EVALUATION OF WARNING LIGHTS ON MAINTENANCE OF TRAFFIC DEVICES AND DEVELOPMENT OF POSSIBLE ALTERNATIVES

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16. Abstract

This report documents the efforts and results of a number of studies and evaluations performed by TTI researchers to evaluate the effect and value of steady-burn warning lights on temporary traffic control devices used to delineate the correct travel path in work zones The effort also included a study of steady-burn warning lights on temporary barrier walls relative to the potential use of delineators currently used on permanent barrier wall. The research includes an assessment of the potential incremental increase in luminance (and benefit of that increase to drivers) during vulnerable driving conditions. These conditions include periods of heavy fog, periods when dew has formed on the reflective sheeting on channelizing devices, periods when dirt and grime have accumulated on the channelizing device, and when channelizing devices are viewed by drivers of large trucks who have a larger observation angle between their eye and the vehicle headlights that are illuminating the reflective sheeting. The researchers assessed the effect of warning light misalignment upon its apparent luminance to drivers, as well as the effect of providing steady-burn warning lights on channelizing devices and temporary barrier walls upon driver visual glance behavior, driving behavior, and driver opinions. Finally, the researchers performed an assessment of the costs of providing steady-burn warning lights and the necessary improvements in work zone safety that would need to be achieved in order to offset those costs. Based on the findings, the researchers recommended that the statewide application of steady-burn warning lights in all work zones be discontinued.

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EXECUTIVE SUMMARY

The objectives of this study were to (a) evaluate the effectiveness of warning lights in work zones on temporary traffic control devices and temporary barrier walls and (b) evaluate the effectiveness of temporary barrier wall delineation alternatives.

To accomplish this, the researchers performed several luminance evaluations, aimed at assessing the impacts of fog, dew, driver observation angle, dirt, and misalignment. In order to assess the impact of using steady-burn warning lights to older drivers, which constitute a significant proportion of the Florida population, the researchers conducted a driving study to evaluate older driver visual glance behavior, lane position, and driver opinions. Finally, the researchers performed a cost-effectiveness analysis to determine the necessary improvements in work zone safety that would need to be achieved in order to offset the cost of providing and maintaining steady-burn warning lights throughout all Florida DOT work zones.

The researchers found that fog adversely affects the apparent luminance, and thus visibility distance, of both retroreflective sheeting and warning lights at very dense fog levels. However, at fog levels one might expect to see in the field, retroreflective sheeting is still likely to be visible at distances needed for path guidance and delineation purposes, and the use of warning lights are unlikely to provide much additional value to motorists.

The researchers also found that the presence of dew on the retroreflective sheeting of a channelizing device can reduce drum luminance by up to 84 percent, but the likelihood of dew formation is not known, given the air pocket that is trapped inside each drum. However, the amount of luminance achieved under dew conditions is still likely to be sufficient for path guidance purposes, which again suggests that warning lights may not provide substantial additional benefit to drivers.

Steady-burn warning lights may substantially increase overall average luminance values of channelizing drums for vehicles with larger observation angles, such as heavy trucks, especially when placed on the left side of the roadway. However, the luminance values of the drums with high intensity sheeting were sufficient to be seen at distances up to 1,000 ft from a truck driver's viewing perspective, suggesting that they would provide sufficient detection and guidance information to truck drivers, even without the use of steady-burn warning lights.

The accumulation of dirt and grime on the retroreflective sheeting of channelizing drums in Florida work zones does have an impact on drum luminance. While the presence of warning lights did increase the overall luminance of drums, a greater increase in luminance was noted when the drums were cleaned by research staff and re-measured.

An evaluation of misaligned lights found in Florida work zones revealed that more than half of the warning lights mounted on drums were misaligned more than five degrees from their optimum viewing angle. In addition, almost all of the warning lights mounted on temporary barrier walls were misaligned more than five degrees. For an LED warning light, this misalignment reduces its apparent luminance to approximately 20 percent of that of a properly aligned warning light.

During the older driver study, the researchers found that the use of steady-burn warning lights on channelizing drums in work zones did not affect the visual glance behavior of older drivers. Likewise, the lights were not found to have a consistent effect on driver lane position when traveling adjacent to the drums. While the study participants did indicate a preference for warning lights to be used on the channelizing drums in work zone, none of the participants noticed the absence of lights on drums in some of the test sections. Rather, the researchers had to call attention to the fact that some drums did not have warning lights on them prior to asking participants about their preference for such lights.

When compared to the use of barrier delineators as specified in Florida DOT standards, the use of warning lights on temporary barrier wall did not did not appear to affect older driver visual glance behavior or vehicle lane position when traveling adjacent to the drums. A majority of study participants expressed a preference for the delineators over the warning lights on temporary barrier walls, citing better visibility as the reason. Once again, however, only two of the study participants recalled noticing a difference in barrier delineation in the work zone.

During the cost-effectiveness evaluation, the researchers determined that the cost of providing, operating, and maintaining LED warning lights is approximately $0.10/day per device, consistent with current bid prices experienced by FDOT. Multiplied by typical light spacing, FDOT's current practices result in LED warning light costs ranging from as high as $20/mile/day for urban arterial work zones down to $6/mile/day for barrier delineation in freeway work zones, where the warning light spacing is much longer.

A crash reduction benefit analysis indicated that the use of warning lights in urban arterial work zones would need to result in more than a 10 percent reduction in all nighttime crashes relative to what would occur if warning lights were not used on the channelizing devices. Although a warning light crash modification factor is not currently available, researchers believe it would be extremely difficult for the addition of warning lights themselves to consistently generate this amount of nighttime crash reduction.

On freeway work zones where warning lights are used to delineate traffic barriers, the longer spacing between lights results in a lower usage cost of approximately $6/mile/day. As a result, such lights could become cost-effective at a lower crash rates relative to a no-light condition. This study showed that a 2 to 5 percent reduction would be needed. However, researchers again questioned whether such a small benefit could be consistently achieved, given the human factors findings from this project. The fact that warning lights could be replaced with retroreflective delineators on the barrier for approximately one-tenth of the cost of warning lights would further diminish the potential incremental safety benefit that the provision of warning lights in lieu of barrier delineators could generate.

Based on the results of these evaluations, the researchers recommend that the statewide application of steady-burn warning lights in all work zones be discontinued.

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CHAPTER 1 INTRODUCTION

BACKGROUND

One of the most important elements of good work zone traffic control is the provision of positive guidance for motorists. Good positive guidance enhances a driver's ability to traverse the work zone in a safe and efficient manner. This is especially true during nighttime and/or adverse weather conditions where visibility is greatly reduced. In such cases, drivers may not have the benefit of seeing much more than lighting and retroreflective material that will guide them through the work zone. In addition, older drivers, who are more likely to have reduced motor skills and reduced visual acuity than younger drivers, may have difficulty navigating nighttime work zones during adverse weather conditions. The 2009 Manual on Uniform Traffic Control Devices (MUTCD) (*1*) recognizes the potential safety benefit of providing enhanced delineation on temporary traffic control (TTC) devices and allows for warning light enhancements on channelizing devices and temporary barrier walls.

However, Florida Department of Transportation (FDOT) is one of only a few state transportation agencies that currently mandates the use of low-intensity steady-burn warning lights during periods of darkness on temporary channelizing devices (*2*). These lights are also required on temporary barrier wall, per FDOT Standard Index 415 Sheet 1 (*3*), which states "Type C Steady-Burn Lights are to be mounted on top of temporary concrete barriers that are used as barriers along traveled ways in work zones. The lights are to be spaced at 50 ft centers in transitions, 100 ft centers on curves, and 200 ft centers on tangent roadways."

When warning lights were initially deployed, channelizing device retroreflectivity was limited to engineer grade sheeting, which is no longer allowed on state roadways in Florida. With the current requirement to use high-intensity sheeting on temporary traffic control devices, the need to continue the use of warning lights has been questioned.

STUDY OBJECTIVES

The objectives of the study were to:

- Evaluate the effectiveness of warning lights in work zones on temporary traffic control devices and temporary barrier walls.
- Evaluate the effectiveness of temporary barrier wall delineation alternatives.

CONTENTS OF THIS REPORT

This report details the two-year research effort to evaluate the effectiveness of steady-burn warning lights on channelizing devices and temporary barrier walls using a variety of methods. Chapter 2 provides a review of past research and existing state policies regarding the use of steady-burn warning lights and temporary barrier wall delineation. Chapter 3 describes how the researchers characterized the attributes of steady-burn warning lights and channelizing device retroreflectivity under a variety of field conditions. Specific implementation and environmental conditions were evaluated, including:

- Foggy condition performance.
- The presence of surface dew on channelizing drum sheeting.
- The effect of differences in headlamp illumination upon channelization device visibility.
- The presence of surface dirt and grime on channelizing drum sheeting.
- The effect of light misalignment in work zones.

Chapter 4 describes the human factors study used to assess the impacts of steady-burn warning lights upon work zone guidance capabilities of older drivers. This study was also used to compare an alternative delineation method for temporary barrier wall to standard (warning light) delineation. Chapter 5 describes an evaluation of the cost-effectiveness of the use of steady-burn warning lights in Florida work zones from a potential safety performance perspective. Finally, Chapter 6 provides the researchers' recommendations regarding the use of steady-burn warning lights in Florida work zones.

CHAPTER 2 LITERATURE REVIEW

PREVIOUS RESEARCH

Previous research has investigated the effectiveness of warning light enhancements on channelizing devices and temporary barrier walls. A brief review of the findings from that body of research is provided below.

Steady-Burn Warning Lights on Channelizing Devices

Steady-burn warning lights are intended to define the edge of the travel path. On Florida DOT projects, they are used to delineate transition, buffer, work, and termination areas of traffic control zones (*2*). NCHRP Report 476 (*4*) suggests that the brightness and size of steady-burn lights are overpowered by large, reflectorized channelizing devices, making the value of steady-burn lights questionable. However, previous research has investigated the effectiveness of steady-burn warning lights on temporary channelizing devices with mixed results.

In a broad study of channelizing devices in 1981, Pain et al. (*5*) found that steady-burn warning lights provided significant increases in detection distance at night to drums with engineering-grade sheeting, but provided no improvements when added to drums with high-intensity sheeting. Measures of effectiveness (MOEs) were detection, vehicle control, and driver preference. The researchers recommended that steady-burn warning lights be used at night on tapers in the transition area. In addition, they concluded that most channelizing devices show reasonably successful detection and path guidance information. Interestingly, the researchers also concluded that a major deterrent to effectiveness was not the device itself, but poor positioning, the presence of dirt on devices, and overturned devices that destroy the visual line created by channelizing devices.

In 1992, Pant et al. (*6*) conducted a study of steady-burn warning lights in work zones for the Ohio Department of Transportation. Participants drove an instrumented vehicle through tangent sections of several work zones on rural, divided highways, both with and without steady-burn warning lights. Field conditions in the work zones included channelizing drums with high-intensity sheeting that were in good condition, as well as some that were described as dirty or worn. The amount of dirt or wear on the devices was not further quantified, so the actual impact on device visibility was not well understood. Weather conditions during the study included rain, fog, and dry weather. MOEs included vehicle speed as the primary MOE, with lateral placement, acceleration noise, weaving, traffic conflict, and driver preference as secondary MOEs. The researchers found no practical differences in the MOEs and concluded that steady-burn warning lights on drums with high-intensity sheeting had little effect on drivers at night and recommended that Ohio DOT discontinue their use in tangent sections.

That same year, Pant et al. (*7*) studied the effect of steady-burn warning lights on the lane-changing behavior of motorists in advance of work zone tapers. This study utilized a different group of work zones than the prior study, but used the same MOEs with the addition of lane-changing data. The researchers recorded traffic volumes at three or four locations in each lane upstream of the taper with and without steady-burn warning lights. The researchers found no significant differences in any of the MOEs, including the proportions of traffic in each lane upstream of the tapers, and concluded that the steady-burn warning lights had no effect on lane-changing behavior of motorists at night when the work zone consisted of drums with high-intensity sheeting and an arrow panel.

However, another driving study published by KLD Associates (*8*) in 1992 found that the use of steady-burn lights on channelizing devices significantly influenced driver behavior in some work zone configurations, such as left lane closures. In this study, drivers of all ages were able to identify lane closures and shoulder closures from greater distances when lights were used on channelizing devices, compared to the same devices with no lights. The researchers found that drivers age 55 and older consistently showed poorer performance than younger drivers in all study conditions (i.e., work zone configuration, device type, and light placement). In addition, they found that the use of lights improved the performance of older test subjects.

More recently, McAvoy et al. (*9*) evaluated channelizing drums with and without steady-burn warning lights for Michigan DOT using field observations of drivers in highway work zones. MOEs included vehicular lateral placement, speed, steering reversals, and traffic crash experiences. The results showed that drivers' lateral lane positioning and guidance capabilities were not impacted by the presence of steady-burn warning lights on drums. The researchers also compared crash experiences prior to construction with those during construction for both the test and control sites and found no differences, concluding that steady-burn warning lights on drums do not impact the occurrence of work zone crashes.

In a related study, McAvoy et al. (*10*) conducted a study of steady-burn warning lights on drums using a nighttime driving simulator. Analysis of the simulator data showed no statistical differences in vehicular lateral placement, speed, and steering reversals. There was a significant difference in simulated traffic crash frequency, with more crashes occurring while drivers were traversing sections of simulated roadways with steady-burn warning lights present on channelizing devices. When attempting to validate the simulator findings with the field studies, there were mixed results. The researchers concluded that although driving simulators can be useful tools in human factors research, they cannot replicate motorists' perceptions of the risks associated with nighttime work zones. In addition, the researchers found that the field condition of channelizing devices was difficult to replicate in a driving simulator, noting that the actual reflectivity of drums was often reduced during real construction due to dust associated with the construction, road debris, or minor dents and tears in the sheeting.

In 2010, Datta et al. (*11*) performed a study sponsored by Michigan DOT to evaluate the safety and mobility impacts associated with the elimination of steady-burn warning lights on drums in construction work zones. Researchers reviewed work zone crash data from 26 states and they observed only slight differences between the rates of work zone crashes in states with different policies regarding the use of steady-burn warning lights on work zone drums. The states that frequently use lights on drums had a slightly higher work zone crash rate among the three groups at 0.059 crashes per million vehicle miles traveled statewide. The states that infrequently use lights on drums had the lowest crash rate of any of the three groups at 0.034 work zone crashes per million vehicle miles traveled. The states that do not use lights on drums had a crash rate of 0.038 work zone crashes per million vehicle miles traveled. Certainly, the lack of actual work zone vehicle-miles of exposure limited the researchers' ability to draw any conclusions regarding these crash rates. Furthermore, no discernible differences were observed between any of the three groups of states when examining work zone crashes as a proportion of total crashes.

Datta et al. further examined work zone crash data within Michigan and concluded that:

- A comparison of data between the two groups of locations, those with and those without without steady-burn warning lights, showed that both groups of work zones experienced reductions in total crashes and nighttime crashes in comparison to the same time period prior to the start of construction.
- The same data showed that a significantly higher proportion of work zone crashes tended to occur during nighttime conditions at locations with steady-burn warning lights (39 percent) compared to locations without steady-burn warning lights (30 percent).
- Among those crashes occurring in the presence of drums, the proportion of the crashes that may have been affected by the drums was indistinguishable between the two comparison groups. The work zones that utilized steady-burn warning lights showed that 20.4 percent of such crashes may have been influenced by the drums, compared to 20.0 percent in the work zones that did not utilize steady-burn warning lights.
- Based upon overall crash trends, as well as the sample of work-zone specific crash data, it appears that drivers age 65 and older were not overrepresented in nighttime work zone crashes involving drums, regardless of the presence of steady-burn warning lights.

The researchers also conducted nighttime luminance evaluations of work zone channelizing drums with and without steady-burn warning lights in Michigan work zones and in controlled tests and they found that:

- The presence of a steady-burn warning light provided very little improvement to drum luminance whether measured in the field or in the controlled environment.
- Prismatic sheeting materials provide the largest improvement to drum luminance, doubling the average luminance of drums with high-intensity sheeting in field testing.
- The luminance increase provided by changing the drum sheeting from high intensity to prismatic was approximately 77 times greater than the luminance increase that can be attained by adding a steady-burn warning light to a drum with high intensity sheeting when measured in a controlled environment.

This study also included a detailed survey of state practices regarding the use of warning lights on channelizing drums. Forty-two states responded to the survey. Although the survey included all channelizing devices, only the use of warning lights on drums were reported in the survey findings. Frequent use was defined as the use of the warning lights in more than 30 percent of work zones. The infrequent use category includes states that use the lights in less than 10 percent of work zones, while the final category was for those states that never use warning lights on channelizing drums. Three states (7 percent) reported that the warning lights were frequently used (Florida, Illinois, and Oklahoma). Ten states (24 percent) reported infrequent use of the warning lights, while 28 states reported that they did not use warning lights on channelizing drums (*11*).

Based on a synthesis of all results, the Michigan study researchers concluded that steady-burn warning lights demonstrated little, if any, additional value to nighttime visibility, improvements in driver behavior, or crashes when used on work zone channelizing drums with high-intensity or prismatic sheeting materials. If Michigan DOT desired additional nighttime brightness on the drums in certain situations, the researchers concluded that the use of prismatic sheeting provides a far greater increase in visibility compared to the addition of a steady-burn warning light to the drum (*11*). As a result of this research, Michigan DOT has eliminated the requirement to use steady-burn warning lights on channelizing devices. The warning lights are now optional at the engineer's discretion (*12*).

Steady-Burn Warning Lights on Temporary Barrier Wall

Concrete barrier placed close to travel lanes can be difficult to see at night, especially when placed on concrete pavement. During hours of darkness, contrast sensitivity is reduced, making it difficult to see objects of all sizes when they are not significantly brighter than their background. Older drivers show a reduced sensitivity to contrast, further diminishing their ability to distinguish objects at night (*13*).

Contrast is reduced even further in rainy conditions and/or under the glare of opposing headlamps, making proper delineation especially important on temporary barrier walls. Further contributing to the visibility challenges is the fact that pavement edge lines near the barrier may be missing or obscured by dirt during construction, leaving motorists to rely solely on the barrier delineation for guidance.

NCHRP Report 476 (*4*) indicates that reflective markings, raised pavement markers, or steady-burn warning lights placed near the top or on top of temporary barrier wall enhance the visibility of the barriers under adverse conditions. It also recommends that some type of delineation enhancement be provided whenever the barrier is placed closer than a few feet from the travel lane.

Several studies of barrier delineation in work zones were performed prior to 1985, with mixed results. Mullowney (*14*) studied the visibility of reflective devices on New Jersey barrier, including the effects of weathering, glare, vertical placement, and wet nighttime conditions on reflectivity, visibility, and durability. He concluded that delineation should be mounted on the top of the barrier so it will retain its reflectivity longer and require less maintenance. Ugwoaba (*15*) performed a study for Washington State DOT in 1987 and recommended side-mounted concrete barrier delineation so that the delineators were not masked by oncoming headlamp glare. Interestingly, he also noted that dirt accumulation on delineators decreased with increasing mounting height and that delineators should be cleaned regularly. In a study of concrete barrier visibility documented in NCHRP Report 236, Pain et al. (*5*) found that reflectors performed better than reflectorized tape. Many other studies in the mid-1980s sought to determine optimum reflector size, shape, brightness, and spacing of reflective delineators on barrier wall, arriving at different conclusions (*16*, *17*, *18*).

In 1988, Ullman and Dudek (*19*) conducted a study of barrier delineation treatments for Texas Department of Transportation (TxDOT). The first phase of the study included an evaluation of five different delineator treatments varying by delineator type, spacing, and mounting positions on the barrier. Observations of nighttime traffic in the lane adjacent to the barrier were recorded, including lane distribution, lane straddling, and lateral distance from the left rear tire to the bottom of the barrier. Overall, the researchers found little difference in the delineation treatments. The second phase of the study was to determine how the visibility and brightness of different types of delineators deteriorate over time because of dirt and road film. In a controlled field study, drivers aged 18 to 56 were asked to provide subjective evaluations of delineator brightness. Although the clean delineators received comparable rankings, subjects did express a preference for side-mounted delineators in lieu of top-mounted delineators, stating that they provided a more direct line of sight, a better indication of the location of the wall, and a more realistic perception of the lane width. With respect to dirt-covered delineators, cube-corner lenses at 50-ft spacing were preferred over treatments with high-intensity sheeting. This was because the cube-corner reflectors did not lose their reflectivity as quickly as the sheeting treatments. Interestingly, the researchers also noted that delineation mounted on the side of the barrier lost its visibility quicker than top-mounted delineation (*19*).

STATE POLICIES FOR STEADY-BURN WARNING LIGHT USE

Steady-Burn Warning Lights on Channelizing Devices

The researchers sought to identify which states require steady-burn warning lights on channelizing devices by accessing state DOT standards online. With the exception of Florida, the researchers found two states that currently require the use of steady-burn warning lights: Arizona and Illinois.

Arizona

Arizona DOT requires the use of steady-burn warning lights on channelizing devices when the roadway is not continuously lighted. The Arizona DOT *Guidelines for Design of Temporary Traffic Control for State Highway Construction, Maintenance, Utility, and Incident Management Operations* (*20*) specifies when steady-burn warning lights are to be used:

> "Type A flashing warning lights shall be placed on each end of each type III barricade whenever the type III barricade will remain in place overnight or whenever the barricade is set during early morning hours or construction extends into the late evening hours. Type C steady burning lights shall be placed on every vertical panel, type I and II barricade and drum during the same periods. The exception to this standard is for sections of roadway that are continuously lighted where neither type of warning light will be required for channelizing devices."

Illinois

Illinois DOT also requires the widespread use of steady-burn warning lights. Article 701.16 of the Illinois DOT *Standard Specifications for Road and Bridge Construction* (*21*) includes a table that outlines the requirements for use of these lights. As shown in Table 2-1, steady-burn lights are required in all nighttime lane closures and tapers.

Table 2-1. Illinois DOT Steady-Burn Light Requirements for Work Zones.

Circumstance	Steady-Burn Lights Required
Daylight operations	None
Devices delineating isolated obstacles, excavations, or hazards exceeding 100 ft in length at night (Does not apply to widening)	Bi-directional
Channelizing devices for nighttime lane closures on two-lane roads	Bi-directional
Channelizing devices for nighttime lane closures on multi-lane roads	Mono-directional
Devices in nighttime lane closure tapers	Mono-directional
Devices delineating patches at night on roadways with an ADT of 25,000 or more	Mono-directional

Illinois DOT also has research currently underway to help them decide if the continued use of warning lights is warranted. The research includes a field study of driver behavior around actual work zone setups, as well as focus groups to gather insight into driver interpretations of work zone setups. The results of the study have not yet been published (*22*).

Temporary Barrier Delineation

The *MUTCD* (*1*) requires that temporary traffic barrier be supplemented with delineation, pavement markings, or channelizing devices for improved daytime and nighttime visibility. For this study, TTI researchers sought to identify state DOT requirements for delineation of temporary barrier wall by accessing state DOT standards online. The researchers obtained data for 31 states. Table 2-2 shows a summary of the findings.

Table 2-2. State Delineation Requirements for Temporary Barrier Wall.

