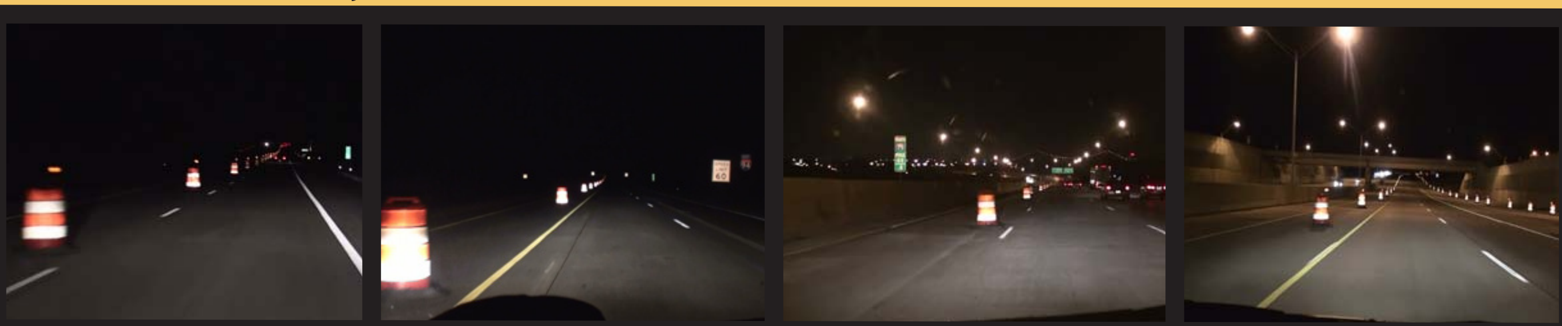
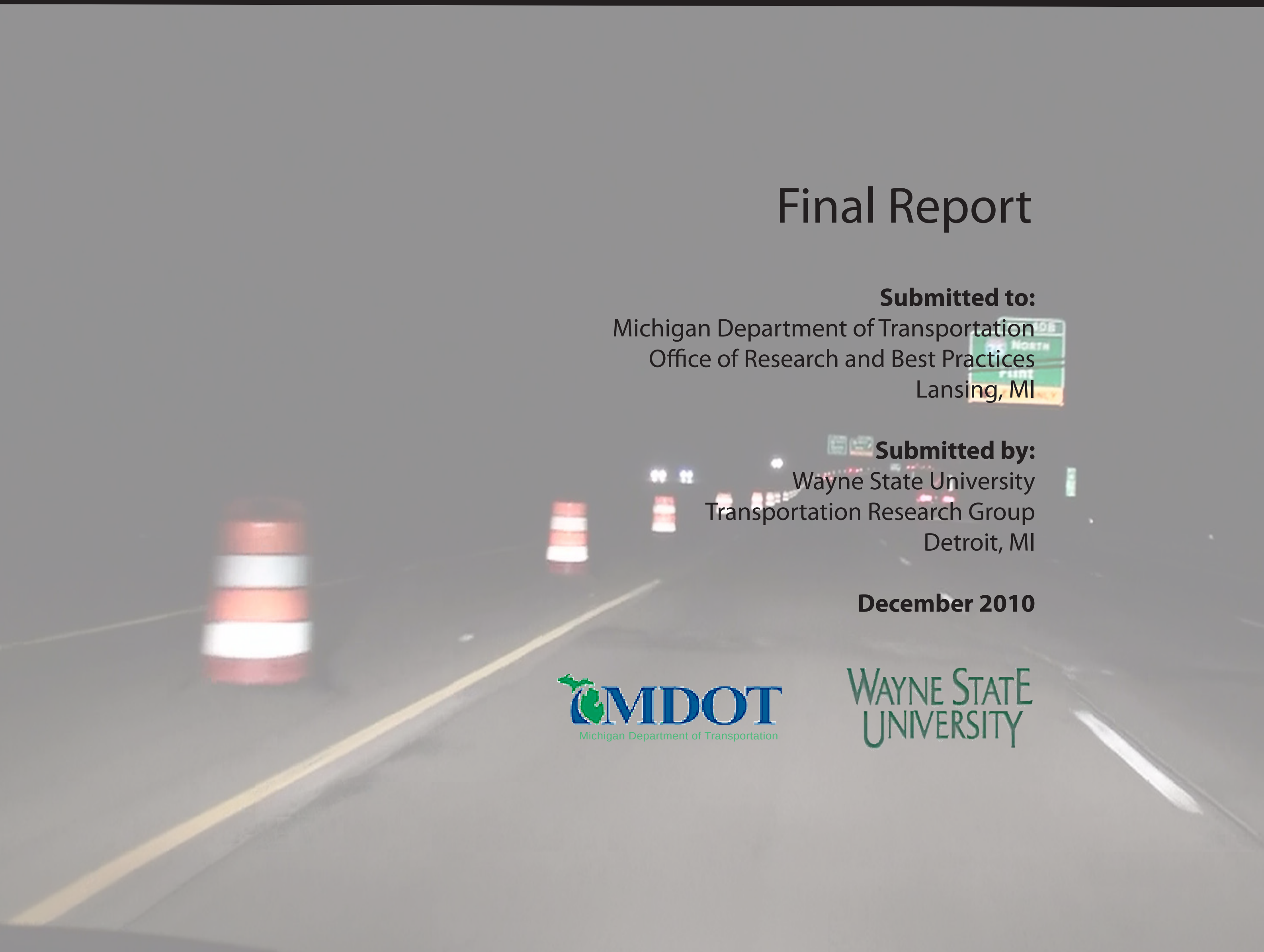
Evaluation of Steady-Burn Warning Lights on Channelizing Drums in Work Zones

