for a few highway segments with light concrete and asphalt pavement colors, the device was not able to detect the yellow markings. Based on image analysis of the digital images taken of the pavement markings and background pavements, it can be concluded that the inability to detect the yellow markings can be related to attributes of the pavement marking color and pavement color, as measured by the three dominant colors (red, green, and blue).

The testing of improved pavement markings at a simulated rain facility confirmed that the pavement marking retroreflectivity has a significant effect on LDWS performance under medium to high rain intensities (0.52 to 0.87 inch/hours) at night light. The ER value was particularly low with the conventional markings that had a low retroreflectivity value. In addition, the results of this study indicated that using wet-reflective tapes (that uses special optics to improve marking visibility at night rainy conditions) or frequent replacement of existing conventional pavement markings to maintain high retroreflectivity will have positive effects on LDWS performance during rain at night light.

The benefit-cost analysis performed in this study indicates that some of the marking improvements can be justified from a benefit-cost analysis point of view for specific traffic operations (AADT level and truck percentage), horizontal alignment, and LDWS market penetration levels. Under these conditions, it is expected that installing wet-reflective tapes with long service life (longer than 6 years) is the most effective alternative followed by more frequent replacement of thermoplastic markings (every 2 years).

For a general segment of a typical freeway, it was found that marking improvements start to be cost-effective at 50% LDWS market penetration for freeways with 80,000 to 100,000 vpd or

above and at 25% market penetration for freeways with very high AADT (160,000 vpd or above). Improving markings on highway segments with horizontal curvature, particularly those with sharp curvatures will result in higher cost-benefit ratios compared to those on general highway segments. Improving the markings on these segments can be justified from a benefit-cost point of view at a lower AADT and/or LDWS market penetration levels compared to general highway segments.

Additional sensitivity analysis can show that the benefit-cost ratio is also a function of truck proportions, shoulder widths, related crash rates on the highway segment under consideration and the proportions of these crashes in night rainy conditions. Furthermore, the costs of wet-reflective tapes may drop in the future due to advancements in technologies and increasing competition. This reduction in tape costs combined with an increase in their service lives will increase their cost-effectiveness compared to other alternatives.

This study confirmed the generally high level of acceptance and satisfaction with the LDWS by truck drivers in the United States. The level of satisfaction was relatively low among the drivers of one of the companies surveyed. The low level of satisfaction of some drivers indicates the need for additional driver education of the system benefits.

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Appendix A
Survey Questionnaire

**Cargo Transporters
Contact Person:**
Danny Abernathy

North Oxford Street
P.O.BOX −339
Claremont, NC 28610

Phone: 828-459-3205/ 828-459-3291
Danny.Abernathy@ctgrp.com

Lane Departure System User Survey

The use of Lane Departure System technology may have the potential to reduce accidents. Please take a moment to help us gather information regarding your experience using this technology. When you have completed this survey, please return the survey to Danny Abernathy at Cargo Transporters.

User and Safety Related

Today's date is ___/___/___	1. Do you utilize Florida's Turnpike for a portion of your route? ☐ Yes ☐ No If so, please estimate the average number of <u>miles per month</u> that you drive Florida's Turnpike. ☐ More than 1000 miles ☐ 500 – 999 miles ☐ Less than 500 miles
2. How long have you been a professional truck driver? ☐ More than 15 years ☐ 11-15 years ☐ 6-10 years ☐ 0-5 years	3. How long have you been driving with a Lane Departure System? ☐ More than 12 months ☐ 9-12 months ☐ 5-8 months ☐ 0-4 months
4. Do you believe that Lane Departure Systems can prevent accidents? ☐ Yes ☐ No	
5. Can you provide an example of how your Lane Departure System may have helped you avoid an accident?	

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6. How confident do you feel using the Lane Departure System in poor (e.g., rain, sleet, fog and general low visibility) roadway conditions?
- ☐ High confidence
- ☐ Medium confidence
- ☐ Low confidence

</td><td>

7. Identify the Lane Departure System that you are currently using.
- ☐ AutoVue™ (Iteris, Inc.)
- ☐ Safe TRAC™ (Assistware, Inc.)
- ☐ Other _____(Please identify)

</td></tr>
</table>

Lane Departure System Related

8. Do you normally drive with the system on? If no, then identify those conditions when you turn the system on.	☐ Yes ☐ No
9. Under what conditions would you tend to turn the system off?	
10. Have you had any maintenance issues with the system? If yes, please identify them.	☐ Yes ☐ No
11. Does weather affect the system? If yes, please identify the types of weather and how they affect the system.	☐ Yes ☐ No
12. Do night conditions affect the system? If yes, please identify the night conditions and how they affect the system.	☐ Yes ☐ No
13. Does the system work better on particular chapters of the Turnpike? No If yes, why do you think this is the case?	☐ Yes ☐

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14. Which type of lane markings does the system better respond to?
- ☐ Edge (continuous) marking
- ☐ Centerline (skip line) marking

</td><td>

15. If you contacted the Lane Departure System's Customer Service, were all problems resolved?
- ☐ Yes, by the company or its representatives
- ☐ No, the problem was not resolved
- ☐ No problems/No contact with Customer Service

</td></tr>
</table>

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16. How satisfied are you with the Lane Departure System? ☐ Very satisfied ☐ Somewhat satisfied ☐ About average ☐ Somewhat dissatisfied ☐ Very dissatisfied	17. How likely are you to recommend the Lane Departure System product to other professional truckers? ☐ Definitely will recommend ☐ Probably will recommend ☐ Not sure ☐ Probably will not recommend ☐ Definitely will not recommend
18. What do you like about the system?	19. What do you dislike about the system?

Alarm Related

20. Do you feel the warnings come at the right time? ☐ Yes ☐ No Comments:	
21. How often do you receive false alarms? ☐ Never ☐ Often ☐ Seldom	22. In what type of conditions do you experience these false alarms?
23. How often does the system <u>not</u> provide an alarm when it is supposed to? ☐ Never ☐ Often ☐ Seldom	24. In what type of conditions do you <u>not</u> receive these alarms?

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25. What type of alarm do you generally prefer?
    ☐   Audio
    ☐   Visual
    ☐   Other _____(Please identify)

Additional Comments

If you have any additional comments about your experience with the Lane Departure System that have <u>not</u> been addressed in this survey, please enter them below.