State	Mounting Location				Reflective Area (in^2)	Color	Spacing (ft)			
	Top	Side	Both	Either			Tangent	Taper	Curve	All
Alabama	X				36	fluor yellow	40	20		
Alaska		X				match				10
Arizona				X	12	match				25
California	X				36	match				S[1]
Colorado	X									50
Delaware						match				50
Georgia	X				100	yellow	40	20		
Idaho					9					
Illinois			X		6.5	match				
Iowa		X				match				12.5
Kansas					7		50		25[2]	
Kentucky				X		match			50-100[3]	
Louisiana		X			7					15
Maine				X	8					30
Maryland			X[4]		96 (top) 7.5 (side)	fluor orange match				48
Massachusetts			X		8	match	20		10	
Michigan		X			7.5	match				20
Mississippi	X				25	match	20		10	
Missouri						match				50
New Hampshire			X		9	match				
New Mexico										
New York[5]					18	match			20	
North Carolina										
Ohio	X				7	match				50
Oklahoma		X			14[6]	match				12.5
Oregon		X			144[7]	fluor orange or white				
Pennsylvania		X			7.5	match				37.5
South Carolina			X[8]		72 (top) 7 (side)	match	20 10	10 1		
Texas			X		7	match				40
Utah					12					
Vermont					7	match				
Virginia	X				96	orange	80	40		
Washington			X			match				40
West Virginia					96	match				20
Wyoming			X			match				20

[1] S is the speed limit (mph)
[2] when curve radius is less than 1900 ft
[3] varies based on degree of curve
[4] requires both fluorescent orange on top and matching on side of temporary barrier wall
[5] NYSDOT also allows warning lights to be used for temporary barrier wall delineation
[6] consists of two 7 square inch delineators, both placed on the side of the temporary barrier wall
[7] consists of 4 in × 36 in corrugated aluminum panels, placed longitudinally along the face of the temporary barrier wall
[8] requires both large reflector on top and small reflector on side

Most states use some type of retroreflective tabs, disks, or panels in lieu of steady-burn warning lights to delineate temporary barrier wall in work zones. Of the 31 state delineation standards reviewed, 25 states specify a mounting location in their online documents. The researchers found a fairly even distribution in the mounting location of the delineators among these 25 states. Seven state DOTs (28 percent) require that the delineators be mounted on the top of the barrier, while another seven state DOTs (28 percent) require that the delineators be mounted on the side of the barrier. Eight state DOTs (32 percent) require that the delineators are mounted on both the top and the side, while three state DOTs (12 percent) allow the delineators to be mounted on either the top or the side.

Some state DOTs have established minimum dimension(s) or surface areas for each retroreflective device, while others specify an exact size. The researchers found size specifications for 25 of the 31 states shown in the table. The most unique delineation standard was found in Oregon. The Oregon DOT *Traffic Control Plans Design Manual* (*23*) calls for reflective barrier panels to be used to delineate the face of temporary concrete barrier wall and enhance conspicuity. A typical panel installation is shown in Figure 2-1. These panels are unique because they are not mounted perpendicular to traffic, so the retroreflective surface area is much smaller than the actual panel dimensions (4 inches wide and 36 inches long). The panels are made from corrugated aluminum and are either fluorescent orange or silver-white in color.

Figure 2-1. Oregon Department of Transportation Reflective Barrier Panels (*23*).

Georgia DOT specifies the largest conventional delineator panel, a minimum 10 inches by 10 inches (100 square inches total). Virginia DOT and West Virginia DOT each specify an eight inch by 12 inch delineator panel (96 square inches). Maryland State Highway Administration (SHA) and South Carolina DOT both require a combination of delineators, specifying a large delineator (96 and 72 square inches, respectively) to be mounted on the top of the barrier and a small delineator (7.5 and 7 square inches, respectively) to be mounted on the side of the barrier. These large delineator panels are significantly larger than the retroreflective tabs or disks used by most states. Fourteen (56 percent) of the 25 state DOTs with size specifications call for a relatively small delineator, having a surface area of 12 square inches or less.

Of the 27 states for which color specifications were found, Alabama and Georgia are the only states that specify a yellow delineator panel, regardless of the color of the edge line adjacent to the temporary barrier wall (i.e., yellow or white). Both Maryland and Virginia require that their larger, top-mounted delineator panels are fluorescent orange in color, while the smaller, side-mounted delineators are required to match the edge line. The remaining 23 states with color specifications (85 percent) specify that the color of the delineators match the edge line.

Delineator spacing requirements were identified for 27 of the 31 states. The majority of these state DOTs (63 percent) have established a fixed spacing requirement for all conditions, and these fixed spacings vary anywhere from 10 to 50 ft. One state DOT (California) calls for the spacing in feet to be equal to the speed limit in mph. Some (11 percent) of the 27 state DOTs reduce the spacing in tapers, while others (11 percent) reduce the spacing in curves.

New York State Department of Transportation (NYSDOT) also allows the use of Type C steady-burn warning lights to delineate temporary barrier wall. The maximum spacing between lights is 40 ft, except in curves with radius less than 2,800 ft, where the lights must have a maximum spacing of 20 ft. Interestingly, the maximum spacing for warning lights is larger than the maximum spacing for retroreflective delineator tabs, which must not exceed 20 ft regardless of geometry. The percentage of NYSDOT work zones that use warning lights on temporary barrier wall in lieu of retroreflective delineators is not known.

SUMMARY

With the development of high intensity sheeting in the early 1970s, many state DOTs have eliminated their requirements for the use of steady-burn warning lights on channelizing devices. Several of the few states that still use the warning lights are questioning the value of continuing to require them. While Arizona DOT continues to require steady-burn warning lights on channelizing devices, Illinois DOT is currently sponsoring research aimed at evaluating their effectiveness. The Michigan DOT research findings recently led the agency to discontinue their requirement and make the warning lights optional at the project engineer's discretion.

Regarding delineation of temporary barrier walls in work zones, the researchers found that most state DOTs require the use of retroreflective delineators. Mounting requirements vary from state to state, with some requiring that the delineators be mounted on the top of the barrier, some on the side, some require both, and others allow for either. Those states that specify a delineator size and color typically require a retroreflective surface area of 12 square inches or less and require that the color of the tab match the adjacent edge line. Delineator fixed spacing requirements vary considerably, from 10 to 50 ft, with a few states decreasing the spacing based on roadway geometry.

CHAPTER 3 PHOTOMETRIC EVALUATION OF WARNING LIGHT PERFORMANCE UNDER VARYING ENVIRONMENTAL CONDITIONS

INTRODUCTION

Adverse weather conditions such as rain and fog can create visibility challenges for some drivers, especially at night. At night, a driver is able to see an object when light from some source, such as a headlamp, shines on the object and reflects back to the driver's eyes. Water droplets that are suspended in the air scatter the projected light traveling to and from illuminated objects. As a result, the amount of light that would normally be returned to a driver from an illuminated object is reduced in rain and fog, making the object less visible. As water droplet size decreases and droplet density in the air increases, visibility decreases. In addition, some of the scattered light from the headlamps is reflected off water droplets themselves directly back to the driver as "backscatter," which reduces the contrast of everything in the driver's field of view. Backscatter can also produce glare, which further reduces contrast and may create visual discomfort. While glare impairs vision for all drivers, it can be especially detrimental for older drivers.

Dew that forms on retroreflective devices, such as channelizing devices, may also limit visibility at night. This is because the dew that forms on the surfaces of traffic control devices can interfere with the retroreflective behavior of the sheeting itself (*24*).

When reduced visibility conditions occur, drivers may be less likely to see objects in their travel path, such as a slow or stopped vehicle, roadway debris, or an animal, and may also be less able to perceive the proper travel path through a work zone due to reduced visibility of delineation and channelizing devices. In this chapter, the researchers focused on the impacts of environmental conditions prevalent in Florida that could diminish the performance of retroreflective sheeting used on channelizing devices, and attempted to determine if and how steady-burn warning lights could potentially mitigate those impacts. Specifically, the researchers quantified the impacts of fog, dew, vehicle type, dirt, and misalignment based on climate data, laboratory testing, and field evaluations.

The researchers reviewed several different studies to determine the minimum brightness that a work zone channelizing device, such as a drum, should have in order to be detected. The researchers were unable to find any current research related to minimum levels of retroreflectivity for channelizing devices. A related study that examined luminance needs for traffic signs was also reviewed (*25*), but the observation angles for these devices are different from channelizing devices. One study, completed in 1988, suggested that a drum covered in all orange ASTM Type II beaded super engineer grade retroreflective material would be detected over 1,000 ft away in a low complexity environment (*26*); however, the retroreflective materials used in that study were dated in comparison to what is available in current markets. The retroreflectivity values for ASTM Type III and IV materials, which are now commonly used, are two to three times higher than Type II, based on the standard geometries as stated in ASTM D4956-09 (*27*).

PREVAILING FOG CONDITIONS IN FLORIDA

The researchers tabulated one year of climate data for 10 Florida cities to identify the number of days that fog was recorded by the Florida Climate Center (*28*). For purposes of this analysis, heavy fog was said to occur when visibility was reduced to less than ¼ mile (or 0.4 km). The results are shown in Table 3-1.

Table 3-1. Number of Foggy Days per Year in Select Florida Cities.

City	FDOT District	Number of Days with Heavy Fog	Number of Days with Any Fog
Tallahassee	3	49	104
Apalachicola	3	43	55
Jacksonville	2	27	50
Pensacola	3	16	24
Daytona Beach	5	12	41
Orlando	5	12	63
Tampa	7	9	12
Miami	4	7	7
West Palm Beach	4	4	5
Key West	6	3	3

FDOT Districts 2, 3, and 5 see more fog than other districts because, in the winter months, warmer coastal air drifts over the cooler land in north and central Florida, developing an adiabatic fog which often dissipates by mid-morning. In Tallahassee, for example, some degree of fog was detected, on average, 104 days per year. If one focuses only on heavy fog conditions as defined above, such conditions were detected, on average, 49 days per year. The duration of the fog varied from a few minutes to several hours, and typically did not occur for the entire day. Any type of fog is rare in the southern part of the state, which includes Districts 4, 6, and 7.

In order to further examine weather conditions in Florida, more extensive climatic data were collected for the four cities with the highest number of heavy fog days (Tallahassee, Apalachicola, Jacksonville, and Pensacola). The geographic distribution of these four cities is shown in Figure 3-1.

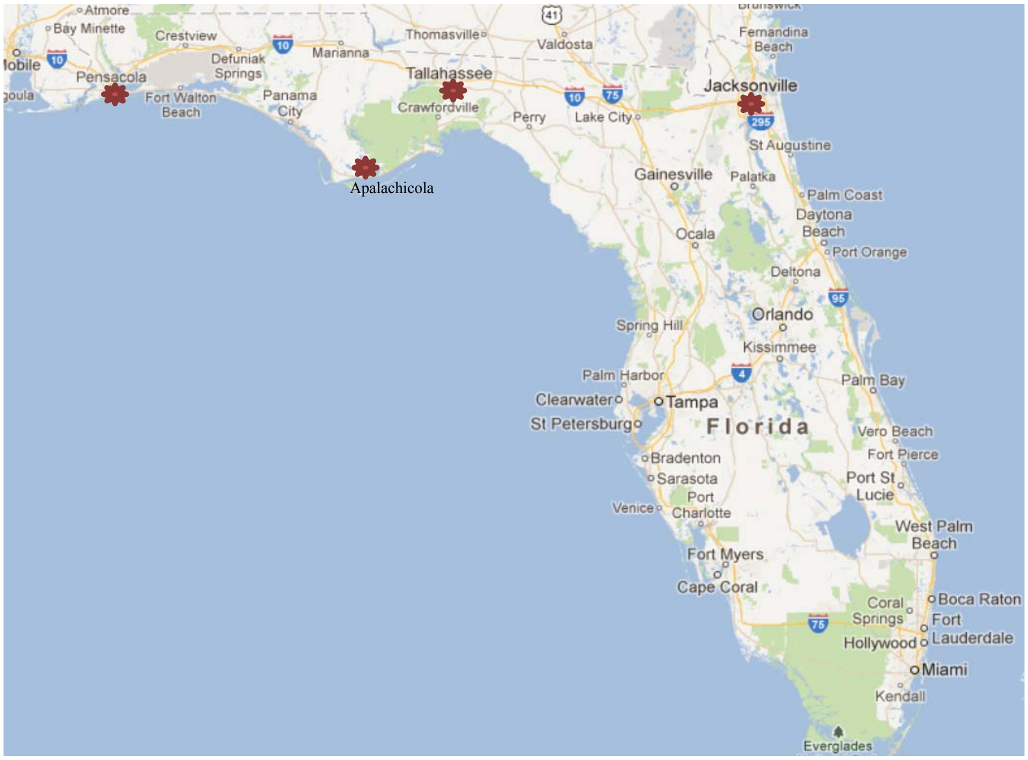
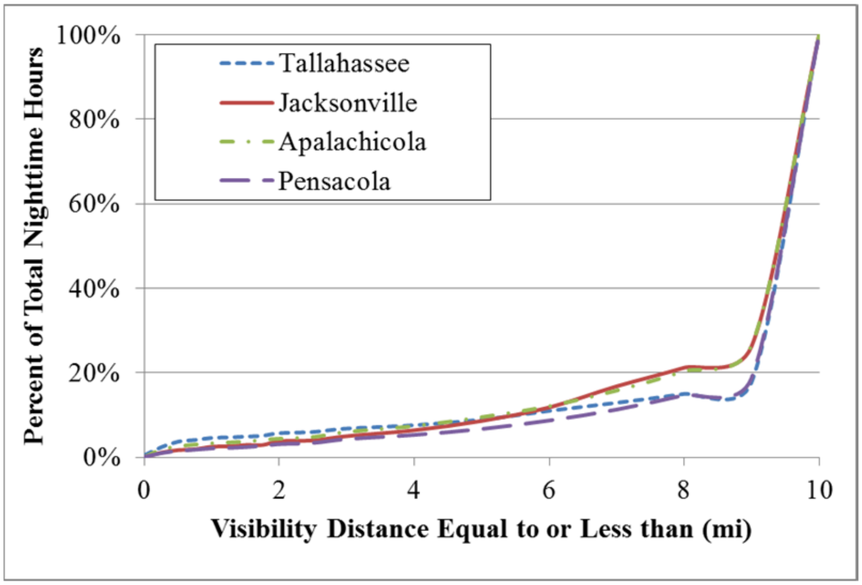
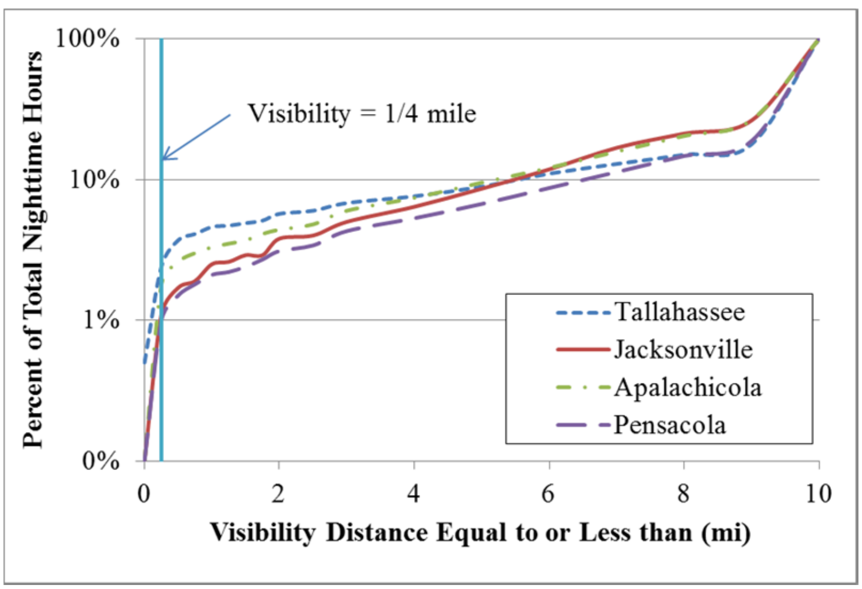


Figure 3-1. Geographical Distribution of the Four Studied Cities in Florida.

The data were obtained for three years (from 2009 to 2011) from the National Climatic Data Center (NCDC) (*29*), which uses data reported by Automated Surface Observing System (ASOS). ASOS is a multi-sensor system installed at more than 900 airports across the United States to measure wind speed and direction, temperature, dew point, cloud coverage, visibility, precipitation, and barometric pressure (*30*). The weather information collected from ASOS is commonly used by pilots and airport-based weather personnel. The data were tabulated and then compared to sunrise/sunset times in order to reduce the dataset to include only periods of darkness. These nighttime periods are when steady-burn warning lights are required on channelizing devices. Because the warning lights are not required in during periods of daylight, daytime fog conditions were not included in the analysis. The nighttime visibility levels as reported by NCDC using ASOS are depicted graphically in Figure 3-2 for the four foggiest cities in Florida.



(a) Nighttime percentages vs. visibility distances (linear scale)



(b) Nighttime percentages vs. visibility distances (logarithmic scale)

Figure 3-2. Cumulative Percentage of Nighttime Visibility.

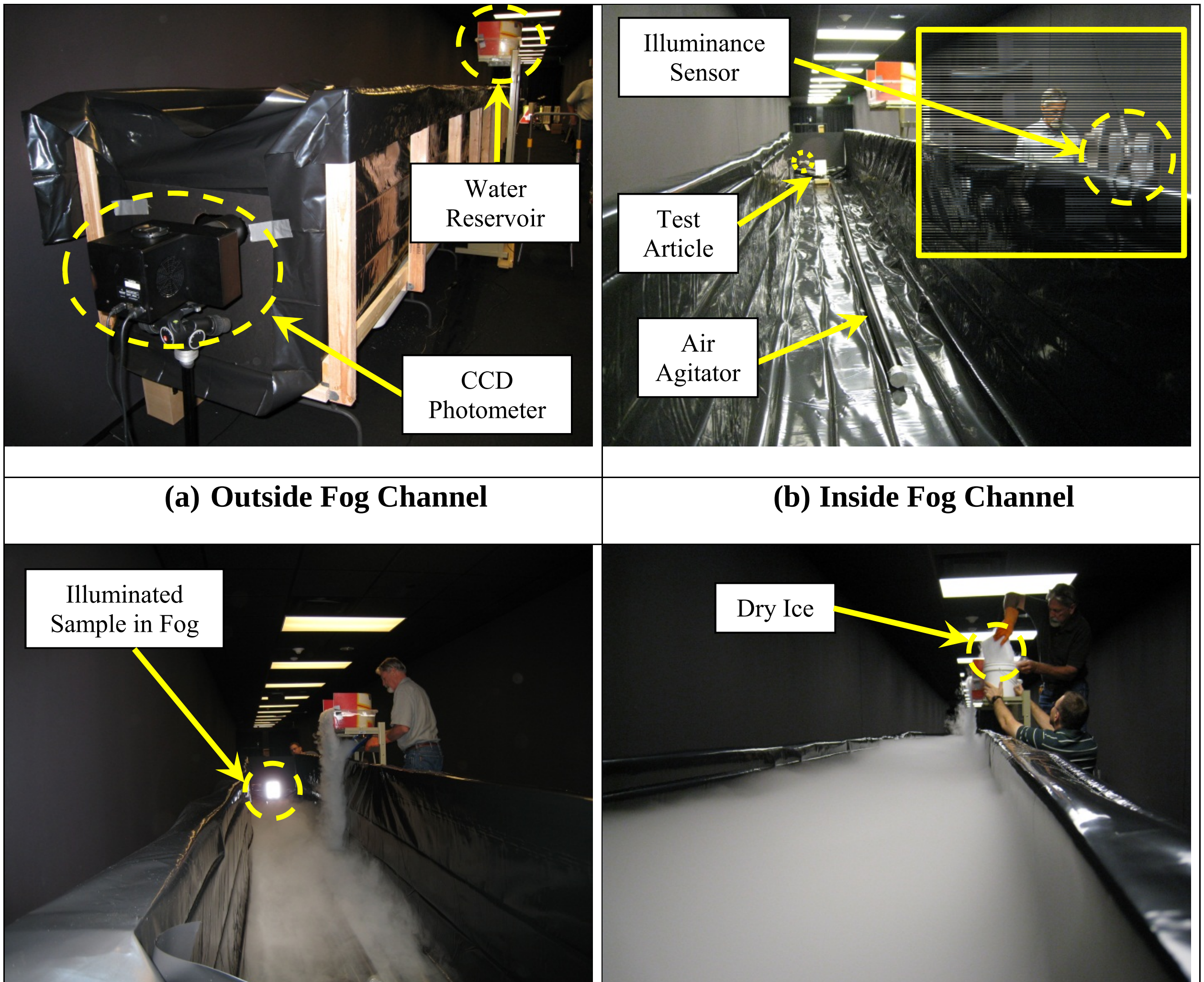
Figure 3-2(a) shows the cumulative percentage of nighttime hours along the y-axis, using a linear scale, for various visibility levels along the x-axis. Given that a visibility level of seven miles is considered a clear condition, this graph shows that Jacksonville and Apalachicola only see visibility levels at night below seven miles around 17 percent of the time. Percentages for Tallahassee and Pensacola were even smaller. So, at least 83 percent of the time, visibility at night is very good. Figure 3-2(b) shows the cumulative percentage of nighttime conditions along the axis using a logarithmic scale. This allows closer inspection of the data at the lower percentages. The graph shows that visibility levels at night fall below ¼ mile, which is considered "heavy fog," less than three percent of the time in Tallahassee, less than two percent in Apalachicola, and around one percent in Jacksonville and Pensacola.

Based on these data, the researchers concluded that periods of heavy fog occurring simultaneously with periods of darkness were very infrequent, even in the foggiest cities in Florida. In addition, these periods of heavy fog typically occur during early morning hours of darkness when traffic volumes are likely at their lowest. Furthermore, during adverse weather, drivers also tend to reduce their speed (*31, 32*).

IMPACT OF FOG ON CHANNELIZING DRUMS WITH STEADY-BURN WARNING LIGHTS

The previous assessment answered the question as to the level of fog exposure that typically exists in Florida. Another question that must be asked is whether steady-burn warning lights themselves could provide significant improvement to path guidance, above that provided by channelizing device retroreflectivity, under such nighttime foggy conditions. Based on the documented infrequent nature of nighttime fog and variability with fog density, it was not feasible for the researchers to collect data under actual fog conditions in Florida, so the researchers created fog in a laboratory setting to measure the luminance of retroreflective sheeting and the illuminance of a steady-burn warning light under varying levels of fog.

A fog channel was constructed in the TTI Visibility Research Laboratory (VRL) using a wood frame lined with six mil polyethylene liner, as shown in Figure 3-3. The fog channel was approximately seven meters long and one meter wide. Fog was created using an elevated water reservoir, shown in Figure 3-3(a), and dry ice, shown in Figure 3-3(d). The reaction between water and dry ice, called sublimation, creates a cloud of true water vapor fog. To circulate the fog and prevent settling in the channel, the researchers added an air agitator, shown in Figure 3-3(b), which consisted of a perforated PVC pipe with a small fan forcing air through the pipe and into the channel. The researchers filled the channel with fog, as shown in Figure 3-3(c), until zero visibility was reached, then allowed the fog to dissipate naturally until clear visibility was reached. The researchers visually determined when zero visibility was reached and when clear visibility was reached.



(a) Outside Fog Channel | **(b) Inside Fog Channel** | **(c) Fog Initiated** | **(d) Maximum Fog Density**

Figure 3-3. Fog Channel in TTI Visibility Research Laboratory (VRL).

For the test, a new sample of white sheeting and a new steady-burn warning light were evaluated separately. On one end of the channel, a calibrated National Institute of Standards and Technology (NIST) projection light source was used to shine light upon the test sample and the Konica Minolta T-10 illuminance meter, which were both placed at the opposite end of the channel. The illuminance meter was placed in a position that a) would not block the light reaching each test sample and b) would not be blocked by the sample being measured. The illuminance meter captured the amount of light falling on the area where the test sample was located and recorded these values, in lux, periodically during the fog dissipation cycles. Illuminance measurements were taken over multiple fog dissipation cycles for each test sample. These values were used to estimate the atmospheric transmissivity of the lab-created fog at various points in time. The researchers used Allard's Law (*33*), shown in Equation 1.

$E = (I * T^x)/x^2$ **(Equation 1)**

where,

E is the illuminance of the light source (lux).

I is the luminous intensity of the light source in the direction of the target (candelas).

T is the atmospheric transmissivity (per mile).

x is the distance between the light source and the target (miles).