MDOT Project Number ORE09-11





Final Report

Submitted to:
Michigan Department of Transportation
Office of Research and Best Practices
Lansing, MI

Submitted by:
Wayne State University
Transportation Research Group
Detroit, MI

December 2010

MDOT
Michigan Department of Transportation

WAYNE STATE UNIVERSITY

1. Report No. RC-1543	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of Steady-Burn Warning Lights on Channelizing Drums in Work Zones		5. Report Date December 2010 6. Performing Organization Code
7. Author(s) Tapan K. Datta, Timothy J. Gates, Peter T. Savolainen, Prasad Nannapaneni		8. Performing Organization Report No.
9. Performing Organization Name and Address Wayne State University-Transportation Research Group Department of Civil and Environmental Engineering 5050 Anthony Wayne Drive, Room #0504 Detroit, MI 48202		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Michigan Department of Transportation Office of Research and Best Practices 425 West Ottawa Lansing, MI 48933		13. Type of Report and Period Covered Draft Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report documents the results of a study to evaluate the safety and mobility impacts associated with the elimination of steady burn warning lights on drums in construction work zones. National crash data are compared among states with different policies regarding the use of steady burn warning lights and an in-depth investigation of Michigan work zone crashes is also conducted. The results of the crash data investigation are supplemented by a series of field studies that examine driver behavior in work zones, both with and without steady burn warning lights. Additional field studies are conducted to assess the luminance characteristics of drums with and without lights, as well as the condition of drums in each type of work zone. The luminance studies are supplemented by additional studies that are conducted in a controlled environment. While the presence of steady burn warning lights is found to marginally increase luminance, all luminance measurements were significantly above recommended visibility minimums regardless of whether steady burn lights were in use. Field study results were mixed as steering reversals occurred more frequently, lateral placement was relatively unaffected, and speeds tended to be slightly higher in work zones where steady burn warning lights were present. Purchasing and maintaining steady burn warning lights are found to add significant tangible and intangible costs, which may not deliver sufficient safety benefits to justify such costs.

17. Key Words Work zone, steady burn warning light, drums, channelization, Michigan		18. Distribution Statement Unlimited	
19. Security Classification (report) Unclassified	20. Security Classification (Page) Unclassified	21. No of Pages 120	22. Price

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INTRODUCTION

One of the most important traffic control requirements to allow for safe travel through work zones is the clear delineation of the edge of the traveled way, a function that is typically achieved by placement of channelizing devices. Due to the dynamic nature of work zones, channelization is generally provided by lightweight and easily movable temporary traffic control devices, such as drums, cones, or vertical panels.