The illuminance of the light source, E, was measured at a known distance, x, in the fog channel. Since the light source was calibrated, the value for I was known. Therefore, atmospheric transmissivity, T, could be calculated for each illuminance value captured by the meter. Typically, this measurement process, from the creation of maximum fog density representing zero visibility to a no-fog condition representing clear visibility, took two minutes or less. Figure 3-4 shows the maximum transmissivity values achieved in the laboratory. Previous research by others to quantify the visibility associated with various levels of atmospheric transmissivity (*34*) is reported in Table 3-2. Comparing the values in Figure 3-4 to those in Table 3-2, it was clear that the TTI researchers were able to generate a fog density, albeit for short periods, that was much greater than what is typically seen in the field.

Meanwhile, the luminance of the test samples was measured using a calibrated Remax/Radiant Imaging PM-1600 charge-coupled device (CCD) photometer, which was placed adjacent to the light source. Measurements were taken over multiple fog dissipation cycles for each test sample. Using synchronized times from the data files, the researchers correlated the measured luminance values of the test samples, measured in candelas per square meter (cd/m^2), to various calculated levels of atmospheric transmissivity.

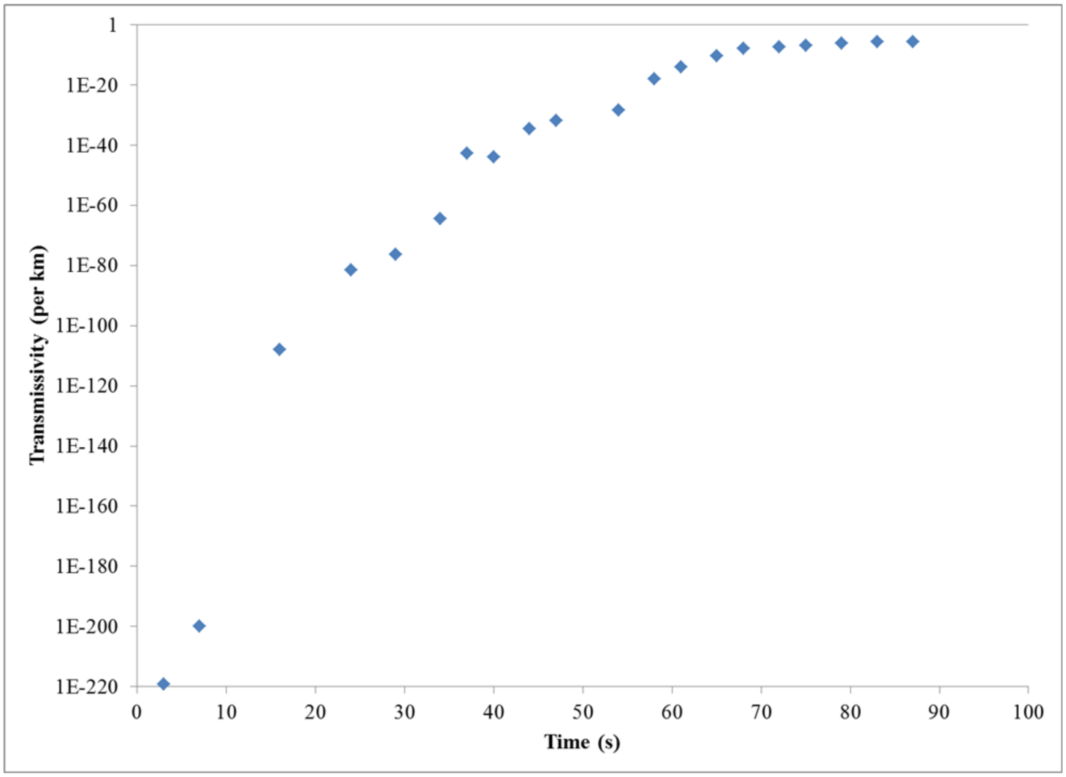


Figure 3-4. Dissipation of Transmissivity Levels Achieved in the VRL Fog Channel.

Table 3-2. Transmissivities and Extinction Coefficients for Various Weather Conditions (*34*).

Code Number	Weather	Maximum Meteorological Optical Range (kilometers)	Maximum Extinction Coefficient (per Meter)	Maximum Transmissivity (per Kilometer)	Maximum Transmissivity (per statute mile)	Maximum Transmissivity (per nautical mile)
9	Exceptionally clear	50+	0.00006-	0.94+	0.91+	0.89+
8	Very clear	50	0.00006	0.94	0.91	0.89
7	Clear	20	0.00015	0.86	0.79	0.76
6	Light haze	10	0.00030	0.74	0.62	0.57
5	Haze	4	0.00075	0.47	0.30	0.25
4	Thin fog	2	0.0015	0.22	0.090	0.062
3	Light fog	1	0.0030	0.050	0.0081	0.0039
2	Moderate fog	0.5	0.0060	0.0025	0.000065	0.000015
1	Thick fog	0.2	0.015	3.1×10^{-7}	3.4×10^{-11}	9.0×10^{-13}
0	Dense fog	0.05	0.060	9.5×10^{-27}	1.3×10^{-42}	6.5×10^{-49}
	Very dense fog	0.03	0.10	4.3×10^{-44}	1.6×10^{-70}	4.8×10^{-81}
	Exceptionally dense fog	0.015	0.20	1.8×10^{-87}	2.6×10^{-140}	2.3×10^{-161}

Equation 2 quantifies the effect of adverse weather on drum luminance through reduced transmissivity.

$$\mathrm{L}' = \mathrm{L} * T^{x} \qquad \textbf{(Equation 2)}$$

where,

L' is the device luminance in inclement weather (cd/m^2).

L is the device luminance in clear weather (cd/m^2).

T and x are as defined above.

The luminance data for the standard Empco model 2006 LED warning light and the white panel of Avery Dennison 6500 ASTM Type IV prismatic sign sheeting, as selected from FDOT QPL, are shown in Figure 3-5. The data collected in the VRL revealed several key findings. First, reduced atmospheric transmissivity due to fog appears to affect both warning lights and retroreflective sheeting in a similar manner at transmissivity values above 1E-140 or so, which encompasses almost the entire range of fog conditions illustrated in Table 3-2 above. Second, Figure 3-5 does imply that it may be possible to achieve a relative visibility benefit from the use of warning lights on drums under visibility conditions where transmissivity levels are below 1E-185 or so. However, this corresponds to a visibility level of approximately 15 meters. This visibility level is almost impossible to achieve naturally. In addition, a typical motorist would be incapable of safely operating a vehicle under such conditions.

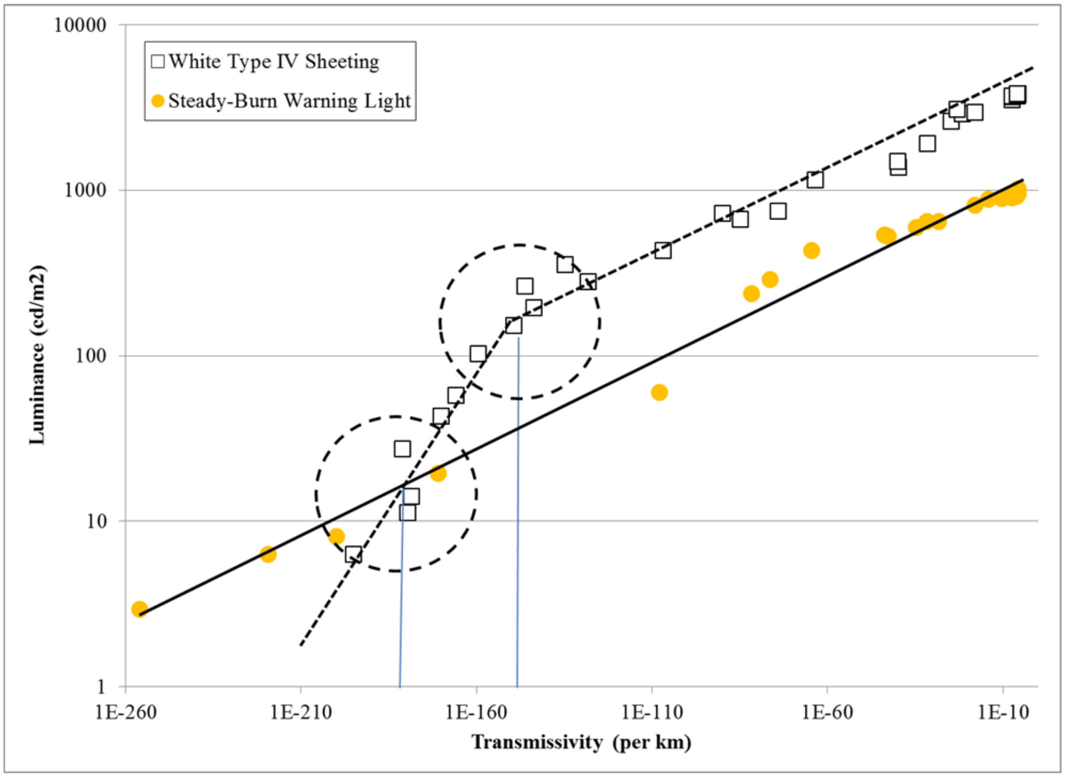


Figure 3-5. Device Luminance versus Fog Visibility Level.

IMPACT OF SURFACE DEW ON VISIBILITY OF CHANNELIZING DRUM SHEETING

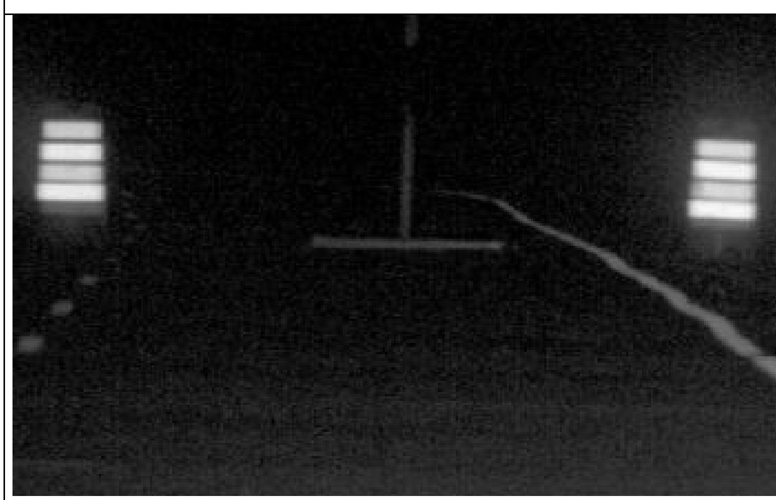
Dew is another type of small water droplet that can impact retroreflectivity. Dew can form on surfaces at night when the object surface becomes cooler than the surrounding air. If the air around the surface cools to the dew point or below, water vapor condenses on the surface, creating dew. In its frozen state, the dew becomes frost and both can reduce the performance of retroreflective sign sheeting.

Hildebrand (*35*) performed a study of in-service traffic signs to quantify the average effects of frost and dew on their retroreflective capabilities. The results were then compared with proposed minimum retroreflectivity standards recently developed by FHWA-sponsored research for inclusion in the MUTCD. Although the effects of frost and dew were found to be variable, average reductions in retroreflectivity levels of 79 percent and 60 percent, respectively, were found. None of the different colored signs sampled with Type I engineering grade sheeting was found to meet the proposed minimum levels when covered in frost or dew (with the exception of signs with white backgrounds covered in dew), even though all signs were in like-new condition. Signs sampled with Type III high intensity sheeting had mixed results. The author concluded that the findings were significant enough that they should be considered in the development of the final version of the FHWA national standards. Furthermore, he recommended that those jurisdictions subject to frequent cycles of frost and dew should review usage guidelines governing the grade of sign materials used, allowing for expected loss of retroreflectivity.

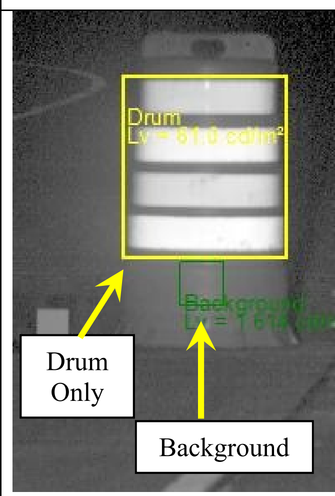
Similar to the research by Hildebrand, TTI researchers in this project sought to estimate the impact of dew on the visibility of channelizing drum retroreflective sheeting through a field evaluation performed at the Texas A&M University Riverside Campus. Considering the climate in Florida, frost was not evaluated. The researchers collected photometric data on relatively new, clean channelizing drums with ASTM Type III sheeting. Both clean non-dew and dew conditions were evaluated. Researchers collected the data using a 2009 Ford Explorer, as shown in Figure 3-6(a). The vehicle uses HB4 Halogen bulbs inside a visually optically aligned (VOA) headlamp and all of the testing was conducted using low-beam headlamps. Luminance measurements were taken using the PM-1600 CCD Photometer, shown in Figure 3-6(b). A single drum with a steady-burn warning light was laterally offset to the left and another to the right of the travel lane approximately 3 ft from edge of the lane to the center of the drum, shown in Figure 3-6(c). The vehicle was centered in the 12-ft travel lane. Researchers then used the CCD photometer to measure luminance values every 50 ft starting 1,000 ft from the drum.

a) Test Vehicle

b) PM-1600 Setup



c) Channelizing Drum Setup



d) Measurement

Figure 3-6. Dew Test Measurement Setup.

The researchers determined the luminance of the retroreflective portion of each channelized drum using Prometric 10.0 software. The researchers selected large regions of retroreflective area on the drum to measure luminance, and then a smaller area where retroreflective sheeting was not present in order to mask out the area in the background not associated with the drum. Figure 3-6(d) shows the two regions reduced from each image. The researchers chose to take the background reading from the bottom of the drum because it was shown that the luminance from the plastic drum surface was greater than the luminance of the image background, which included the pavement, horizon, and anything else near and around the drum. The average luminance provided from the background reading was used to set a threshold in the software that represented a minimum pixel luminance for the image. Using this threshold value, researchers could then remove any image pixels that were at or below the threshold value from the image calculations, and thus only assess the luminance of the sheeting itself. The researchers measured and recorded the drum luminance without the presence of surface dew at predetermined distances. The researchers then chilled the drum below the dew point in order to create dew on the drum surface. To accomplish this, the researchers laid the drum horizontally on the pavement and loaded the inside of the drum with ice until dew formed. Once the dew formed, the drum was gently stood upright over the ice bags with the dew-covered side facing the test vehicle, as shown in Figure 3-7.

Figure 3-7. Formation of Dew on Surface of Channelizing Drum for Luminance Evaluation.

Luminance values were again recorded with the CCD photometer at predetermined distances. Although the assessment performed with dew on the device took several minutes, it was assumed that the dew level remained fairly constant during the testing (i.e., the researchers could not visually detect any significant difference in dew levels on the drum over the duration of the test). Figure 3-8 shows the data from the dew test. The researchers found that surface dew reduced drum luminance by as much as 84 percent. As the test vehicle got closer to the drum, the impact of dew did appear to decrease. Whether this decreasing effect was a result of increased headlamp illumination due to being closer to the drum or an evaporation of the dew from the drum surface over time (as the researchers took measurements closer to the drum) could not be determined.

Although the researchers were able to generate dew on the drum surface for purposes of this test, it was not clear whether such dew will regularly form on drums in locations such as Florida. Unlike traffic signs, channelizing drums have a trapped pocket of air inside the device that acts as a thermal barrier to minimize temperature changes. Consequently, one cannot simply review temperature and dew point climate data from a location to determine the potential likelihood of dew formation on channelizing drums. Given that the researchers were able to note that the channelizing drum was still visible at 1,000 ft under the dew condition created for the test, it is unlikely that a reduction in drum visibility due to the formation of surface dew is a significant problem, even in high humidity locations such as Florida.

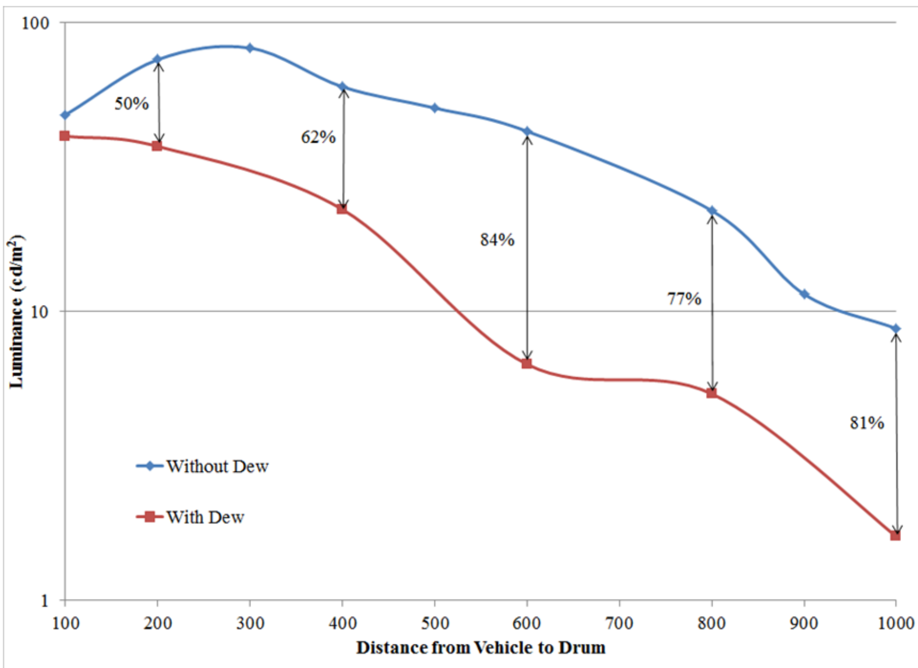


Figure 3-8. With Dew versus without Dew.

IMPACT OF VEHICLE TYPE ON VISIBILITY OF CHANNELIZING DRUMS WITH STEADY-BURN WARNING LIGHTS

The performance of retroreflective materials is dependent on the observation angle between the light source (i.e., headlamps) and the driver's eye. Obviously, different vehicle types will create slightly different observation angles for drivers. Variations in driver eye height and headlamp height contribute to the difference in observation angles. To assess the difference in apparent luminance by vehicle type, the researchers conducted a test of two channelizing drums with steady-burn warning lights. The researchers used a 2010 Kenworth semi-tractor and a 2009 Toyota Camry Hybrid. The change in the calculated observation angle with respect to distance for the two different vehicles are shown in Figure 3-9. The setup at the Riverside Campus was similar to the dew test described in the previous evaluation, but with steady-burn warning lights placed on the drums. The Kenworth had sealed-beam halogen headlamps, and the Toyota had halogen HB4 projector headlamps. All tests were conducted using low-beam headlamps.

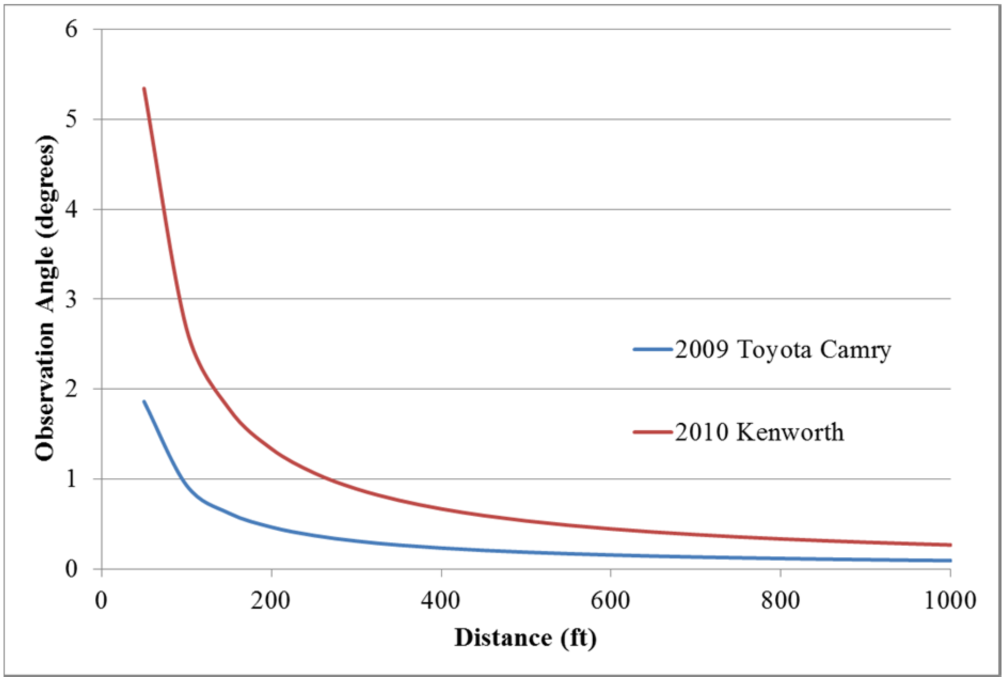


Figure 3-9. Observation Angle by Vehicle Type.

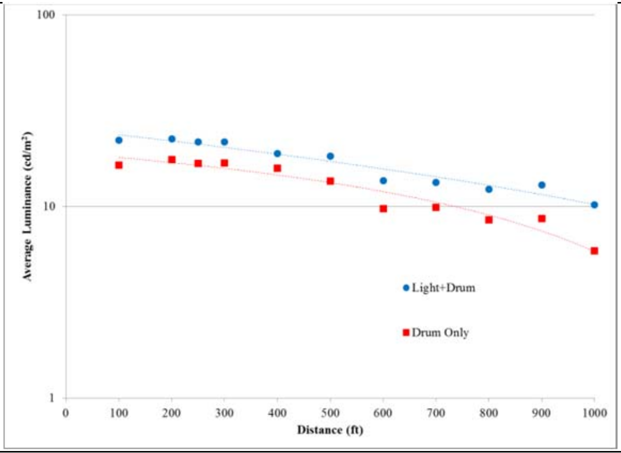
Since warning lights were added, the luminance data reduction method had to be modified slightly. Three regions were measured for each image: 1) drum with steady-burn warning light, 2) drum only, and 3) background. As discussed previously, the background was used to set the threshold value for the regions of interest. Figure 3-10 shows the measurement setup and the data reduction regions of interest used.

a) Channelizing Drum Setup	b) Measurement

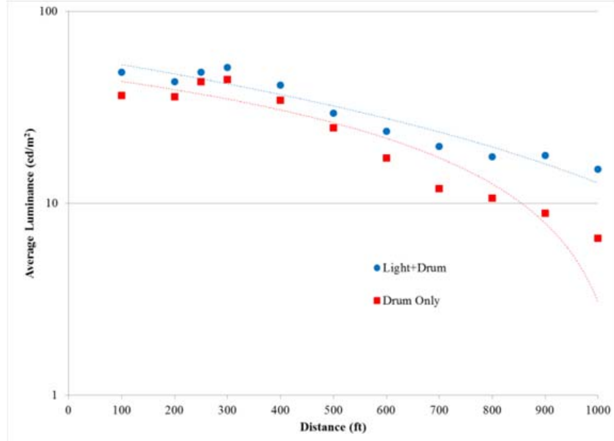
Figure 3-10. Vehicle Comparison Measurement Setup.

Figure 3-11 shows the luminance of the drums with and without warning lights for the two different test vehicles. First, the warning light did appear to increase the overall brightness of the devices for both vehicles; however, the benefit was greater for the Kenworth, the vehicle with the larger observation angle. While the drums overall were brighter on the right side of the road than the left, there appeared to be a larger difference in luminance between the drum with a warning light versus the drum without a warning light on the left side of the road. In other words, drums with warning lights appeared to offer greater potential benefit to vehicles with large observation angles when positioned on the left side of the road. Such a finding was not unexpected, as headlamps are aimed down and to the right to reduce the potential for creating glare conditions for oncoming motorists. Thus, less light falls on the left side of the road than on the right.

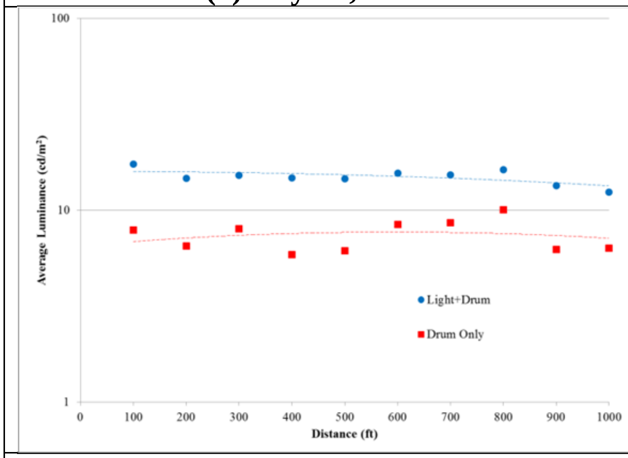
Another interesting trend seen in the data was that the drum luminance, even without a warning light, tended to remain more consistent over distance for the Kenworth than the Toyota. Consequently, at farther distances, drum luminance observed from the Kenworth was actually higher than from the Toyota. This is illustrated in Figure 3-12, which shows the average luminance values of drums with no steady-burn warning light present on the right side of the road. In essentially all situations measured, however, luminance values achieved were far above those necessary for detection and guidance, even for the drums 1,000 ft away.



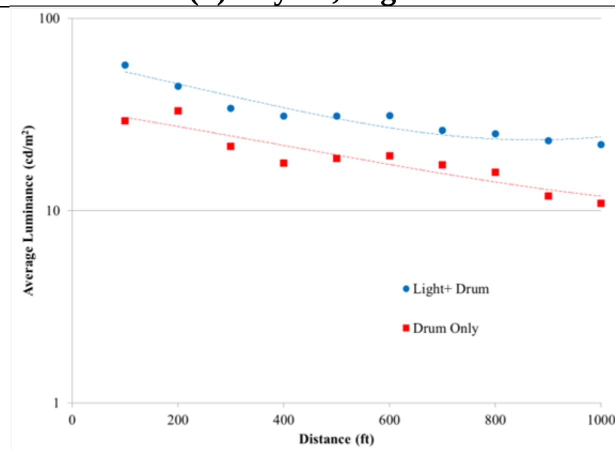
(a) Toyota, Left Side



(b) Toyota, Right Side



(c) Kenworth, Left Side



(d) Kenworth, Right Side

Figure 3-11. Average Luminance Values by Vehicle Type, Drum Placement, and Distance.

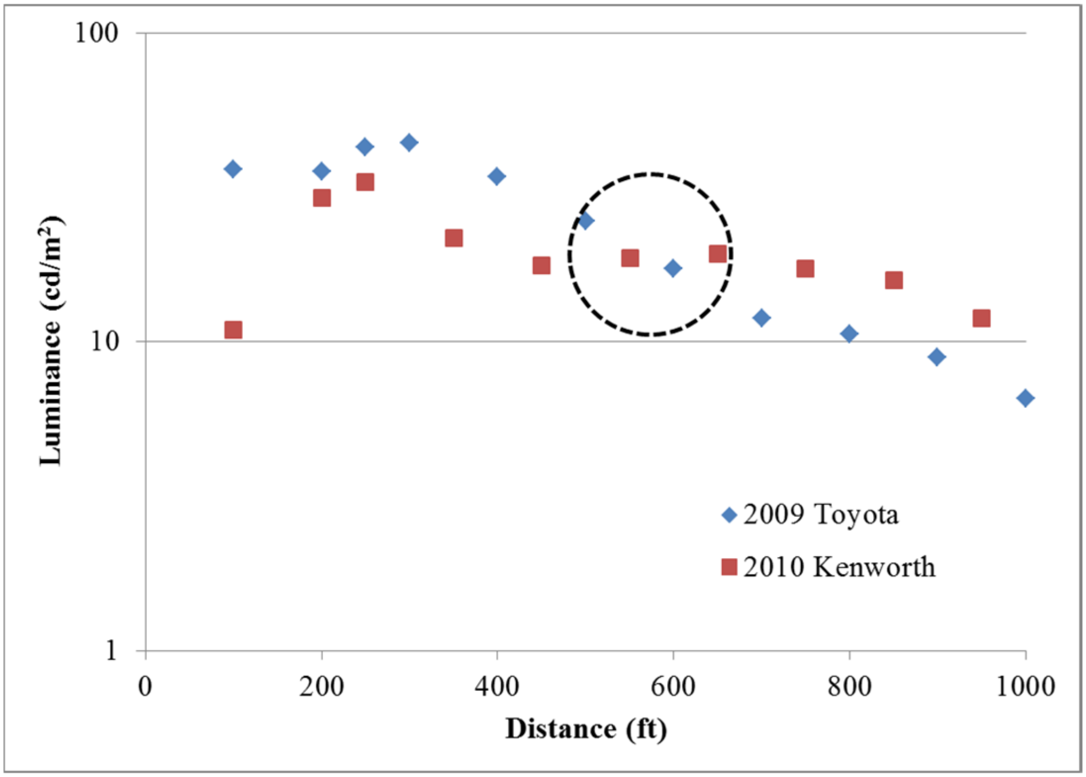


Figure 3-12. Average Luminance of Right Side Drum without Warning Light.

IMPACT OF DIRT ON VISIBILITY OF CHANNELIZING DRUMS WITH STEADY-BURN WARNING LIGHTS

The researchers sought to identify the impact of surface dirt and grime on channelizing devices found in Florida work zones. To accomplish this, the researchers collected photometric data for 72 channelizing devices located in 10 different work zones in Districts 1, 2, 4, 5, and 7. The researchers randomly selected channelizing drums within each work zone. Using the CCD Photometer, the researchers took four images of each channelizing device. The first image showed the drum and attached warning light in their existing condition. The researchers then covered the warning light with a black vinyl opaque bag and captured another image. Next, the researchers cleaned the surface of the drum with a mild soap solution, dried the surface with cloths, and a third image was taken. Finally, the bag was removed from the drum, the warning light lens was wiped clean with a damp cloth, and a final image was captured.

The data were reduced using the same background threshold technique previously described in this chapter. The researchers discovered that the exposure settings on the camera, which varied based on external lighting conditions, had a significant impact on the luminance readings. As a result, the researchers used only the data collected with exposure settings less than or equal to 25 milliseconds. In a few cases, passing vehicles likely impacted the luminance readings to the point that higher luminance readings occurred when the warning light was covered than when it was visible. However, the general trend was reflected in the average luminance values. The researchers noted significant differences in the luminance values for the drums with high intensity sheeting when compared to those with prismatic sheeting. Therefore, the data were separated for the analysis, resulting in a dataset consisting of 27 drums with high intensity sheeting and 12 drums with prismatic sheeting. The luminance results are shown in Figure 3-13.

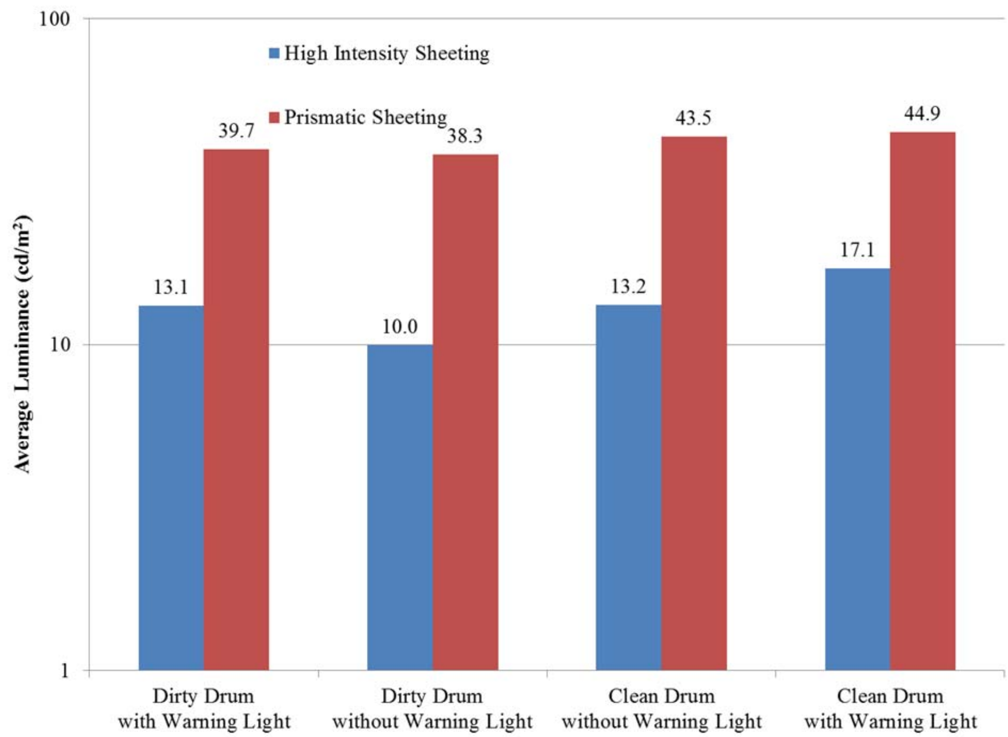


Figure 3-13. Average Luminance Results from Field Studies.

The drums with prismatic sheeting had higher average luminance values than those with high intensity sheeting. For the drums with high intensity sheeting in their existing condition (which includes the attached warning lights), the average luminance was 13.1 cd/m^2. When the warning lights were covered, the average luminance dropped to 10.0 cd/m^2. Thus the average contribution of the warning light to the overall luminance of the device was 3.1 cd/m^2. This represents about a 26 percent improvement in luminance when the warning light was added to a typical dirty drum.

When the drums were cleaned and the warning lights remained covered, the average luminance increased from 10.0 cd/m^2 to 13.2 cd/m^2. The difference of 3.2 cd/m^2 was approximately the same incremental change experienced by the addition of the warning lights. In other words, keeping the drums clean adds the same amount of luminance as adding the warning lights. Maintaining clean devices is already a requirement in FDOT standards. Section 102-9.1 of the *2013 Standard Specifications for Road and Bridge Construction* states that the contractor should "Keep temporary traffic control devices in the correct position, properly directed, clearly visible and clean, at all times" (*36*).

When the warning lights on the clean drums were uncovered and wiped clean, the average luminance increased from 13.2 cd/m^2 to 17.1 cd/m^2, an increase of 3.9 cd/m^2. The warning light contribution to the overall luminance of the clean drum and warning light combination was about 23 percent.

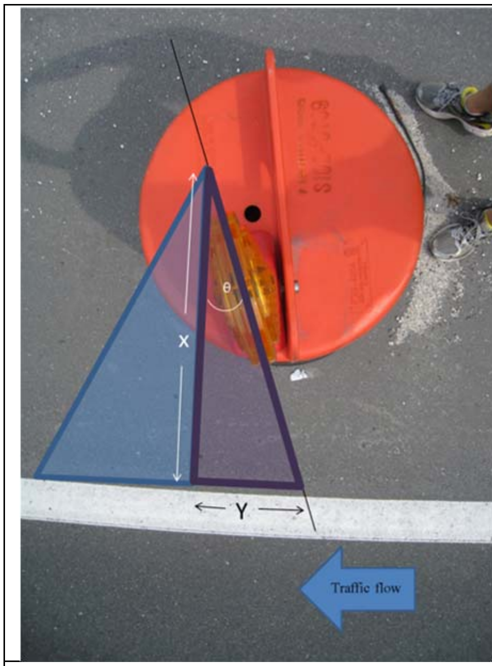
For the drums with prismatic sheeting in their existing condition (which includes the attached warning lights), the average luminance was 39.7 cd/m^2, which was about three times higher than the average luminance of 13.1 cd/m^2 that was found on the drums with high intensity sheeting. When the warning lights were covered, the average luminance decreased slightly to 38.3 cd/m^2, indicating that the luminance contribution of the warning lights on the drums with prismatic sheeting was relatively small. The difference, 1.4 cd/m^2, represents only a four percent improvement in luminance when the warning lights were added to dirty drums with prismatic sheeting. When the drums with prismatic sheeting were cleaned and the warning lights remained covered, the average luminance increased from 38.3 cd/m^2 to 43.5 cd/m^2, a difference of 5.2 cd/m^2. This represents a 14 percent increase in luminance by simply cleaning the drum sheeting. When the warning lights were uncovered and wiped clean, the average luminance increased only 1.4 cd/m^2, from 43.5 cd/m^2 to 44.9 cd/m^2. The warning light contribution to the overall luminance of the clean drum and warning light combination was about three percent, indicating that their impact was very small when the drums had prismatic sheeting.

Drums are used by traffic control providers over long periods of time in several different work zones. The age of the drums with prismatic sheeting was likely to be far less than the age of the drums with high intensity sheeting. This is because the FDOT standards did not incorporate the use of prismatic sheeting into their QPL for plastic drum sheeting (*37*) until October 2009. Drums with prismatic sheeting found in Florida work zones were assumed to be less than four years old, while drums with high intensity sheeting could be 10 years old and have much more wear than the drums with prismatic sheeting. The exact ages of the drums used in this analysis were known.

IMPACT OF MISALIGNMENT ON VISIBILITY OF STEADY-BURN WARNING LIGHTS

Misalignment of Steady-Burn Warning Lights on Channelizing Drums

During another field visit, the researchers noted that many warning lights deployed in the field appeared to be ineffective for reasons other than their photometric value. In some cases, the drums were improperly oriented. In other cases, the channelizing device had been damaged or the warning light was improperly aimed. In these conditions, the lights appeared to provide little or no benefit to motorists at night (in the opinion of the researchers). Therefore, in order to quantify the degree to which warning light orientations found in the field affected warning light visibility, the research team photographed vertical and horizontal views of approximately 175 randomly selected devices in tangent sections of 14 different work zones in Districts 1, 2, 5, and 7 during daylight hours. Using the methodology shown in Figure 3-14, the researchers determined the angles of horizontal and vertical misalignment of each warning light.



(a) Estimation of Horizontal Angle

(b) Estimation of Vertical Angle

Figure 3-14. Methodology for Estimating Skew of Warning Lights on Drums.

The warning light orientations found in the field are depicted in Figure 3-15. The X-axis represents the horizontal degrees of skew (or angle of horizontal misalignment); negative means the light was aimed toward the lane, while positive means the light was aimed away from the lane. Similarly, Y-axis values represent the vertical degrees of skew (or angle of vertical misalignment); negative means the light was aimed toward the ground, while positive means the light was aimed toward the sky. As the data in Figure 3-15 illustrates, the researchers found that over half of the devices (55 percent) were aimed more than five horizontal degrees away from the line they were delineating. There was little variation in the vertical angle. This was likely due to the manner in which the warning lights were bolted to the drums, which did not allow much vertical rotation when tightly fastened.

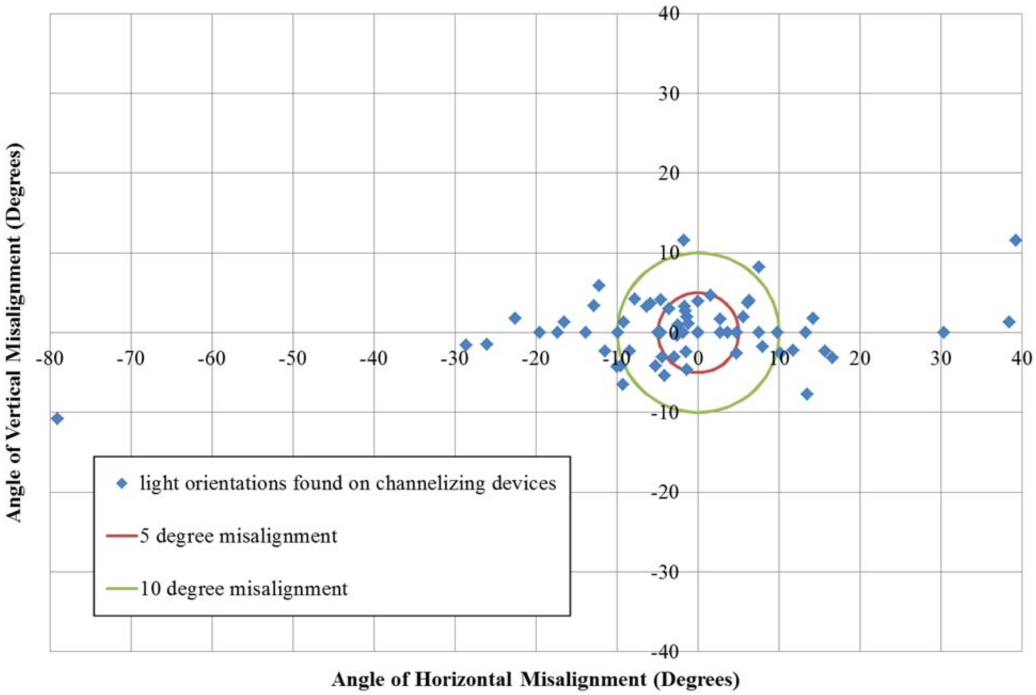


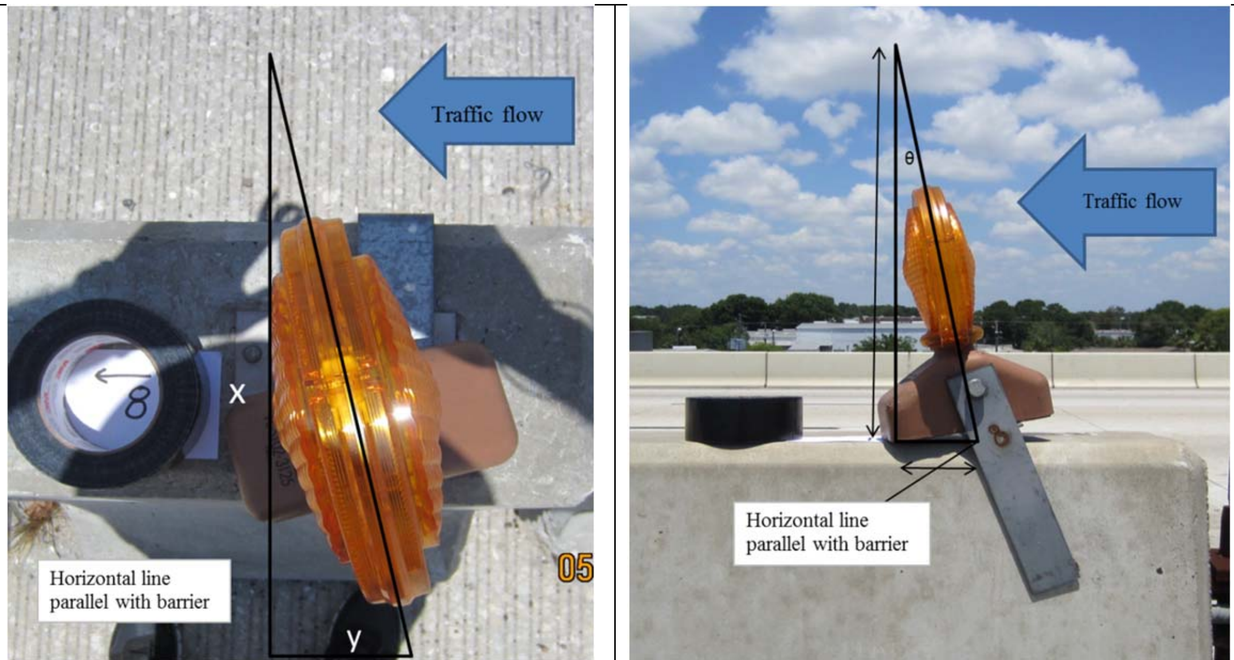
Figure 3-15. Orientations of Warning Lights on Drums from Field Study.

Misalignment of Steady-Burn Warning Lights on Temporary Barrier Wall

During the field visits, the researchers also found that warning lights placed on barrier walls were also subject to misalignment. In this scenario, misalignment was primarily due to leaning of the lights, as shown in Figure 3-16. It appears that slack in the mounting bracket contributed to the misalignment, allowing for vertical rotation of the warning light.

Figure 3-16. Example of Warning Light Misalignment on Temporary Barrier Wall.

The researchers captured images of 107 warning lights mounted on temporary barrier walls in four different freeway work zones, all located in District 7. Using the methodology shown Figure 3-17, the researchers determined the angles of horizontal and vertical misalignment of each warning light. The results are shown in Figure 3-18. The X-axis represents the horizontal degrees of skew. In this case, negative means the light was aimed away from the lane, while positive means the light was aimed toward the lane. Similarly, Y-axis values represent the vertical degrees of skew; negative means the light was aimed toward the ground, while positive means the light was aimed toward the sky.



(a) Estimation of Horizontal Angle	(b) Estimation of Vertical Angle

Figure 3-17. Methodology for Estimating Skew of Warning Lights on Barrier Wall.

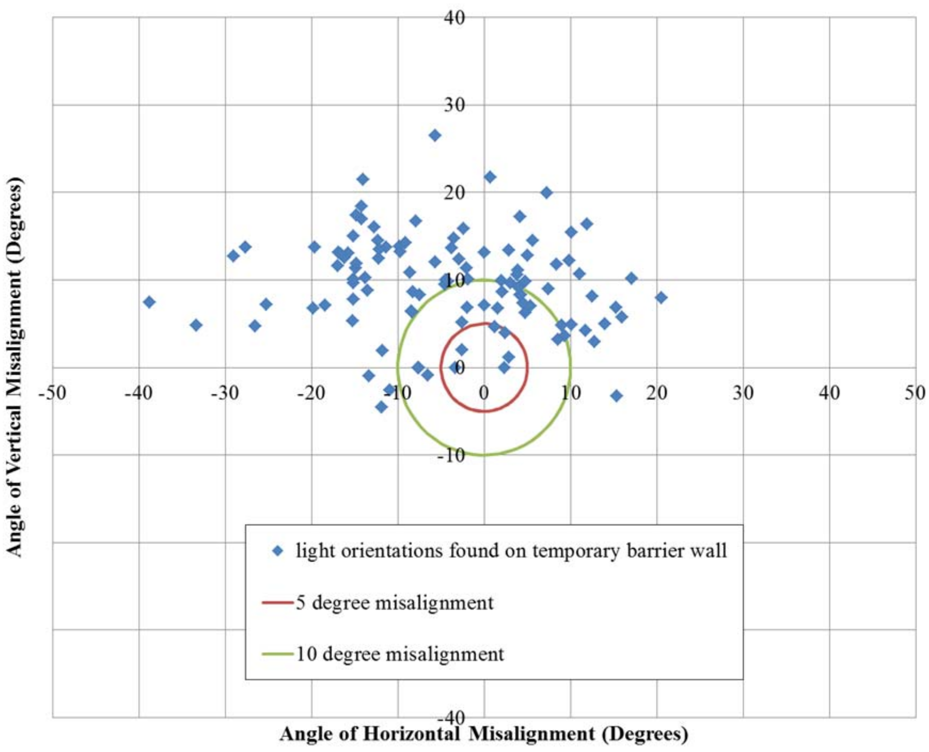


Figure 3-18. Orientations of Warning Lights on Temporary Barrier Walls from Field Study.

The leaning effect of the warning light shown in Figure 3-16 is clear from the graph, as most of the data points were above the x-axis. Only six devices (6 percent) remained within the five degree misalignment circle, meaning that they were not misaligned more than five degrees in both the horizontal and vertical positions. Another 26 devices (24 percent) remained within the 10 degree misalignment circle. The remaining 75 warning lights (70 percent) were more than 10 degrees out of alignment in both directions.

Visibility Reduction Due to Misalignment of Warning Lights

Using a goniometer in the VRL, the TTI researchers quantified the impact of horizontal misalignment on warning light brightness. Using an FDOT-approved LED warning light, the light output was measured with no horizontal skew (0 degrees), then again at small, incremental horizontal rotations. The researchers recognized the minor differences between the horizontal and vertical molding patterns in the warning light lens surface. While the loss of light brightness due to vertical skew was not evaluated in the VRL, the researchers do not expect the results to be much different from the horizontal skew readings. The results of the horizontal skew evaluation were plotted as a percent of the luminance value with no skew and are shown in Figure 3-19.