To help avoid additional congestion due to work zones, roadway agencies often require road work to be performed during off-peak periods, sometimes at night. Maintaining traffic through nighttime work zones poses increased delineation challenges due to diminished visibility. To help overcome these nighttime visibility issues, the Manual on Uniform Traffic Control Devices (MUTCD) requires such traffic control devices to be retroreflective or internally illuminated. For this reason, some road agencies use steady burn warning lights on work zone traffic control devices to increase nighttime visibility.

Until recently, plastic drums with steady burn warning lights had been the primary channelizing device utilized in work zones throughout the State of Michigan. However, MDOT has discontinued the use of lights on drums in work zones for all projects let on or after August 6th, 2009. This change in policy provides an opportunity to re-evaluate the effectiveness of steady burn warning lights as a delineation device under real-life situations.

The primary goal of this research is to evaluate the safety and mobility impacts associated with the use of steady burn warning lights on drums in roadway work zones. To accomplish this objective, the following research questions were addressed as a part of this study:

1.) What are the findings from past research on the use of steady burn warning lights?

2.) What are the practices in other states regarding the use of steady burn warning lights?

3.) What are the crash experiences in states with different policies regarding the use of steady burn warning lights?

4.) How does the presence of steady burn warning lights on drums affect the crash characteristics in Michigan work zones?

5.) How do steady burn warning lights on drums affect driver behavior in Michigan work zones?

6.) To what degree do steady burn warning lights affect the luminance of drums as drivers approach work zones in Michigan?

7.) How do the costs compare between the use of drums with and without steady burn warning lights?

8.) What were the ultimate conclusions regarding the use of steady burn warning lights?

To answer these questions, a methodology was developed that included the following:

- Review of the state-of-the-art related to the use of drums in construction work zones, both with and without the presence of steady burn warning lights.
- Survey of state Departments of Transportation (DOTs) to determine the current state-of-the-practice in the United States related to the use of steady burn warning lights on drums and other devices for the purpose of work zone channelization.
- Review of the work zone crash experiences of states with various policies regarding work zone channelization, including a comparison of work zone crash trends between states.

- Analysis of crash data from Michigan work zones with and without steady burn warning lights on channelizing drums.
- Analysis of sample driver behavioral data in work zones through a series of field studies to evaluate differences in driver behavior and performance as it relates to the use of steady burn warning lights.
- Comparison of luminance data for channelizing drums with and without steady burn warning lights through a series of luminance tests conducted in both the field and a controlled environment.
- Estimate cost-benefit characteristics of use and non-use of steady burn warning lights on drums, including both tangible and intangible factors.

What are the findings from past research on steady burn warning lights?

The following list presents a concise summary of the literature review findings:

1. Work zones tend to cause an increase in crashes on roadways and fixed object crashes are predominant at night. Past research has not shown the use or non-use of steady burn warning lights to have a significant impact on work zone crashes.
2. Nighttime work zone crashes are generally rare events. As a result, researchers typically utilize other intermediate measures of effectiveness, such as those related to nighttime driver behavior/performance, to assess potential safety-related benefits of work zone traffic control devices. Several driver behavior/performance evaluations have investigated the effectiveness of steady burn warning lights on various channelization and/or delineation devices in work zones.

3. Steady burn warning lights on Type 1 barricades with engineering-grade sheeting provide significant increases in the detection distance of the devices. However, steady burn warning lights did not produce changes in driver behavioral MOEs, including mean speed, lateral placement, or point of lane change upstream of the work zone. These results should be viewed cautiously, as they apply to warning lights on Type 1 barricades with engineering-grade sheeting – neither of which is commonly used by MDOT for channelization in work zones.

4. Steady burn warning lights on vertical panels with high intensity sheeting provided no differences in the percentage of correct driver action responses in work zones when viewed at distances of 1,020-ft or less. At viewing distances of 1,330-ft and above, greater correct response percentages were observed when the vertical panels included steady burn warning lights. However, because channelizing devices provide greater assistance in lane-positioning guidance rather than advance warning, viewing distances over 1330-feet are not necessarily applicable for determining the effectiveness of steady burn warning lights on channelizing devices.