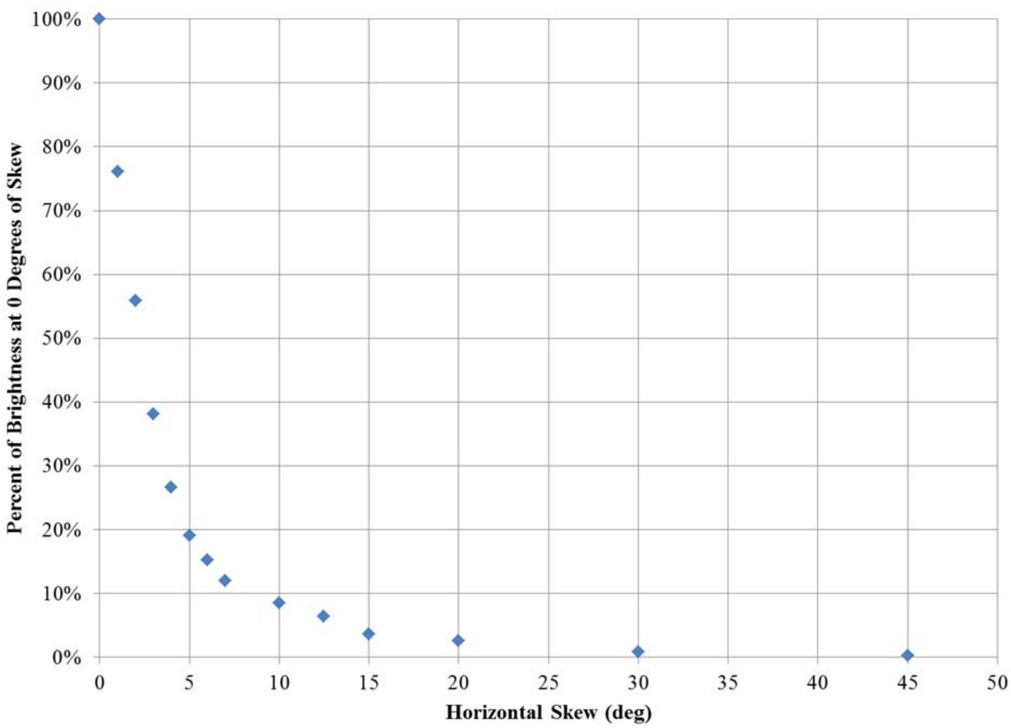


Figure 3-19. Impact of Horizontal Skew on Warning Light Brightness.

These results show that horizontal rotations as small as five degrees can reduce warning light brightness to less than 20 percent of its original value. When rotation exceeds 10 degrees, luminance values drop to less than 10 percent of the original value. In contrast, the luminance of a channelizing drum remains fairly constant regardless of its orientation, so long as the sheeting on the drum is fairly uniform with respect to wear and abrasions. Overall, more than half

(55 percent) of the warning lights mounted on channelizing drums and almost all (94 percent) of the warning lights mounted on temporary barrier walls were more than five degrees out of alignment in both the horizontal and vertical directions. Misalignment of warning lights found in the field is a significant impediment to their effectiveness.

SUMMARY

In this chapter, the researchers summarized several evaluations performed to quantify warning light effectiveness. Specifically, the researchers quantified the impacts of fog, dew, vehicle type, dirt, and misalignment based on climate data, laboratory testing, and field evaluations.

As part of the fog evaluation, the researchers found that the occurrence of heavy fog at night in Florida was rare. In northern Florida cities, where fog was more common, visibility falls below ¼ mile less than three percent of the time, often in the early morning hours when traffic volumes are very low. In the VRL, the researchers demonstrated that warning lights may provide some benefit when visibility is extremely poor. However, this benefit was realized at visibility levels of 15 meters, or about 50 ft. This visibility level is almost impossible to achieve under natural conditions and should this fog level occur in the real world, motorists would not likely attempt to operate a vehicle under such conditions. At fog levels one might expect to see in the field, researchers concluded that drum sheeting without warning lights is still likely to be visible at distances needed for path guidance and delineation purposes and the use of warning lights is unlikely to provide much additional value to motorists.

During the dew evaluation, the researchers found that the presence of dew can reduce drum luminance by up to 84 percent. However, the amount of luminance achieved under dew conditions is still likely to be sufficient for path guidance purposes, which again suggests that warning lights may not provide substantial additional benefit to drivers. Furthermore, researchers were unsure as to whether dew formation regularly occurs on drums, given the air pocket that is trapped inside the drum.

During the vehicle type evaluation, the researchers found that steady-burn warning lights may increase overall average luminance values for vehicles with larger observation angles, such as heavy trucks, especially when placed on the left side of the roadway. However, the luminance values of the drums with high intensity sheeting were sufficient to be seen at distances up to 1,000 ft away and would provide sufficient detection and guidance information without the use of steady-burn warning lights.

During the dirt evaluation, the researchers found that surface dirt and grime on drums found in Florida work zones had an impact on device luminance. While the presence of warning lights did increase overall luminance of channelizing drums, a greater increase in luminance was noted when the drums were cleaned. The data showed that the luminance of the cleanest drums with high intensity sheeting and clean warning lights was comparable to the luminance of the dirtiest drums with prismatic sheeting and no warning lights.

An evaluation of misaligned lights found in the field revealed that more than half of the warning lights mounted on drums were misaligned more than five degrees. In addition, almost all of the warning lights mounted on temporary barrier wall were misaligned more than five degrees. For an LED warning light, this misalignment results in a significant reduction in luminance. Lab testing shows that a five degree misalignment results in luminance values approximately 20 percent of that of a properly aligned warning light.

It is feasible that drivers of large trucks traveling under heavy fog conditions and needing to rely only on channelizing devices on the left side of the travel lane may benefit from the presence of steady-burn warning lights if the drums are extremely dirty. However, the relative frequency such a sequence of events is likely to be so small as to be negligible relative to even a minor incremental cost of providing such warning lights.

CHAPTER 4 EFFECTS OF STEADY-BURN WARNING LIGHTS ON OLDER DRIVER BEHAVIOR

INTRODUCTION

In this chapter, researchers describe the human factors study performed to determine the effects of steady-burn warning lights on older driver perception and behavior in work zones. For this study, 32 Florida participants over the age of 55 were recruited to drive an instrumented vehicle through a work zone and then provide their opinions about the guidance available to them through the work zone. Two scenarios were used in the study. The first scenario included a comparison of channelizing drums with and without warning lights in an urban arterial setting. The second scenario included a comparison of temporary median barrier walls delineated with yellow retroreflective tabs and with standard warning lights in a rural freeway setting. Two FDOT District 7 construction projects were used in the study.

METHODOLOGY

The researchers used three measures of effectiveness for the human factors study:

- Eye-tracking glances.
- Lane-keeping.
- Driver opinions.

A survey was used to garner driver opinions. The equipment used in the study is described below.

Eye-Tracking Equipment

Study participants drove a 2006 Toyota Highlander, shown in Figure 4-1. The vehicle was equipped with a faceLAB™ eye-tracking system, which was used to record driver glances via in-vehicle video cameras.

Figure 4-1. Instrumented Vehicle Used During Human Factors Study.

Figure 4-2 shows the faceLAB™ dash-mounted eye-tracking infrared (IR) transmitters and cameras. The transmitters emitted a very low level of light and did not impact the driving task. The left and right cameras recorded pupil information for each eye, respectively, which was used to estimate the location of the driver's glances. Although not shown in the figure, a forward scene camera was also mounted behind the vehicle's rear-view mirror and was used to capture the view out in front of the vehicle. All of this information was recorded by equipment that was stored in the rear of the vehicle.

Figure 4-2. Dash-Mounted Eye-Tracking Equipment.

Figure 4-3 shows the researcher's station in the back seat of the vehicle. The researchers used the keyboard and monitor to the run the equipment.

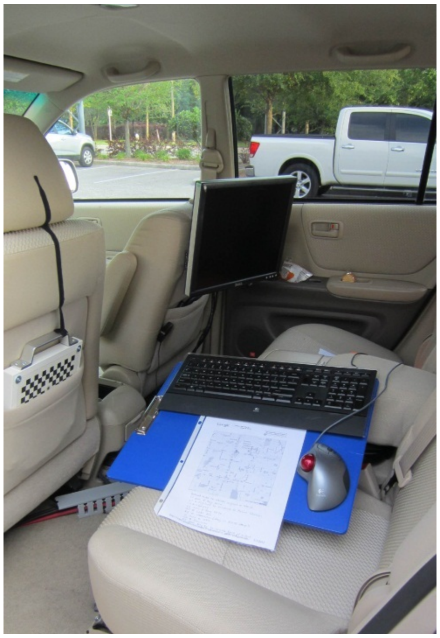


Figure 4-3. Eye-Tracking Researcher's Station.

Figure 4-4 shows the equipment in the rear of the vehicle. It includes a global positioning system (GPS), computer, power inverter, backup power supply, and external hard drive. This equipment collectively stored the vehicle's position and speed data, as well as the study participant's eye glances and the forward scene video.

Figure 4-4. Data Collection Equipment in the Instrumented Vehicle.

Lane-Keeping Equipment

Lane-keeping data were recorded with an outboard video camera mounted on the side of the instrumented vehicle. Prior to each evening of data collection, the camera was installed and calibrated using a marked board placed on the ground and extending out from the rear tire of the vehicle. The board was marked in 2-inch increments. This setup is shown in Figure 4-5.

Figure 4-5. Lane-Keeping Video Camera and Calibration Board.

Using video from the lane-keeping camera, a screenshot of the calibration video was used to determine the offset distance from the rear tire to the edge of the lane line. For example, in Figure 4-6, the lane line in the parking lot was approximately 14 inches from the tire.

Figure 4-6. Video Image of Calibration Board from Outboard Lane-Keeping Camera.

Driver Opinions

The researchers also used a survey form to get driver opinions of the traffic control devices used in the work zone. The questions were aimed at:

- Determining if the drivers noticed any differences in the work zone (i.e., warning lights present or not).
- Soliciting their opinion of how well the traffic control devices led them through the work zone.
- Identifying which of the treatments they preferred.

DATA COLLECTION AND ANALYSIS

Ulmerton Road Study of Warning Lights on Channelizing Drums

For the urban arterial portion of the study, the researchers used the Ulmerton Road (SR 688) reconstruction project in Pinellas County. The construction area is shown on the map in Figure 4-7. The 5-lane facility was being widened to include an additional lane in each direction, along with other drainage improvements. The posted speed limit was 45 mph and the area land use was mixed, including retail businesses, residential, and government offices. With the exception of gas stations, most of the businesses were closed at night. Several businesses had lighted parking lots and there were several high billboards in the work zone. There was no street lighting present. Signalized intersections were located at approximately half-mile increments.

The researchers documented the work zone setups with photographs, video, and GPS identification of key locations.

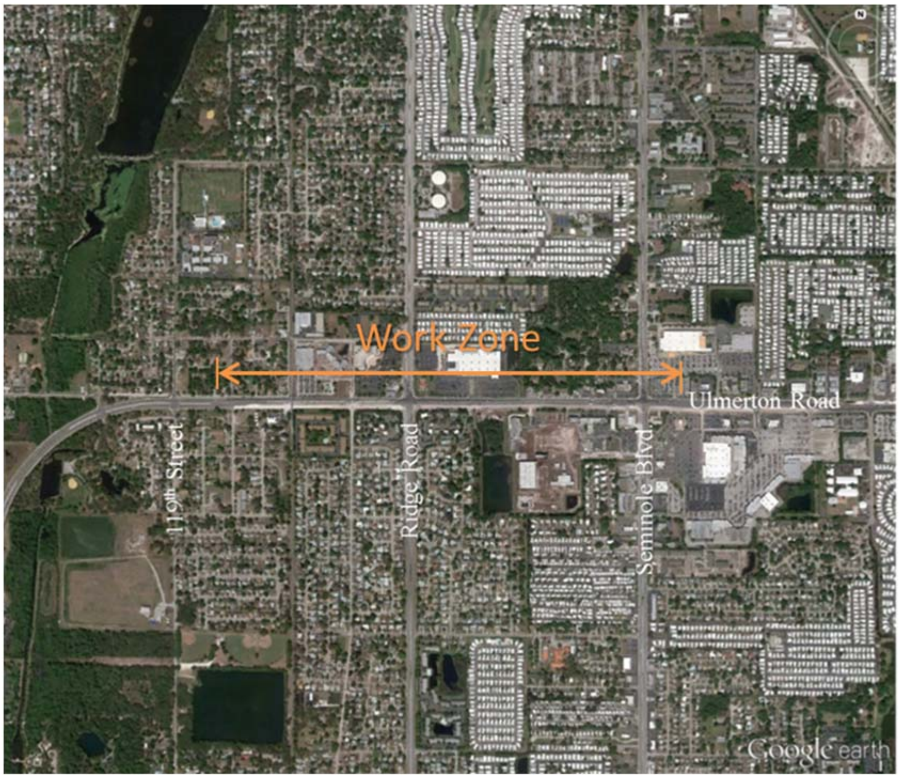


Figure 4-7. Location of Ulmerton Road Reconstruction Project in Pinellas County, Florida.

To perform the study, participants met the researchers at an appointed time in a meeting room in the lobby of a local hotel. Upon arrival, each study participant reviewed and signed an Informed Consent Form that detailed the procedures, risks, and compensation associated with their participation in the study. The voluntary nature of the study and confidentiality of their data was assured. After signing the consent form, demographic data were collected, and each participant was required to pass three eye exams: (1) Snellen acuity exam, (2) Ishihara colorblindness test, and (3) Vistech contrast sensitivity test. Once passing the eye tests, each participant was then escorted to the instrumented vehicle to begin the driving portion of the study. The participants drove a predetermined route through the work zone while the eye-tracking and lane-keeping videos were recorded. The drive lasted approximately 15 minutes. The researchers ran 17 participants at this work zone. However, equipment failure resulted in loss of data for two participants, while emergency vehicle response to a nearby traffic incident forced the researchers to eliminate one participant's data, leaving only 14 participants for which full data sets were collected.

The treatments evaluated consisted of channelizing drums with and without steady-burn warning lights. The treatments were all located on the right side of the roadway and participants drove in the right lane. Table 4-1 summarizes the treatment areas used in the study, while Figure 4-8 shows the treatment locations within the work zone.

Table 4-1. Ulmerton Road Warning Light Treatments.

Treatment ID	Direction	Limits	Treatment Length (ft)	Warning Lights Present?	Lane Width (ft)	Number of Driveways	Drum Offset (ft)
EXP1	WB	From west of Seminole to Lowe's entry	1,600	No	11	13	2-3
STD2	WB	From west of Ridge to Pinellas Trail	1,200	Yes	11	5	2-3
EXP3	EB	From east of 117th to west of Ridge	1,400	No	12	1	2-6
STD4	EB	From east of Ridge to west of Pinellas County offices	1,100	Yes	12	2	3-5

EXP=Experimental Section, STD=Standard Treatment Section, WB= Westbound, EB=Eastbound

Figure 4-8. Treatment Locations at the Ulmerton Road Work Zone.

While the length of each of the treatment segments was approximately the same, the lane widths were different in each direction. Furthermore, the EXP1 treatment segment had significantly more driveways than the other segments. In addition, the channelizing drum offsets (i.e., distances from the drum to the lane edge line) in the westbound direction were smaller and more consistent than those in the eastbound direction. A scene view from each treatment section is shown in Figure 4-9.

(a) WB EXP1 Treatment | (b) WB STD2 Treatment

(c) EB EXP3 Treatment | (d) EB STD4 Treatment

Figure 4-9. Nighttime Scene View of Treatment Segments at Ulmerton Road Work Zone.

The difference in the number of driveways in each segment is also apparent from the figure. For example, the EXP1 treatment segment shown in Figure 4-9(a) has significantly more visual clutter on the right side than the other treatment segments. This was due to the presence of lighted signs, parking areas, frequent business entrance signs, and driveways with closely-spaced drums in the radii. The researchers recognized that this difference may have impacted the data. Ideally, the best scenario would have been to switch the experimental and standard treatments in each segment after running half of the participants at this work zone. However, the contractor was not able to make the additional treatment switches for the researchers, so the experimental and standard treatments had to remain in the same locations for all participants that drove through the work zone.

Eye-tracking Data

Each study participant had their glances calibrated before driving through the work zone. This was accomplished by having the driver park the vehicle facing a rectangular object, such as a gate or fencing, and stare at each corner of the object while the researcher used the faceLAB™ software to calibrate the dash-mounted cameras. This process helps to ensure the accuracy of the eye-tracking data. A scene view from the eye-tracking calibration process is shown in Figure 4-10.

Figure 4-10. Scene View from Eye-Tracking Calibration Process.

Once the equipment was ready, the study participants drove through the work zone and the equipment recorded a continuous video of the driving task. The time-synchronized eye-tracking video and forward scene view videos were overlaid to create the driving video for each participant. A screenshot from a sample video is shown in Figure 4-11. The green circle indicates the location of the driver's glance.

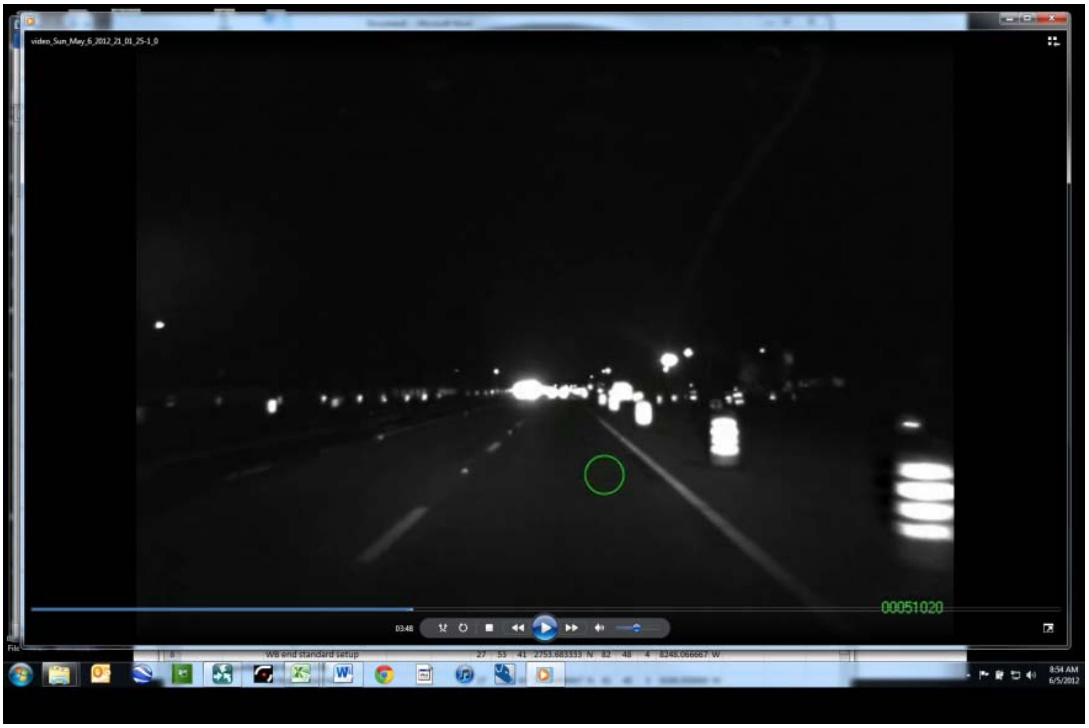


Figure 4-11. Scene View with Driver Glance Location.

Glances at exact items in the driver’s view cannot be confidently identified through eye-tracking systems such as the one used in this study. For example, a glance at a drum, particularly far ahead, cannot be discerned from a glance at the warning light on the top of the drum. Therefore, to reduce and analyze the data, the researchers established numbered zones or glance regions, which are represented by the blue lines overlaid on the video screenshot shown in Figure 4-12. A glance at or between the lane lines, such as the one shown, were determined to be in Zone 0. Each time a new glance was identified (i.e., the green circle jumped to a new location) the zone number for that glance was recorded. Once all the glances were categorized for the treatment areas, the percent of glances in each region could be tabulated for each subject.

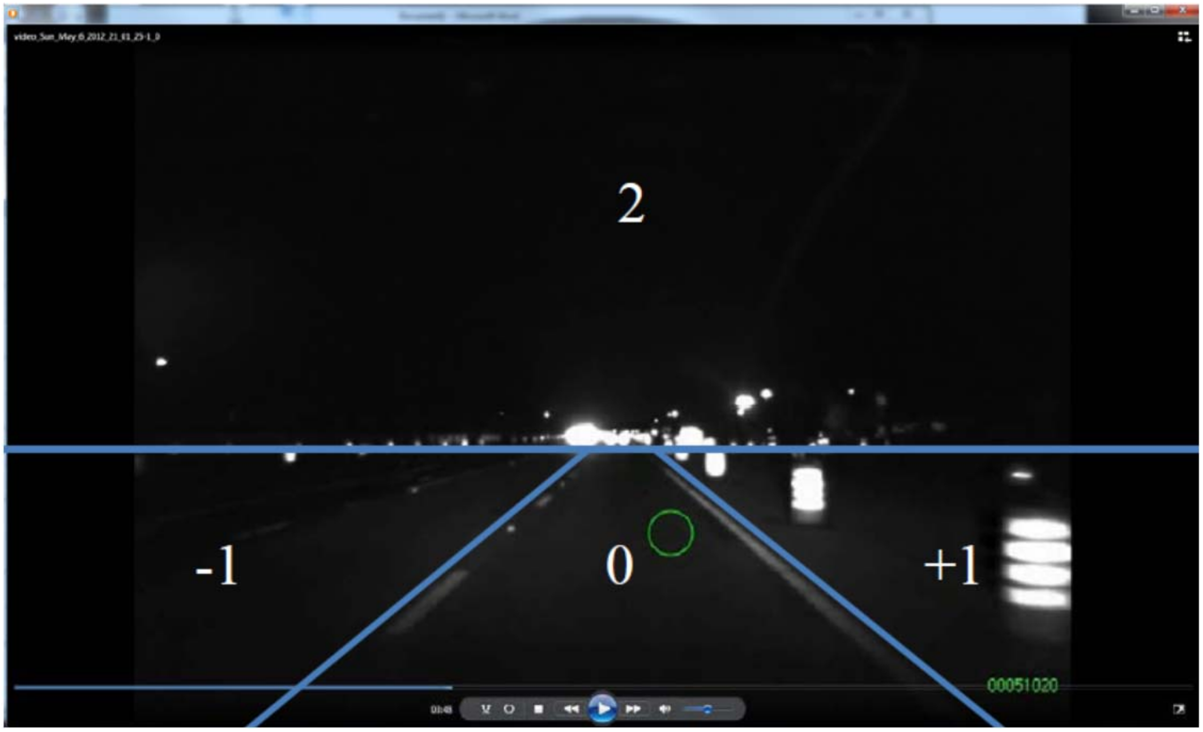


Figure 4-12. Scene View with Driver Glance Location and Glance Zones.

Lane-Keeping Data

As noted previously, lane-keeping data were recorded for each participant using an outboard camera mounted over the right rear tire. The camera position was calibrated so that distances from the lane line to the edge of the tire, or offsets, could be measured on-screen by playing back the video data. Using the on-screen time display, the offset was recorded once per second during the playback. The results were summarized in table format. Since the westbound lanes of Ulmerton Road consisted of 11 ft lanes, and researchers recognized that lane width would impact lane position, these data were analyzed separately from the data for areas with 12 ft lanes.

Driver Opinions

Upon completion of the driving task, each participant answered survey questions regarding the traffic control that was used in the work zone. Questions included:

- As you were driving through, did you notice anything about the work zone that changed? If so, what?
- How would you rate the effectiveness of the warning lights on the devices in guiding you through the work zone on a scale of one to five with one being the best and five being the worst?
- Overall, how well did the traffic control devices guide you through the work area?
- Overall, of the two treatments that you just drove through, which set up did you feel did the best job in guiding you through the area and why?

The survey responses were recorded by the researcher for each participant. Upon completion of the survey, the participants were paid for their time and dismissed.

I-75 Study of Barrier Delineators

The I-75 work zone, located in Hillsborough County, was used to compare retroreflective barrier delineators to standard warning lights on temporary concrete barrier walls in a rural freeway setting. The approximate location of the reconstruction project is shown in Figure 4-13.

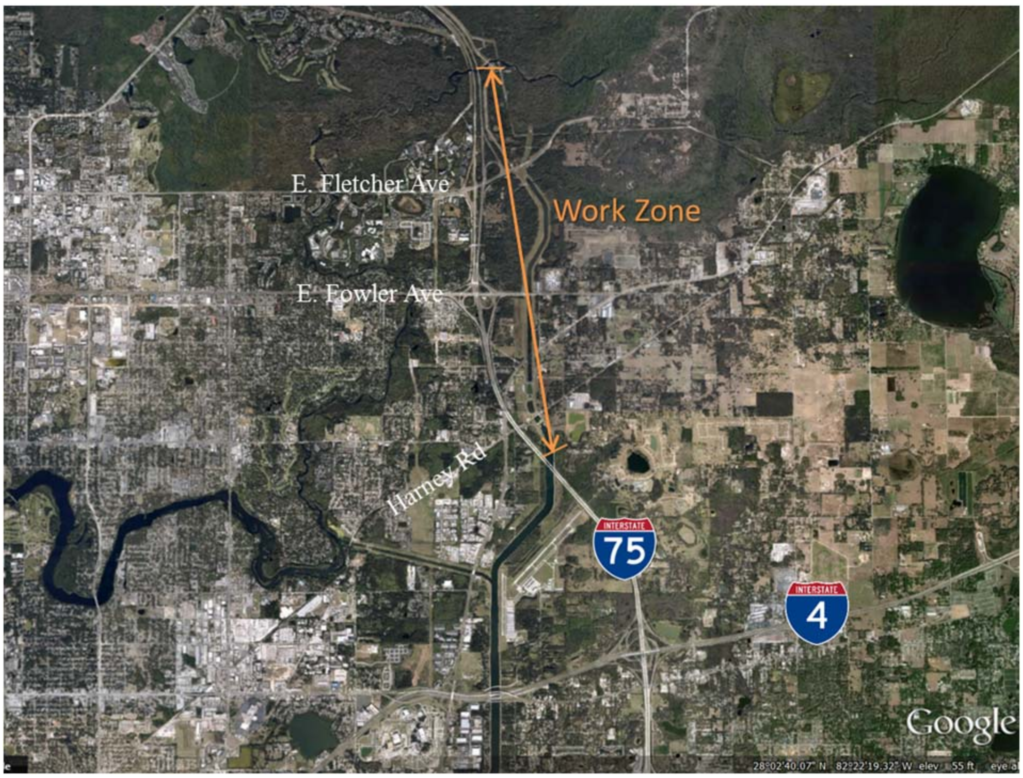


Figure 4-13. Location of I-75 Reconstruction Project in Hillsborough County, Florida.

Generally speaking, the same research protocol from the Ulmerton Road project was used at this location. This work zone was a reconstruction project, which included widening of the freeway from four lanes to six. Each direction of traffic was separated by approximately 95 ft of median, and most of the construction equipment was located in the median. Temporary barrier walls kept traffic separated from the median and was located approximately 2 ft behind the left lane line. The freeway had high mast overhead lighting. The researchers obtained data for 15 participants at the I-75 work zone.

In the experimental treatment segment, the barrier delineators were placed on top of the barrier walls over two 2,000 ft tangent sections at 40 ft spacing, consistent with FDOT's standard index 410 for permanent barrier wall delineation (*38*). The yellow delineators were selected from the FDOT Qualified Products List (QPL) for concrete barrier wall delineation (*39*). A sample is shown in Figure 4-14. The retroreflective area on each delineator was 3 inches wide and 4 inches high.

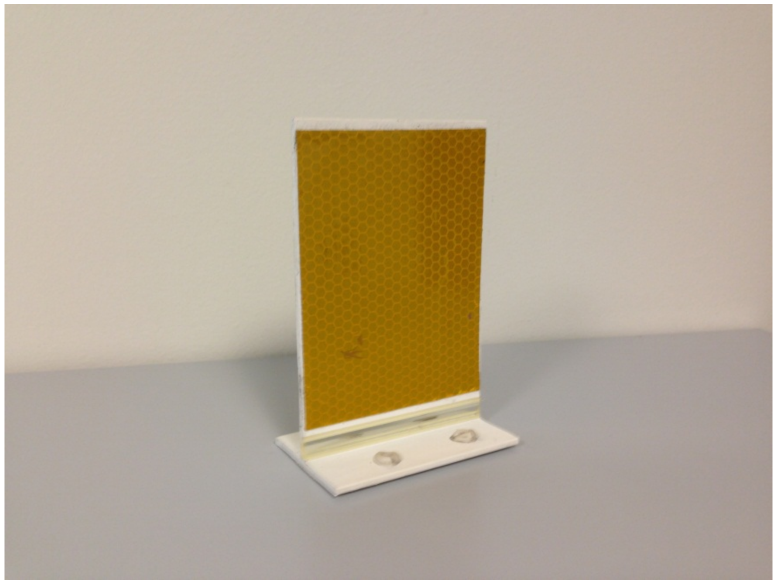


Figure 4-14. Typical Barrier Wall Delineator Used in I-75 Experimental Treatment.

The standard treatment consisted of warning lights on top of the barrier walls along two other 2,000 ft tangent section at 200 ft spacing, also in accordance with FDOT standard index 415 (*3*). The participants drove through one experimental and one standard barrier delineation treatment segment in the northbound direction in the left lane on I-75 at approximately 65 mph. Immediately after this, they drove through one experimental and one standard barrier delineation treatment segment in the southbound direction. Table 4-2 summarizes the treatment areas used in the study, while Figure 4-15 shows the location of each treatment on the construction area map.

Table 4-2. I-75 Barrier Wall Treatments.

Treatment ID	Direction	Limits	Treatment Length (ft)	Delineation	Barrier Offset (ft)
EXP1	NB	From Fowler Ave. exit gore to Fowler Ave. bridge	2,000	Retroreflective Tabs	2
STD2	NB	From Cow House Creek bridge to S. of Fletcher Ave	2,000	Lights	2
STD3	SB	From Tampa Oaks Blvd to Cow House Creek bridge	2,000	Lights	2
EXP4	SB	From Fowler Ave. bridge to McRae Rd.	2,000	Retroreflective Tabs	2

EXP=Experimental Treatment Section, STD=Standard Treatment Section, NB=Northbound, SB=Southbound

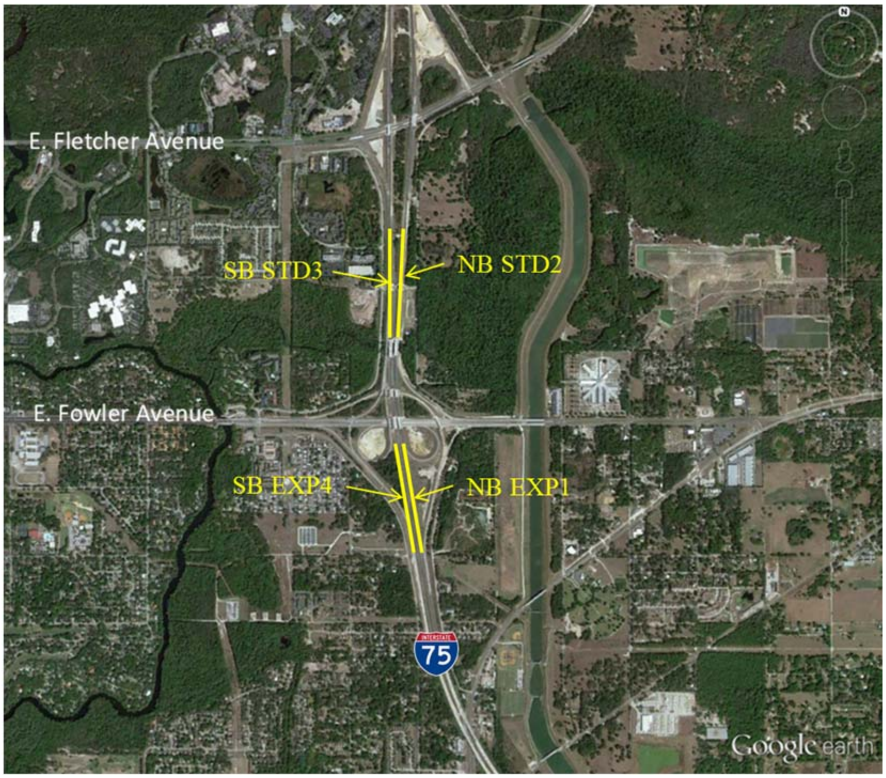


Figure 4-15. Treatment Locations at the I-75 Work Zone.

A scene view from each treatment section is shown in Figure 36.

(a) NB EXP1 Treatment

(b) NB STD2 Treatment

(c) SB STD3 Treatment

(d) SB EXP4 Treatment

Figure 4-16. Nighttime Scene View of Treatment Segments at I-75 Work Zone.

Eye-Tracking Data

Similar to the analysis protocol used for the Ulmerton work zone, the eye-tracking data for I-75 participants were summarized by tabulating each driver's visual glances in each of the regions shown in Figure 4-17. In this case, Region -1 was the area of interest, since this was where the barrier walls were located.

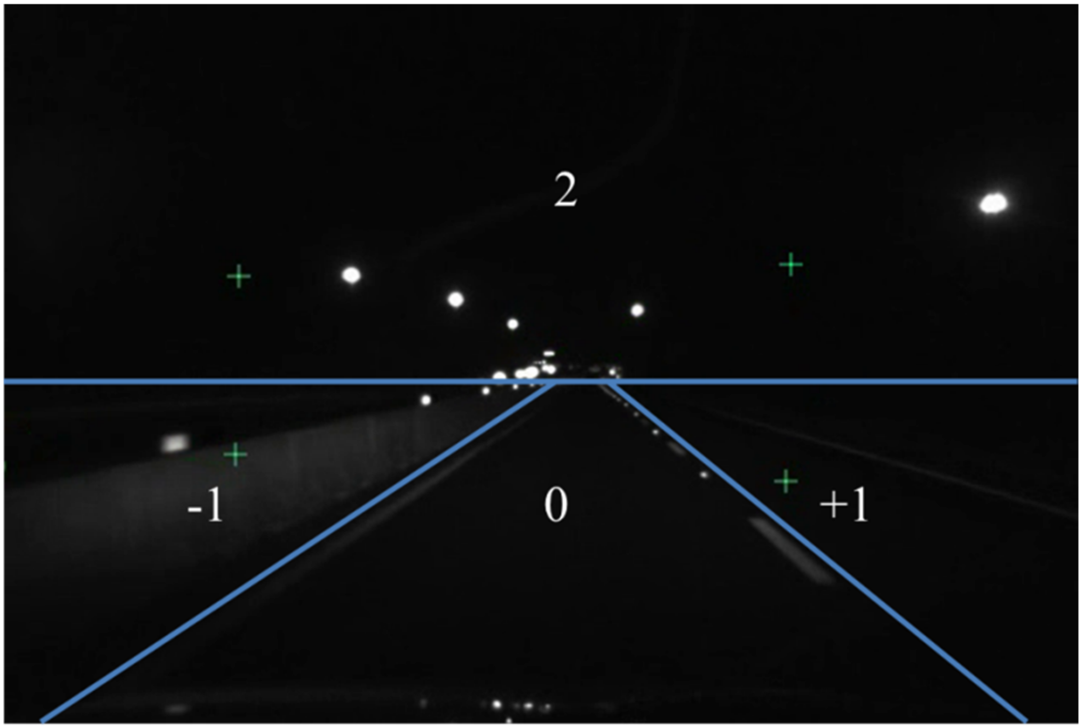


Figure 4-17. I-75 Scene View with Driver Glance Regions.

Lane-Keeping Data

Lane-keeping data were recorded for each participant using an outboard camera mounted, this time over the left rear tire. In this work zone, the treatments were on the left side of the vehicle. The camera position was calibrated so that distances from the lane line to the edge of the tire, or offsets, could be measured on-screen by playing back the video data. Using the on-screen time display, the offset was recorded once per second during the playback. The results were summarized in table format.

Driver Opinions

Upon completion of the driving task, each participant answered survey questions regarding the traffic control that was used in the work zone. The questions were similar to those asked in the Ulmerton Road work zone.

RESULTS

Ulmerton Road Study of Warning Lights on Channelizing Drums

Eye-Tracking Results

The researchers found that there was a significant difference in glance behavior between drivers. For example, some drivers focused primarily in Region 0 (within the lane lines) for most of their driving time, while others had more variation in glances. The presence of other traffic also impacted driver glances, as some drivers focused on the taillights of other vehicles traveling in their same direction. In addition, some drivers had much longer glances in each region, which impacted their total number of glances overall. Participants who drove the course later in the evening tended to have fewer glances to the left (toward oncoming traffic), when traffic volumes were lower than earlier in the evening. An example of these differences is shown in Figure 4-18, which illustrates the eye-tracking data for two of the participants.

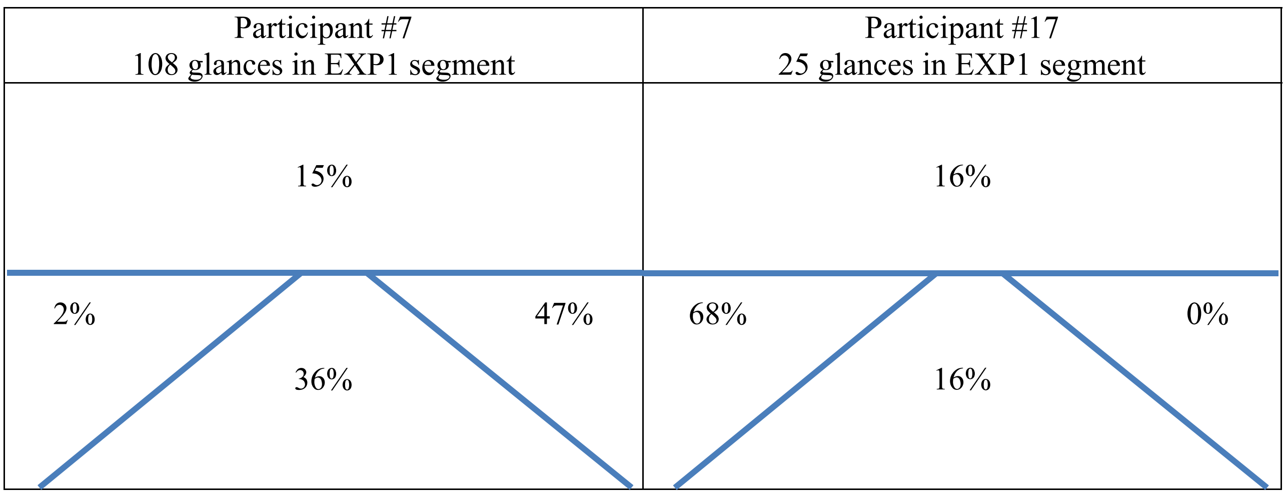


Figure 4-18. Variation in Driver Glances across Regions.

Figure 4-18 shows that Participant #7 tended to focus on the right side more than any other region. Participant #17 was following slightly behind another vehicle in the adjacent lane and tended to focus on the taillights of that vehicle. These differences in driving style indicate that other factors, such as traffic volume, may have more influence over driver behavior than the presence of warning lights. The eye-tracking data were summarized for each treatment segment and are shown in Table 4-3.

Table 4-3. Eye-Tracking Results for Ulmerton Road Work Zone.

Region	Treatment							
	Westbound				Eastbound			
	EXP1		STD2		EXP3		STD4	
	Number of Glances	Percent of Total	Number of Glances	Percent of Total	Number of Glances	Percent of Total	Number of Glances	Percent of Total
+1 (Right Side)	136	20%	87	13%	35	10%	43	11%
2 (Above Horizon)	120	18%	145	21%	59	17%	82	22%
-1 (Left Side)	179	27%	166	25%	111	31%	123	33%
0 (Within Lane Lines)	234	35%	278	41%	148	42%	130	34%
TOTAL	669	100%	676	100%	353	100%	378	100%

While the dataset for the Ulmerton Road study has 2076 separate glances over four treatment areas, the data rely on the eye-tracking data for only 14 participants. Having fewer participants means that data from a single participant can significantly impact the overall results. For example, participant #7 contributed 51 of the 136 glances (38 percent) to the right side (Region 1) in the EXP1 treatment area, as well as 23 of the 43 glances (53 percent) to the right side in the STD4 treatment area. Despite this apparent fixation on the right side, survey results, presented later in this report, showed that this participant failed to notice that warning lights were not present on the channelizing drums in the EXP sections.

In Table **4-3**, one sees that participants had a higher percentage of glances (20 percent) in the right side region, where the channelizing drums were located within the EXP1 treatment segment, than with any other treatment segment. This glance percentage was statistically different from all other segments when using the test of proportions with confidence interval of 95 percent. This difference was likely due to the presence of more visual clutter in this segment, as previously mentioned, since a similar percentage was not evident in Region +1 in the EXP3 treatment segment. The EXP3 treatment segment percentage was statistically the same as the two STD treatment segments. Using the data from Table 4-2, the researchers examined the relationship between the percentage of glances to the right region and the presence of driveways. The results are shown in Figure 4-19.

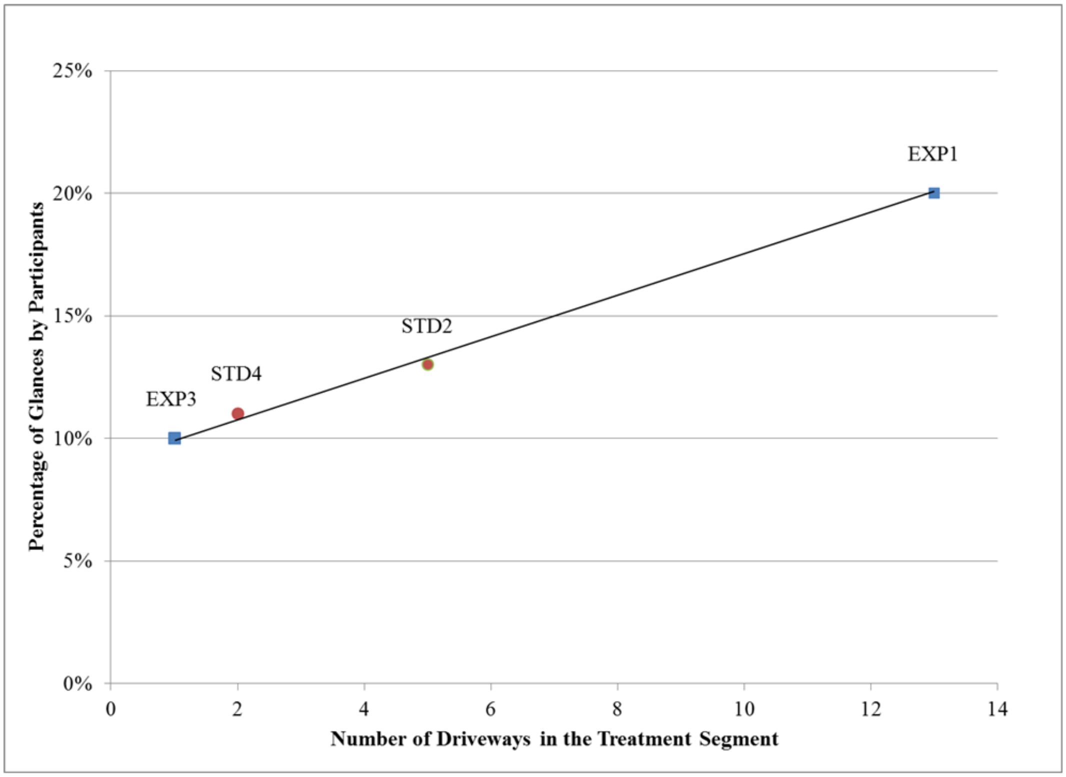


Figure 4-19. Glances to the Right Side (Region +1) in the Ulmerton Road Work Zone.

Figure 4-19 suggests a strong relationship between the percentage of glances to the right side and the presence of driveways, regardless of treatment type. The researchers believe this was likely the reason for the statistical differences between the EXP1 eye-tracking data and the data for the other segments. One could conclude that the strong linear relationship in Figure 4-19 implies that the warning lights themselves had little, if any, effect on driver glance behavior.

Lane-Keeping Results

The westbound data for the 14 participants are shown in Table 4-4.

Table 4-4. Lane-Keeping Data for Westbound Ulmerton Road Segments.

Statistics	Treatment Segment	
	EXP1 (n=312)	STD2 (n=295)
Average Distance from Tire to Edge Line (inches)	30.7	29.6
Standard Deviation	9.2	6.2

A student t-test statistical comparison of means at 95 percent confidence interval indicated that there was no difference in lane-keeping between the two treatments in the westbound direction. This result is not surprising, given that the lane widths and drum offsets were consistent among these two segments. Data for the eastbound direction are shown in Table 4-5.

Table 4-5. Lane-Keeping Data for Eastbound Ulmerton Road Segments.

Statistics	Treatment Segment	
	EXP3 (n=186)	STD4 (n=160)
Average Distance from Tire to Edge Line (inches)	42.3	33.2
Standard Deviation	9.0	10.4

A student t-test statistical comparison of means at 95 percent confidence interval indicated that there was a difference in lane-keeping between the two treatments in the eastbound direction. The eastbound treatment segments each had 12 ft lane widths, which does explain the slightly greater distances between the tire and the edge line (>33 inches) than was observed in the westbound direction (<31 inches). In addition, looking back to Table 4-1, the westbound treatment segments had more consistent placement of traffic control features than the westbound treatment segments, which also may have contributed to the difference in average tire to edge line distances. Given these conditions, the researchers concluded that the statistical difference in the eastbound treatments segments could have been due to the variation in drum offsets and not necessarily due to the presence or absence of warning lights on the drums.

Driver Opinion Results

After each of the 17 participants drove the predetermined route through the work zone treatments, the participants were asked their opinion of various work zone features. The first question was "As you were driving through, did you notice anything about the work zone that changed?" Fifteen participants did not, but two participants said that they did. When these two were asked to explain what they noticed, one participant stated that he/she noticed some signs with the drums, while the other noticed the barriers being stored in the right-of-way. In summary, nobody noticed the absence of warning lights on the drums in 1500 (±) ft segments of the work zone.

After the first five participants completed the study, the researchers realized that nobody was identifying the treatment differences and therefore, no valuable information could be obtained through the remaining questions. So a more specific question was added to the survey for the remaining 12 participants. After the first question, the researchers showed each participant two photos which demonstrated the difference between the experimental (without warning lights) and standard (with warning lights) treatments. After pointing out the differences, the next question was "Did you notice this specific change in the work zone?" Eleven of the remaining 12 participants (89 percent) did not recall noticing the difference, even when prompted with the photos.

The next question asked the participants to rate how well the traffic control devices guided them through the entire work zone, using a Good-Fair-Poor scale. All of the participants (100 percent) gave a Good rating to the work zone. The researchers then asked each participant why this rating was given. The results are shown in Table 4-6.

Table 4-6. Participants' Stated Reasons for Rating the Traffic Control Devices as "Good."