5. Steady burn warning lights on drums had little impact on driver behavioral MOEs, including vehicular speed, lateral placement, acceleration frequency, steering reversals, erratic maneuver rate, or lane change location upstream of the work zone.

6. Human vision begins to deteriorate significantly with age starting in the late forties and early fifties. Older persons often have visual difficulty when driving at night as they require greater illumination to see objects clearly and are more likely to be affected by glare than younger drivers.

7. Luminance is a general measure of "brightness" and represents the quantity of visible light leaving a point on a surface in a given direction. Luminance measurement is the most appropriate measurement unit for devices with both light emitting components (such as steady burn warning lights) and retroreflective components (such as sheeting materials) because it is a general measurement of brightness.

8. Research has suggested that at least 2.2 to 3.65 seconds of preview time is necessary for drivers (including older drivers) to maintain proper lane positioning while still providing some margin of driver error and comfort. Because the primary function of work zone drums is to channelize and delineate the edge of the travel way, the drums assist in providing lane-positioning guidance to drivers.

9. There currently exists no established minimum luminance requirement for work zone traffic control devices. Minimum luminance recommendations for basic sign legibility (i.e., recognition of a single letter or reading a simple word) have been investigated with a range of 2.3 cd/m^2 to 3.2 cd/m^2 being recommended. Minimum luminance values within this same range are conservative for the detection of work zone channelization, such as that provided by channelizing drums.

What are the practices in other states regarding the use of steady burn warning lights?

A questionnaire survey was developed and distributed to appropriate representatives at each state DOT (excluding Michigan). This survey included questions pertaining to the types of traffic control used for delineation/channelization in work zones.

The survey sought to obtain detailed information pertaining to standard work zone applications for each state, including the use of drums with or without warning lights and alternative channelization devices specific to both daytime and nighttime operations. Survey responses were received from 42 state departments of transportation, including Michigan. Eight states did not respond to the survey (Alaska, Delaware, Hawaii, Louisiana, Massachusetts, New Mexico, North Carolina, and Tennessee).

What are the crash experiences in states with different policies regarding the use of steady burn warning lights?

Work zone crash data was examined at the statewide level for Michigan and other states where such data was available. This allowed for a comparison of crash trends over time and a determination of whether the use of steady burn warning lights tend to have a substantive effect on such trends.

Aggregate crash data was collected pertaining to each state's population, vehicle miles traveled (VMT), percentage of construction projects with lights on drums and no lights on drums, total crashes, and number of crashes which occurred within work zones. This data was obtained through the agency contacts identified during the state-of-the-practice survey, as well as through supplemental searches conducted by the WSU-TRG to identify other available sources of information. Data was requested for the period from 2006 through 2008. Complete information was obtained for all of the requested data categories from 26 states.

These 26 states were divided into three groups based upon the percentage of statewide work zones that utilized steady burn warning lights on drums for delineation/channelization, as follows:

- **Group 1:** States that do not use lights on drums for any construction work zones.
- **Group 2:** States that use lights on drum in at least 30 percent of construction work zones (i.e., frequent use of lights on drums).
- **Group 3:** States that use lights on drums in between 1 and 10 percent of construction work zones (i.e., infrequent use of lights on drums).

Among the work zone crash data obtained for 26 states, only slight differences were observed between the rates of work zone crashes in states with varying policies regarding the use (frequent, infrequent, or no use) of steady burn warning lights on work zone drums. The states that frequently use lights on drums exhibited a slightly higher work zone crash rate among the three groups at 0.059 crashes per million vehicle miles traveled. 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. No discernable differences were observed between any of the three groups of states when examining work zone crashes as a proportion of total crashes.

How does the presence of steady burn warning lights on drums affect the crash characteristics in Michigan work zones?

The state-by-state comparison of work zone crash data was supplemented by a more detailed analysis of Michigan work zone crashes in order to gain further insight into the potential impacts of the use/non-use of steady burn warning lights on work zone safety. Data for crashes occurring in sample groups of work zones in the

State of Michigan were obtained in order to compare work zones with and without steady burn warning lights on drums. The specific work zone locations and other relevant information, such as the project time periods and work zone boundaries, were identified based on information obtained from MDOT and their website. Work zones that were either shorter than ½ mile, or did not include drums (some sites used cones only), were not used in the crash study.