Reason Stated	Number of Participants
Path was clearly defined	7 (58%)
Had no difficulty driving	2 (16%)
Work zone was well lit	1 (8%)
Not sure why	2 (16%)
Total	12 (100%)

Seven of the 12 participants (58 percent) indicated that the path was clearly defined, with another two (16 percent) indicating that they had no difficulty. One participant stated that the work zone was "lit up well," while the remaining two could not identify a reason why they thought the traffic control was good. Interestingly, despite having knowledge of the differences in the work zone at this point in the survey, none of the participants indicated that delineation was better in the areas where the warning lights were present or worse in areas where the warning lights were not present.

The final question asked the participants to indicate their preference regarding the use of warning lights by selecting the treatment that did the best job of guiding them through the work zone. The results are shown in Table 4-7.

Table 4-7. Participants' Stated Preferences for the Use of Warning Lights on Drums.

<table>
<tr><th>Preference Stated</th><th>Number of Participants</th><th>Percent of Total</th><th>Stated Reason for Preference</th><th>Number of Participants</th></tr>
<tr><td rowspan="3">Drums with warning lights</td><td rowspan="3">8</td><td rowspan="3">(67%)</td><td>Better visibility</td><td>3</td></tr>
<tr><td>Better at getting driver attention</td><td>4</td></tr>
<tr><td>More lights are better</td><td>1</td></tr>
<tr><td>Drums without warning lights</td><td>2</td><td>(16%)</td><td>Didn't notice them missing</td><td>2</td></tr>
<tr><td>No preference</td><td>2</td><td>(16%)</td><td>N/A</td><td>2</td></tr>
<tr><td>Total</td><td>12</td><td>(100%)</td><td></td><td>12 (100%)</td></tr>
</table>

Eight of the 12 participants (67 percent) preferred the lights. When asked why, three participants indicated that the lights provided better visibility (i.e., for seeing further down the road). Four participants indicated that they were better for getting driver attention (i.e., seeing a drum better) than drums with no lights, while one participant simply indicated that more lights were better. Two of the 12 participants (16 percent) preferred no warning lights, indicating that they did not notice them missing, while the remaining two participants (16 percent) had no preference.

The preference for the warning lights was not surprising to the researchers. Past studies have shown that motorists consistently indicate a preference for, and perceived value of, higher levels of luminance and lighting in a visual scene when directly asked, even when other measures of performance suggest that the higher levels were not noticed or did not appear to have an impact on driving behavior (*40*).

I-75 Study of Barrier Delineators

Eye-Tracking Results

The eye-tracking data were summarized for each treatment segment and are shown in Table 4-8.

Table 4-8. Eye-Tracking Results for I-75 Work Zone.

Region	Treatment							
	Northbound				Southbound			
	EXP1		STD2		STD3		EXP4	
	Number of Glances	Percent of Total	Number of Glances	Percent of Total	Number of Glances	Percent of Total	Number of Glances	Percent of Total
-1 (Left Side)	104	20%	56	19%	82	21%	64	18%
2 (Above Horizon)	142	27%	91	31%	100	25%	72	20%
+1 (Right Side)	70	13%	45	15%	45	11%	90	25%
0 (Within Lane Lines)	206	40%	105	35%	166	42%	138	38%
TOTAL	522	100%	297	100%	393	100%	364	100%

The same driver glance variations were found in the I-75 eye-tracking data as was seen in the Ulmerton Road eye-tracking data. Again, a small data set of 15 participants was all that could be collected, primarily due to recruitment challenges and rain on two evenings. Having fewer participants means that data from a single participant can significantly impact the overall results. The dataset for the I-75 study has 1,576 separate glances over the four treatment segments. In this study, glances to the left side (Region -1) were of interest to the researchers. As shown in Table 4-8, the percentages of glances to Region -1 appear to be very similar across all treatment segments (20 percent, 19 percent, 21 percent, and 18 percent). Using a test of proportions for each paired comparison, there were no statistical differences in Region -1 glances for any of the treatment segments. Unlike the Ulmerton Road work zone, the researchers did not see a volume effect upon glances to the left, regardless of the amount of opposing traffic present, most likely due to the fact that the road was median separated by at least 95 ft in all treatment segments. There was a difference in the glances to Region +1 in the EXP4 treatment area (25 percent) when compared to the other segments (13 percent, 15 percent, and 11 percent). This difference was attributed to the presence of merging traffic on a southbound entrance ramp in the EXP4 treatment area. The main attention given by participants was within the lane lines (Region 0), a region that included the left edge line (40 percent, 35 percent, 42 percent, and 38 percent).

Lane-Keeping Results

Lane-keeping data from the instrumented vehicle video were summarized for each treatment segment. Data for all 15 participants were merged and statistical descriptors are given in Table 4-9.

Table 4-9. Lane-Keeping Data for I-75 Participants.

Statistics	Treatment Segment			
	EXP1 (n=244)	STD2 (n=171)	STD3 (n=219)	EXP4 (n=225)
Average Distance from Tire to Edge Line (inches)	39.6	39.0	39.2	39.8
Standard Deviation	7.6	9.5	12.9	9.1

A student t-test statistical comparison of means at 95 percent confidence interval indicates that there were no differences in lane-keeping between any of the treatment segments. Based on all of the data presented, the researchers concluded that the replacement of warning lights with retroreflective delineators on barrier walls did not appear to have any impact on older driver behavior.

Driver Opinion Results

Upon completion of the driving task, a survey was conducted to garner driver opinions of the freeway work zone traffic control. Participants were first asked if they noticed anything about the work zone traffic control that changed. The results are shown in Table 4-6.

Table 4-10. Participants' Recognition and Identification of Changes in the Work Zone.

Recognition of Change	Change Recognized	Number of Participants	Percentage of Participants
Yes	Speed Limit	6	(40%)
	Pavement	1	(7%)
	Barrier Delineators	2	(13%)
No	N/A	6	(40%)
Total		15	(100%)

Nine of the 15 subjects (60 percent) responded positively. When asked to describe that change, six of these nine participants noted that the speed limit changed in the work zone. There was, in fact, a work zone speed limit reduction in this work zone. One participant noted that the pavement changed, while only two participants noticed the barrier delineators or "square lights." The remaining participants (40 percent) indicated that they did not notice anything changing in the work zone. After showing each participant the two types of delineation treatments using photos from the work zone, two additional participants recalled noticing the barrier delineators, but the remaining participants still did not recall noticing them.

The participants were also asked to indicate their preference regarding the warning lights and barrier delineators. The results are shown in Table 4-11.

Table 4-11. Participants' Stated Preferences for the Use of Warning Lights on Barrier Walls.

Preference Stated	Number of Participants	Percent of Total	Stated Reason for Preference	Number of Participants
Barrier wall with warning lights	4	27%	Familiar	1
			Indicated Construction	1
			Prefer yellow color	1
			More visible	1
Barrier wall with delineators	7	46%	More visible, brighter or more distinctive	4
			Less distracting or less obtrusive	2
			Closer spacing	1
No preference	4	27%	N/A	4
Total	15	(100%)		15 (100%)

Four participants (27 percent) indicated a preference for the warning lights over the retroreflective delineators, stating that they were familiar and indicative of construction activities, noting that the yellow color stood out from other white lights, and they were generally more visible. Seven (46 percent) participants indicated a preference for the delineators. Their preference was supported with comments indicating that they thought the delineators were more distinctive/more visible at night, less distracting/less obtrusive than the warning lights, and the closer spacing was helpful in knowing where to drive. Finally, the remaining four participants (27 percent) indicated no preference of one over the other.

SUMMARY

The human factors study provided data and insight for the researchers to better understand how drivers respond to steady-burn warning lights in work zones. At the Ulmerton Road work zone, some channelizing drums had warning lights, while others did not. While the researchers did find differences in driver eye-tracking behavior from segment to segment in the work zone, these differences were more likely due to traffic volume and frequency of driveways, rather than the presence of the warning lights. When comparing older driver lane-keeping in the work zone, the researchers obtained mixed results. However, the differences may have been due to inconsistent offset of the channelizing drums from the lane line, rather than the presence or absence of warning lights. The survey results indicated that, when asked directly, more participants preferred the warning lights in this work zone, citing better visibility and attention-getting. However, the measures of effectiveness did not appear to indicate any differences in driving behavior, and the participants did not notice the absence of lights on drums in some of the test sections prior to pointing that fact out by the researchers.

At the I-75 work zone, some sections of the temporary barrier walls had warning lights, while others had yellow retroreflective barrier delineators. The researchers found no differences in eye-tracking or lane-keeping behavior between the two treatments. The survey results indicated that more participants had a preference for the barrier delineators over the warning lights, citing better visibility as the reason. However, only two of the study participants recalled noticing the difference in the work zone.

CHAPTER 5 COST-EFFECTIVENESS EVALUATION

INTRODUCTION

The argument for using warning lights in work zones is that they provide an incremental benefit to safety. Ideally, the additional costs of using warning lights should be offset by that safety benefit; in other words, the reduction in crash costs should equal or exceed the costs of the devices. While it was possible to assess the costs of using warning lights on channelizing devices or on barriers, the effects of the lights on safety are not currently known. Surrogate measures (i.e., eye-tracking and incremental photometric effects of the lights) examined through this research and elsewhere suggest that the lights have minimal, if any, effect. Consequently, although a crash reduction estimate does not exist for the lights, one can estimate the amount of crash reduction that would be required to offset the costs of the lights, and then make a judgment as to whether that magnitude of crash reduction is likely or even possible.

This chapter consists of two parts. The first part describes the process used to collect and analyze warning light cost data in Florida. The second part documents a computation of crash cost increases that could be expected to occur in two types of work zones and the crash cost reductions (i.e., safety benefits) that would have to occur by using the warning lights in order to justify their use on a benefit-cost basis.

WARNING LIGHT COST ANALYSIS

This part of the chapter describes an analysis of costs associated with the use of warning lights and alternative devices. These costs include the capital cost of purchasing the devices, battery costs for warning lights, and maintenance costs. A highway work zone, by its nature, is a temporary installation. Most construction contractors typically begin with a pre-purchased inventory of devices. However, the contractors will likely need to purchase some new devices, both at the beginning of the project and throughout its duration due to accidents, theft, and other losses of the devices.

The following input data would be needed to analyze warning light costs for a given project (*41*, *42*):

- Work zone duration (years).
- Work zone length (miles).
- Number of devices.
- Capital cost per device ($).
- Battery life span (weeks, for warning lights only).
- Battery cost ($/light, for warning lights only).
- Device replacement rate (% of devices/year).
- Maintenance time (hr/week/mile).
- Maintenance worker wage rate ($/hr) and "loaded" rate ($/hr).
- Disposal cost ($/device).

Ultimately, a generic cost estimate could be developed on per-length-per-time basis (i.e., $ per mile per year). Researchers focused on developing such a unit cost based on Florida DOT experiences. The input data were obtained through telephone conversations with several device manufacturers and maintenance of traffic contractors. Information was also collected regarding barrier delineators that are available as alternative devices that could be used to replace warning lights used on concrete barriers.

Warning lights manufactured by Empco-Lite®, a line of Elgin Molded Plastics, Inc. were used in this analysis (*43*). The following three types of warning lights were included in the analysis:

- Incandescent (Model 400).
- LED (Model 2006).
- LED with solar assist (Model 2006 Plus).

According to the Empco-Lite representative, some incandescent warning lights are still sold, but they have mostly been supplanted by LED lights because of battery life issues. During the telephone conversations, two maintenance of traffic contractors stated that they no longer use incandescent warning lights for any of their operations.

Capital Cost

The Empco-Lite representative indicated the following capital costs for warning lights:

- $23 for incandescent.
- $30 for LED.
- $41 for LED with solar assist.

He explained that these figures represent reasonable average prices, but that there may be considerable variation in what maintenance of traffic contractors actually pay for the warning lights.

Battery Life and Cost

The Empco-Lite representative specified a battery life of two weeks for incandescent warning lights, 6–7 months for LED warning lights, and 18 months for the LED warning light with solar assist. All of these estimates were based on steady-burn operation for nighttime applications.

Visual inspection of a sample incandescent warning light supplied by Empco-Lite revealed that the light was equipped with a single 0.35-W bulb that draws 70 mA of electric current. The incandescent warning light was designed to contain two 6-V lantern batteries, though it can operate with one battery. The following equation was used to obtain an independent estimate of battery life span for the incandescent warning light:

$$t_{life} = \frac{1}{7T_{day}} \frac{T_{batt} N_{batt}}{I}$$ **(Equation 3)**

where:

t_{life} = battery life span (weeks).

T_{day} = number of hours of use per day (hr).

T_{batt} = battery capacity (A-hr).

N_{batt} = number of batteries used.

I = electric current (A).

The use of Equation 3 reveals that for an incandescent warning light equipped with two batteries, a battery life span of two weeks corresponds to a battery capacity of about 4.5 A-hr. This battery capacity was consistent with a typical advertised capacity for rechargeable 6-V lantern batteries (*44*) and some alkaline 6-V lantern batteries (*45*). However, some industrial-grade 6-V lantern batteries that have advertised 21 A-hr capacities are also available (*46*). Application of Equation 3 reveals that if these batteries were used, a battery life span of 9.5 weeks could be obtained for incandescent warning lights.

Visual inspection of a sample LED warning light revealed that the light was equipped with two 5-mm 3-V LEDs. These types of LEDs typically draw 20 mA of electric current (*47*). The LED warning light was designed to contain four D batteries, though it can operate with two batteries. The use of Equation 3 reveals that for an LED warning light equipped with four batteries, a battery life span of six months corresponds to a battery capacity of about 16.5 A-hr. This battery capacity was consistent with the expected capacity for alkaline D batteries (*48*).

Costs for 6-V lantern batteries and D batteries were estimated as $12.00 per pair and $9.60 per set of four, respectively, based on data from several online sources (*44*, *49*, *50*). It was assumed that the contractor would be able to obtain a 25 percent discount off retail battery prices and that disposable alkaline batteries would be used.

Warning Light Life Span

A maintenance-of-traffic contractor in Florida stated that warning lights typically last about eight years if not damaged by an external force, and that the typical replacement rate for warning lights was about three percent per year. Assuming an exponential decay rate for the devices, a life span of eight years implies a replacement rate of 12.5 percent per year. Hence, it is likely that the actual replacement rate varies depending on work zone conditions and the age of the warning lights that were used in initial deployment. The contractor further explained that the three most common events causing warning light failure are theft, damage by contractor, and vandalism.

Maintenance Costs

When asked about maintenance tasks, the maintenance-of-traffic contractor in Florida explained that his maintenance workers simply pass through the work zone periodically and make needed adjustments to the warning lights along with the rest of the devices present (drums, barricades, etc.). The maintenance workers typically remove and replace dim or nonfunctional lights and bring them back to the shop for servicing. The service tasks may include changing batteries, cleaning, and repairing or replacing broken parts. Field maintenance was usually limited to swapping lights in this manner, or realigning lights that were not properly oriented.

The contractor further explained that his company typically disassembles nonfunctional warning lights, discards broken parts, sorts the remaining intact parts, and reassembles the parts to form “new” lights. The Empco-Lite representative stated that this practice was common among contractors.

The contractors from Florida stated that their maintenance workers are paid salaries in the range of \$11.50–\$12.00 per hour. On average, it was estimated that the LED warning lights require about 4.5 minutes per week (or 0.075 hours per week) of maintenance effort in a “typical” one-mile work zone. Using the average battery life spans for the warning lights, per-mile maintenance requirements for incandescent and LED solar assist lights were then estimated as 1.05 hours per week and 0.027 hours per week, respectively. This calculation accounts for the time needed to replace batteries.

The contractors were asked about disposal cost issues for devices that were broken or worn. Both indicated that their disposal costs were negligible. The Florida contractor explained that his company disposes of spent warning light parts along with their everyday business waste.

Table 5-1 summarizes the warning light components tabulated in this research. Also shown is an estimate of barrier delineators that could be used in lieu of warning lights on temporary barrier wall. As the table illustrates, the cost per day of the warning lights differs dramatically depending on whether the older incandescent technology or LED technology is being used. Overall, incandescent warning lights were nine to 10 times more expensive to use than were the LED lights. Interestingly, the values of the LED lights (\$0.09 to \$0.10 per device per day) match up well with the reported statewide item average unit cost of \$0.10/device/day that was reported in FDOT’s Annual Statewide Average Unit Cost data sheet for the year 2011 (*51*). While dramatically lower than the \$0.91 per device per day cost of the older incandescent lights, it was still significantly higher than the \$0.01 per device per day costs of a barrier delineator for locations where warning lights are used on concrete barrier wall.

Table 5-1. Cost Input Data for Delineation Devices.

Device	Incandescent Warning Light	LED Warning Light	LED Solar Assist Warning Light	Barrier Delineator
Capital Cost (\$/device)	\$23	\$30	\$41	\$7
Battery Life (wk)	2	28	78	Not applicable
Battery Cost (\$/device)	\$12	\$9.60	\$9.60	Not applicable
Replacement rate (%/yr)	10	10	10	5
Maintenance Time (hr/wk/mi)	1.05	0.075	0.027	0
Maintenance Worker Wage Rate (\$/hr)	\$12	\$12	\$12	\$12
Loaded Rate Multiplier	1.5	1.5	1.5	1.5
Cost per Device per Day	\$0.91	\$0.10	\$0.09	\$0.01

Results

An analysis tool was developed to incorporate the preceding cost data and work zone description data and to produce cost estimates for the use of warning lights and alternative devices. The tool was formulated as a spreadsheet program to compute both the average cost per device per day (as was shown in Table 5-1 above), and the cost per mile per day. The costs of warning lights in work zones were calculated for two types of work zones:

- Urban arterial work zone with channelizing drums delineating the edge of the roadway.
- Rural freeway with temporary barrier wall separating travel lanes from the work space.

Costs were estimated for a typical one-mile section of work zone on each facility. For the urban arterial work zone, a 45 mph speed limit was assumed, indicating that drums would be placed at a 50-feet spacing as per FDOT specifications (*2*). Over a one-mile work zone, this would result in 106 drums (and lights, if used) per mile per direction. If used on both sides of the roadway, there would be 212 drums and warning lights per mile. For the freeway work zone using temporary barrier wall, the warning lights would be positioned at a 200 ft spacing on tangent sections and a 100 ft spacing on curves (*3*). Assuming a 50/50 split of straight and curvilinear alignment, a total of 35 warning lights would be used per mile of barrier within the work zone. Sections with barrier on both sides of the directional roadway would have 70 warning lights per mile.

Table 5-2 and Table 5-3 summarize the incremental costs of providing warning lights in the two types of work zones. As expected, costs were highest for the incandescent warning lights (which was why they were being replaced over time with the more cost-effective LED devices). Even when considering only the LED lights, however, costs on a per mile per day basis range between $9.54 and $21.20 in an urban arterial work zone depending on whether channelizing devices would be used on one side of the road only or on both sides. One would expect similar, but slightly lower costs, for any freeway work zones that used channelizing drums as well, since drum spacing would typically be greater on a higher speed facility. On freeway facilities where warning lights are used on temporary barrier wall, the additional costs per day of using LED warning lights in lieu of barrier delineators was substantially less, ranging between $2.80 and $6.30 per mile per day. Extrapolating these per day rates to annualized values, one sees that the provision of warning lights in work zones costs between $3,482 and $7,738 per mile per year in urban arterial work zones, and between $1,022 and $2,300 per mile per year in rural freeway work zones where temporary barrier wall is used.

Table 5-2. Costs of Using Warning Lights on Drums in an Urban Arterial Work Zone.

Device	Incandescent Warning Light	LED Warning Light	LED Solar Assist Warning Light
Number of devices per mile:			
Used on one side of road	106	106	106
Used on both sides of road	212	212	212
Cost/light/day	$0.91	$0.10	$0.09
Cost/mile/day:			
Used on one side of road	$96.46	$10.60	$9.54
Used on both sides of road	$192.92	$21.20	$19.08
Cost/mile/year:			
Used on one side of road	$35,208	$3,869	$3,482
Used on both sides of road	$70,416	$7,738	$6,964

Table 5-3. Costs of Using Warning Lights on Temporary Barrier Wall in a Rural Freeway Work Zone.

Device	Incandescent Warning Light	LED Warning Light	LED Solar Assist Warning Light
Number of devices per mile:			
Used on one side of road	35	35	35
Used on both sides of road	70	70	70
Difference in cost/device/day	($0.91−$0.01) = $0.90	($0.10−$0.01) = $0.09	($0.09− $0.01) = $0.08
Cost/mile/day:			
Used on one side of road	$31.50	$3.15	$2.80
Used on both sides of road	$63.00	$6.30	$5.60
Cost/mile/year:			
Used on one side of road	$11,498	$1,150	$1,022
Used on both sides of road	$22,996	$2,300	$2,044

WARNING LIGHT BENEFIT ANALYSIS

Given the nominal costs of using warning lights in work zones listed in Table 5-2 and Table 5-3, the next step in this analysis was to determine the magnitude of crash reduction (i.e., the added effectiveness of warning lights) that would need to occur in order to offset the costs of using warning lights in work zones. Currently, crash modification factors (CMFs) associated with the use of warning lights in addition to existing work zone channelization retroreflectivity, roadway delineation, and/or barrier delineation do not exist (*52*). However, given that the research previously documented in this report has shown a very minimal influence of warning lights above and beyond the use of retroreflective drums without lights and the provision of delineators on temporary barrier wall instead of lights, one would anticipate only a very minor (if any) reduction in work zone crash costs. If one can quantify the percent reduction in crashes that would be required to offset the costs of using the warning lights, the reasonableness and likelihood of achieving that magnitude of a reduction can at least be evaluated using engineering judgment.

Crash Frequency Estimation

The crash cost estimation analysis began with an estimation of crash frequency on two example types of roadways—an urban arterial with four lanes and a two-way left turn lane (TWLTL), and a rural six-lane freeway. Variables describing the characteristics of the example roadway segments are listed in Table 5-4. These characteristics were chosen to represent typical roadways, with some characteristics that describe expected conditions in a work zone (e.g., lane widths of 11 ft on the rural freeway segment).

Table 5-4. Example Roadway Segments for Crash Frequency Estimation.

Urban Street Segment	Rural Freeway Segment
Length 1 mi Number of lanes: 4 Median type: TWLTL AADT: 35,000 veh/d Type of on-street parking: None Median width: 15 ft Lighting: Not present Automated speed enforcement: None Major commercial driveways: 4 Minor commercial driveways: 4 Major industrial/institutional driveways: 0 Minor industrial/institutional driveways: 0 Major residential driveways: 0 Minor residential driveways: 0 Other driveways: 0 Posted speed: Greater than 30 mph Roadside fixed object density: 10 objects/mi Offset to roadside fixed objects: 6 ft	Length: 1 mi Number of lanes: 6 Horizontal curve present: No Lane width: 11 ft Outside shoulder width: 8 ft Inside shoulder width: 4 ft Median width: 10 ft Rumble strips present: No Barrier presence in median: Centered Median barrier width: 2 ft Clear zone width: 30 ft Barrier presence on roadside: None Ramp presence on segment: None Weaving section presence on segment: None AADT: 130,000 veh/d

The crash frequencies for these two segments were estimated using methodologies found in the *Highway Safety Manual* (HSM). Specifically, the urban street methodology found in Chapter 12 of the 1st Edition HSM was used to analyze the urban street segment (*53*), and material developed by Bonneson et al. for proposed inclusion in a future HSM edition was used to analyze the urban freeway segment (*54*, *55*).

The urban street HSM methodology provides estimates of the expected fatal-and-injury (F+I) crash frequency and property-damage-only (PDO) crash frequency. The proposed urban freeway methodology provides estimates of the crash frequency for the K, A, B, C, and PDO severities. These methodologies were applied to obtain estimates in terms of crashes per mile per year.

In both cases, the estimated crash frequency represents crashes occurring in all hours of the day. Devices such as warning lights are intended to reduce nighttime crashes, so it was necessary to determine the frequency of crashes occurring at night. To obtain the distribution of crashes by light condition, the distribution reported by NHTSA in 2010 (*56*) was applied to the estimated crash frequencies. This distribution is provided in Table 5-5.

Table 5-5. Nationwide Crash Distribution by Light Condition.

Severity Category	Crash Count by Lighting Condition				Dark-Condition Crash Percentage
	Dark	Dark but Lighted	All Dark Crashes	All Light Conditions	
Fatal	5389	8535	13,924	30,196	46.1%
Injury	253,000	138,000	391,000	1,542,000	25.4%
F+I	258,389	146,535	404,924	1,572,196	25.8%
PDO	594,000	419,000	1,013,000	3,848,000	26.3%

The dark-condition crash percentages in the rightmost column of Table 5-5 were multiplied by the HSM-derived crash frequencies to obtain the night crash frequencies for the two example roadway segments. These crash frequencies represent estimated values for segments having the characteristics listed in Table 5-4 under normal (i.e., non-work-zone) nighttime conditions. Crash modification factors (CMFs) derived by Ullman et al. (*57*) were used to obtain an estimate of the additional crashes that would occur due to the presence of a work zone. These CMFs are provided in Table 5-6.

Table 5-6. Nighttime Work Zone CMFs.

Work Activity in Progress?	Lane Closure Present?	Crash Severity	CMF
Yes	Yes	F+I	1.423
Yes	Yes	PDO	1.748
Yes	No	F+I	1.414
Yes	No	PDO	1.666
No	No	F+I	1.114
No	No	PDO	1.330

All of the CMFs are greater than one, indicating that the presence of a work zone was associated with an increase in crashes to varying degrees, depending on whether work activity was in progress and whether a lane closure was in effect during the work activity. Subtracting one from these CMF values yielded the crash increase proportion associated with work zone presence.

To estimate the number of crashes incurred due to work zone presence, the nighttime crash frequencies for the two example roadway segments were multiplied by the crash increase proportions derived from the CMFs in Table 5-6. For example, weighted-average proportions were determined for what was defined as an “active nighttime” work zone described by the following characteristics:

- Work activity and lane closure present: two nights per week.
- Work activity but no lane closure present: three nights per week.
- No work activity and no lane closure present: two nights per week.

A work zone with these characteristics would ultimately yield weighted average CMFs of 1.331 for F+I crashes and 1.593 for PDO crashes. That is, F+I crashes would be expected increase by 33.1 percent and PDO crashes increase by 59.3 percent due to the work zone activity. Conversely, for a more typical “no night work” type of work zone, the values for no lane closures or work activity in Table 5-6 would be appropriate (i.e., an 11.4 percent increase in F+I crashes, 33.0 percent increase in PDO crashes).

Crash Cost Estimation

The safety cost associated with work zone presence was determined by quantifying the costs of the nighttime work-zone-related crashes. This computation begins with an estimation of crash costs for the various severity levels. Council et al. published estimated crash costs for various aggregations of severity levels (*58*). Their costs were tabulated in 2001 dollars, and they described a procedure to update the costs by using the consumer price index (CPI) and the employment cost index (ECI). The CPI and ECI for 2001 and 2012 were obtained from the Bureau of Labor Statistics (*59*, *60*) and used to update the costs from Council et al. to 2012 dollars. These cost computations are shown in Table 5-7.

Table 5-7. Crash Cost Computations.

Severity Level	2001		2012	
	CPI = 177.10	ECI = 95.9	CPI = 231.32	ECI = 99.9
	Human Capital	**Comprehensive**	**Human Capital**	**Comprehensive**
K	$1,245,579	$4,008,885	$1,626,919	$4,505,483
A	$111,376	$216,059	$145,474	$254,524
K/A/B/C (all F+I)	$68,846	$158,177	$89,294	$182,981
B	$41,882	$79,777	$54,704	$94,180
C	$28,405	$44,868	$37,101	$54,251
PDO	$6,390	$7,428	$8,346	$9,428

The comprehensive costs in the last column of Table 5-7 were used in assessing the cost of nighttime crashes occurring because of the presence of a work zone. The computations are summarized in Table 5-8 and Table 5-9 for both an active night work zone (four nights with activity [two of which involved temporary lane closures] and three nights of inactivity) and for a work zone where no work was performed at night. For the urban arterial scenario, the work zone was expected to generate an average of $270 of additional crash costs per night if some of the work was to occur at night, and an average of $104 per night if no work activity typically occurred (i.e., it was a traditional project where work occurred primarily during the day).

Table 5-8. Additional Nighttime Crash Costs for a Typical Urban Arterial Work Zone.

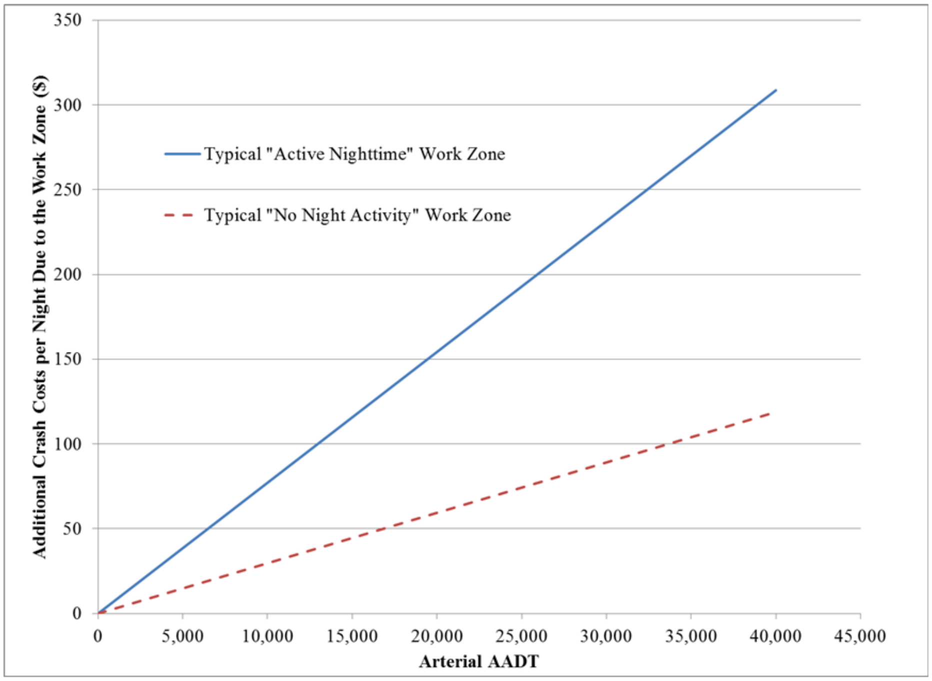
Work Zone Activity Level	Severity Level	Number of Crashes per year			Night Work Zone Crash Cost per Year	Total Work Zone Crash Cost per Night
		Total	**Night**	**Additional—Night Work Zone**		
Active Night Work Zone	F+I	5.10	1.31	0.43	$79,521	$270
	PDO	12.90	3.40	2.02	$18,999	
Inactive Night Work Zone	F+I	5.10	1.30	0.15	$27,400	$104
	PDO	12.90	3.40	1.12	10,565	

Table 5-9. Additional Nighttime Crash Costs for a Typical Rural Freeway Work Zone.

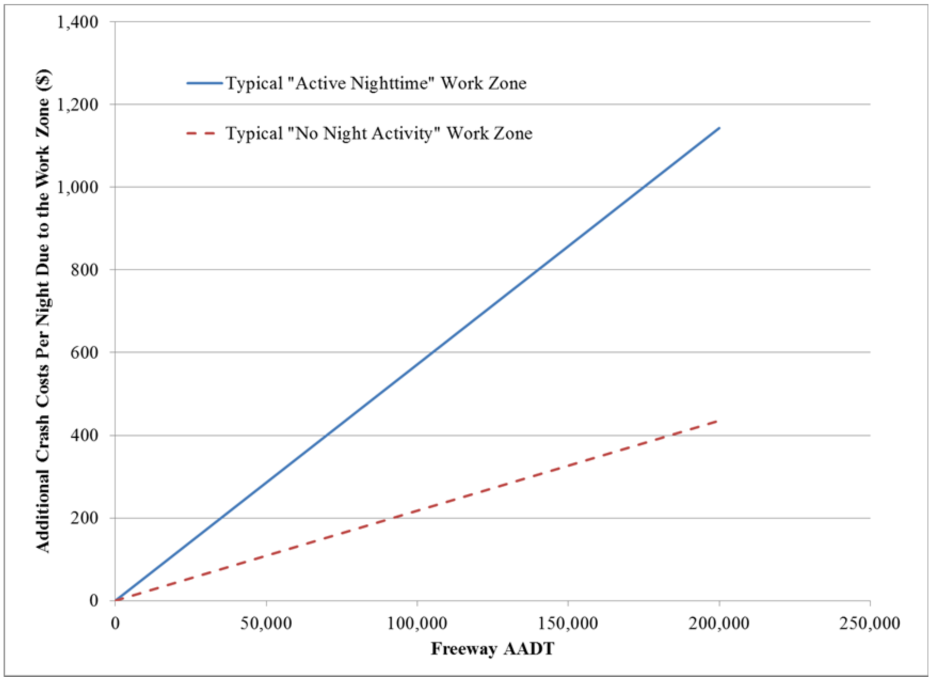
Work Zone Activity Level	Severity Level	Number of Crashes per Year			Night Work Zone Crash Cost per Year	Total Work Zone Crash Cost per Night
		Total	Night	Additional—Night Work Zone		
Active Night Work Zone	K	0.21	0.10	0.03	$143,708	$743
	A	0.43	0.11	0.04	$9,248	
	B	3.14	0.8	0.26	$24,780	
	C	10.22	2.59	0.86	$46,498	
	PDO	31.79	8.37	4.97	$46,819	
Inactive Night Work Zone	K	0.21	0.1	0.01	$49,516	$283
	A	0.43	0.11	0.01	$3,186	
	B	3.14	0.8	0.09	$8,538	
	C	10.22	2.59	0.30	$16,021	
	PDO	31.79	8.37	2.76	$26,036	

COMPARISON OF WARNING LIGHT COSTS TO SAFETY BENEFIT NEEDED TO JUSTIFY THOSE COSTS

Although the relationship between crash costs and traffic volumes on a facility are not truly linear, a reasonable approximation of the effect of volume on crash costs can be obtained by dividing the per night crash costs in Table 5-8 and Table 5-9 by the traffic volume level for which they were computed (i.e., 35,000 vehicles per day for the urban arterial, 130,000 vehicles per day for the rural freeway). These results are shown in Figure 5-1.



(a) Typical Urban Arterial



(b) Typical Rural Freeway

Figure 5-1. Relationship between Roadway AADT and Additional Work Zone Crash Costs.

With these crash costs estimates available, it was possible to compare them to the costs of providing warning lights. The goal was to determine the percentage of these increased crash costs that would have to be eliminated through the addition of warning lights in order to justify their use. Figure 5-2 and Figure 5-3 highlight some hypothetical crash cost reduction percentages, overlaid with the costs of warning lights. Since warning light costs are independent of volume on a facility, they were shown as a horizontal line across the entire range of AADTs considered. As shown in Figure 5-2, even a fairly unrealistic assumption of a 10 percent reduction in crashes due to the warning lights would be insufficient to offset the costs of incandescent warning lights that average about $200/mile/day (from Table 5-2). Considering the more cost-effective LED lights (an approximate $20/mile/day cost was shown to reflect both types of LED devices), one sees that costs of the lights could only reasonably be justified if they were able to reduce nighttime work zone crashes by 10 percent (a fairly unrealistic expectation) in work zones with nighttime work activity, and even then only on facilities that served traffic demands of at least 30,000 vehicles per day. If the work zone was a more typical project where activity occurred during daylight hours only, even a 10 percent crash reduction assumption would be insufficient to justify the costs of the lights.

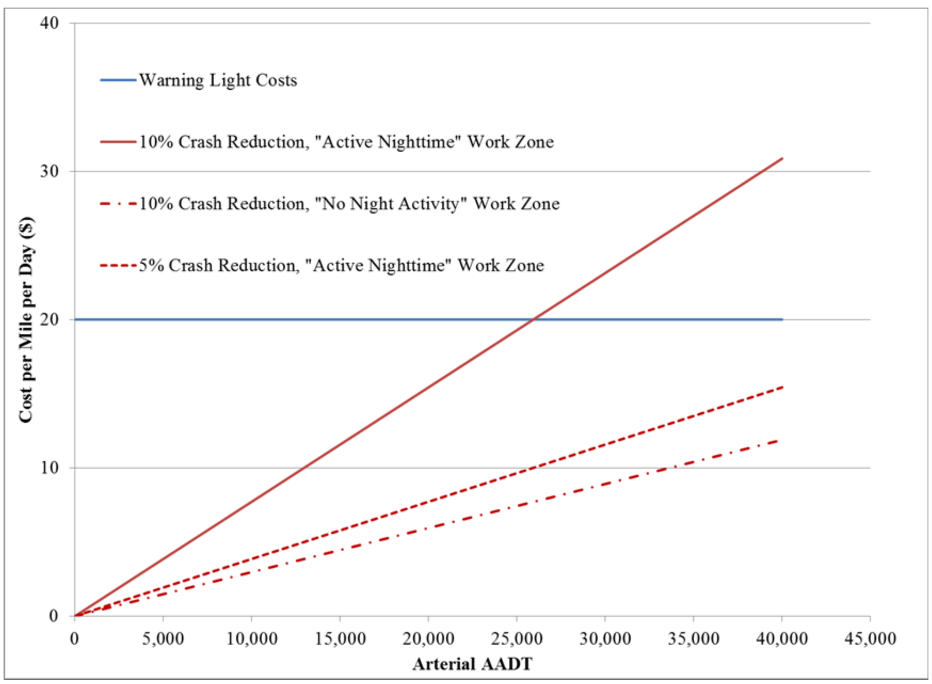


Figure 5-2. Trade-Offs between Warning Light Costs and Potential Crash Cost Reductions: Urban Arterial Work Zones.

The trade-offs were somewhat better for freeway facilities when warning lights are used on barriers, due to the much greater spacing at which the warning lights are used. As shown in Figure 5-3, the use of LED warning lights results in costs that were only about $6/mile/day (from Table 5-3). Meanwhile, a two percent reduction in crash costs would offset these costs once AADTs exceeded 50,000 vehicles per day at work zones with nighttime activity and once AADTs reach about 140,000 vehicles per day at typical "no nighttime activity" work zones. If a greater than five percent crash cost reduction were assumed, warning lights could be justified on a cost basis at "no nighttime activity" work zones where AADTs exceeded 50,000 vehicles per day. However, such a reduction may be unrealistic, given the results of the human factors study described earlier in this report.

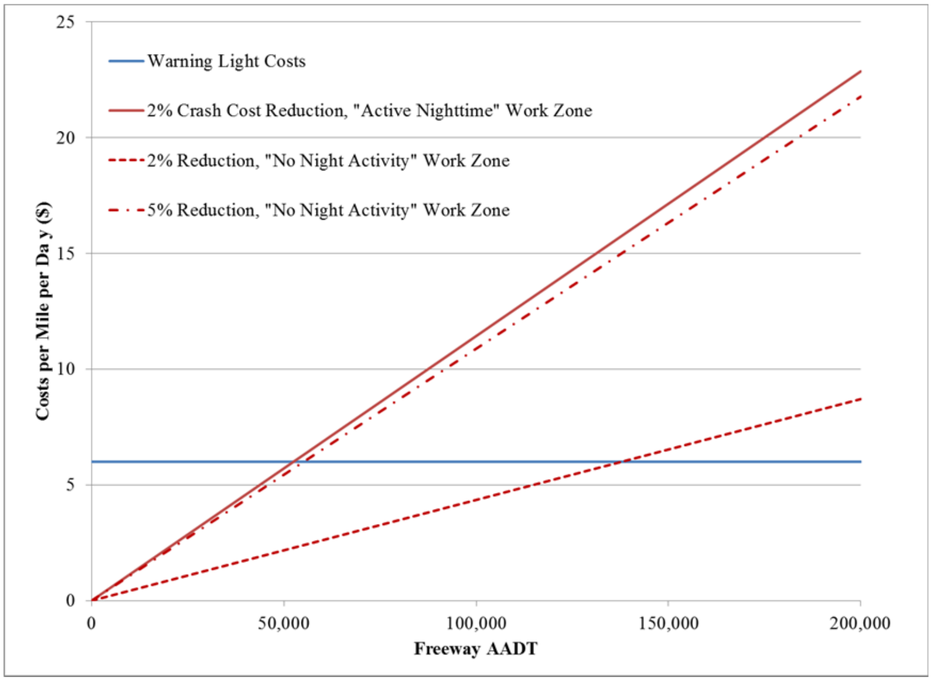


Figure 5-3. Trade-Offs between Warning Light Costs and Potential Crash Cost Reductions: Rural Freeway Work Zones with Temporary Barrier Wall.

SUMMARY

Costs of LED warning lights were approximately $0.10/day, consistent with current bid prices experienced by FDOT. Multiplied by typical light spacing, FDOT's current practices resulted in LED warning light costs ranging from as low as $6/mile/day for barrier delineation on freeway work zones to about $20/mile/day for urban arterial work zones where channelizing device spacing is smaller and more lights are typically used.

To offset these costs, the crash reduction benefit analysis documented in this chapter indicates that warning lights in urban arterial work zones would need to result in more than a 10 percent reduction in all nighttime crashes relative to what would occur if warning lights were not used on the channelizing devices. Although a warning light crash modification factor is not currently available, researchers believe it would be extremely difficult for warning lights to be able to consistently generate this amount of nighttime crash reduction.

On freeway work zones where warning lights are used to delineate traffic barrier, the longer spacing between lights results in a lower usage cost of approximately $6/mile/day. As a result, such lights could become cost-effective at a lower crash reduction level (analyses in this chapter indicate between a two and five percent reduction would be needed) relative to a no-light condition. However, researchers again question whether such a small benefit could be consistently achieved given the human factors findings from this project. The fact that warning lights could be replaced with retroreflective delineators on the barrier would further diminish the potential incremental benefit that the provision of warning lights could generate.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

This report documents the effect and value of steady-burn warning lights on temporary traffic control devices used to delineate the correct travel path in work zones, and on temporary barrier walls relative to the potential use of delineators currently used on permanent barrier walls. The evaluation consisted of the following:

- Assessment of the potential incremental increase in luminance (and benefit of that increase to drivers) during vulnerable driving conditions. These conditions include periods of heavy fog, periods when dew has formed on the reflective sheeting on channelizing devices, periods when dirt and grime accumulates on the channelizing device, and when channelizing devices are viewed by drivers of large trucks who have a larger observation angle between their eye and the vehicle headlights that are illuminating the reflective sheeting. The effect of warning light misalignment upon its apparent luminance to drivers was also assessed.
- Assessment of the effects of providing steady-burn warning lights on channelizing device and temporary barrier walls upon driver visual glance behavior, driving behavior, and driver opinions.
- Assessment of the costs of providing steady-burn warning lights and the necessary improvements in work zone safety that would need to be achieved in order to offset those additional costs.

The sections that follow summarize the key conclusions from each of these evaluations and researcher recommendations for future warning light use.

CONCLUSIONS

Photometric Evaluation of Warning Light Performance under Adverse Environmental Conditions

- Fog adversely affects the apparent luminance (and thus visibility distance) of both retroreflective sheeting and warning lights. The effect appears to be more significant for sheeting at very dense fog levels. Based on data collected in the VRL, this occurred only once fog density reached a visibility level of 50 ft or less. This fog level is likely impossible to achieve in the field. At fog levels one might expect to see in the field, researchers concluded that retroreflective sheeting is still likely to be visible at distances needed for path guidance and delineation purposes, and the use of warning lights is unlikely to provide much additional value to motorists.
- The presence of dew on the retroreflective sheeting of a channelizing device can reduce drum luminance by up to 84 percent. Once again, however, the amount of luminance achieved under dew conditions is still likely to be sufficient for path guidance purposes, which again suggests that warning lights may not provide substantial additional benefit to drivers. Furthermore, researchers were unsure as to whether dew formation regularly occurs on channelizing device drums, given the air pocket that was trapped inside each drum.

- Steady-burn warning lights may substantially increase overall average luminance values of channelizing device drums for vehicles with larger observation angles, such as heavy trucks, especially when placed on the left side of the roadway. However, the luminance values of the drums with high intensity sheeting were sufficient to be seen at distances up to 1,000 ft away from a truck driver's viewing perspective, suggesting that they would provide sufficient detection and guidance information to truck drivers even without the use of steady-burn warning lights.
- The accumulation of dirt and grime on the retroreflective sheeting of drums in Florida work zones does have an impact on device luminance. While the presence of warning lights did increase overall luminance of channelizing drums, a greater increase in luminance was noted when the drums were cleaned by research staff and re-measured.
- An evaluation of misaligned lights found in the field revealed that more than half of the warning lights mounted on drums were misaligned more than five degrees from their optimum viewing angle. In addition, almost all of the warning lights mounted on temporary barrier wall were misaligned more than five degrees. For an LED warning light, this misalignment reduces its apparent luminance approximately 20 percent of that of a properly aligned warning light.
- It is feasible that drivers of large trucks traveling under heavy fog conditions and needing to rely only on channelizing devices on the left side of the travel lane for path guidance may benefit from the presence of steady-burn warning lights if the drums are extremely dirty. However, the relative frequency of such a sequence of events is likely to be so small as to be negligible compared to even a minor incremental cost of providing such warning lights.

Effects of Steady-Burn Warning Lights on Older Driver Behavior

- Steady-burn warning lights used on channelizing drums in work zones did not affect the visual glance and tracking performance of older drivers. Likewise, the lights were not found to have a consistent effect on driver lane position when traveling adjacent to the drums.
- When compared to the use of barrier delineators as specified in Florida DOT standards, the use of warning lights on temporary barrier wall did not appear to affect older driver visual glance and tracking performance, or vehicle lane position when traveling adjacent to the drums.
- When asked directly, the older driver study participants did indicate a preference for warning lights to be used on the channelizing drums in work zone, citing better visibility and attention-getting. However, none of the participants noticed the absence of lights on drums in some of the test sections. Rather, the researchers had to call attention to the fact that some drums did not have warning lights on them prior to asking them their preference for such lights or not.
- When compared to the use of barrier delineators on temporary barrier walls, more study participants actually had a preference for the delineators over the warning lights, citing better visibility as the reason. Once again, however, only two of the study participants recalled noticing the difference of the devices on the barrier in the work zone.

Warning Light Cost-Effectiveness Evaluation

- Analysis of the component, operation, and maintenance cost of an LED warning light indicates an overall cost of approximately $0.10/day, consistent with current bid prices experienced by FDOT. Multiplied by typical light spacing, FDOT's current practices resulted in LED warning light costs ranging from as high as $20/mile/day for urban arterial work zones (where channelizing device spacing is smaller and more lights are typically used) to as low as $6/mile/day for barrier delineation on freeway work zones.
- A crash reduction benefit analysis indicated that warning lights in urban arterial work zones would need to result in more than a 10 percent reduction in all nighttime crashes relative to what would occur if warning lights were not used on the channelizing devices. Although a warning light crash modification factor is not currently available, researchers believe it would be extremely difficult for the addition of warning lights themselves to be able to consistently generate this amount of nighttime crash reduction.
- On freeway work zones where warning lights are used to delineate traffic barrier, the longer spacing between lights resulted in a lower usage cost of approximately $6/mile/day. As a result, such lights could become cost-effective at a lower crash reduction level (analyses in this chapter indicate between a two and five percent reduction would be needed) relative to a no-light condition. However, researchers again question whether such a small benefit could be consistently achieved given the human factors findings from this project. The fact that warning lights could be replaced with retroreflective delineators on the barrier (which are approximately one-tenth of the cost of warning lights) would further diminish the potential incremental safety benefit that the provision of warning lights in lieu of reflectors could generate.

RECOMMENDATIONS

Based on the results of these evaluations, the researchers recommend that the statewide application of steady-burn warning lights in all work zones be discontinued.

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