The study sample included 31 work zone locations that used drums with steady burn warning lights, while 25 work zone locations used drums without steady burn warning lights. The locations without steady burn warning lights typically provided a smaller data collection period due to the fact that the policy eliminating the use of warning lights on drums only went into effect in August 2009. A review of both aggregate crash statistics, as well as a detailed, manual review of individual crash report forms led to the following conclusions:

- A comparison of data between the two groups of locations (with and 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.

- This crash data review also showed that a significantly higher proportion of work zone crashes tended to occur during nighttime conditions at locations with steady burn warning lights (39.4%) compared to locations without steady burn warning lights (29.7%).

- 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 are **not overrepresented** in nighttime work zone crashes involving drums, regardless of the presence of steady burn warning lights.

Collectively, the results of this in-depth investigation of Michigan crash data did not indicate that the presence or absence of steady burn warning lights created a substantive impact on work zone safety. This was true of both the general driving population, as well as among drivers age 65 and above. These findings were also consistent with the results of the comparison between states with different policies regarding the use of steady burn warning lights.

How do steady burn warning lights on drums affect driver behavior in Michigan work zones?

Due to the relatively infrequent and random nature of work zone crashes, particularly those that may be influenced by the presence of drums, additional studies were conducted in order to determine whether various aspects of driver behavior and performance were different between work zones with and without steady burn warning lights on drums. Specifically, a nighttime field evaluation was performed at several work zones on MDOT roadways throughout the State to assess the driver behavior-related characteristics with respect to the presence (or absence) of steady burn warning lights on channelizing drums.

A total of 28 work zones in 15 counties throughout the lower peninsula of Michigan were utilized for the driver behavioral study. Each work zone was located on an MDOT roadway. Each study location included one or more sections of channelizing drums that were at least ½ mile in length, which was established as the minimum distance necessary to effectively assess driver behavior and performance in work zones. The study locations were randomly selected from a list of eligible work zone sites in Michigan. The work zones selected for use in this study collectively represented a broad range of work zone scenarios.

Driver behavioral data collection was performed at the study sites during periods of darkness between January and May of 2010. The studies were conducted from the early evening (after dark) hours until well after midnight. As such, a wide range of traffic volumes were observed and a diverse sample of drivers was included as a part of this study. The nighttime driver behavior data collection was performed from a survey vehicle by recording the movements of randomly selected subject vehicles as they were followed through the work zone by the survey vehicle. Each pass through the work zone would typically begin several hundred feet upstream of a section of channelizing drums. As the survey vehicle approached the section of drums, the driver would position the vehicle directly behind the selected subject vehicle. If multiple travel lanes were available in the work zone, only vehicles traveling in the lane closest to the channelizing drums were observed. The survey vehicle driver made reasonable attempts to maintain a 4 to 8 second spacing from the rear of the subject vehicle throughout the entire work zone.

Data for a total of 1,236 subject vehicles was captured during the video review process, representing an average of 44.1 vehicles per sample study site. Of the total sample, 664 of these vehicles were observed in work zones without steady burn warning lights on drums, while the remaining 572 vehicles were observed in work zones with steady burn warning lights on drums. Thus, the minimum sample size requirement of 532 vehicular observations was achieved for each group. Passenger vehicles comprised 97.1 percent of the data set, while commercial vehicles made up the remaining 2.9 percent.

Nighttime spot speed measurements were also performed at a randomly selected sample of work zone locations. Only freeway sites were utilized for the spot speed study. This was because freeway locations had consistent work zone speed limits (i.e., 60 mph when no workers were present and 45 mph when workers were present), while the work zone speed limits at arterial locations varied widely. The data collectors selected a suitable vantage point from an overpass located in the middle of a long section of work zone that utilized channelizing drums. Spot speeds for randomly selected free-flowing vehicles (i.e., minimum 5 second headways) were then measured from the parked data collection vehicle using a radar gun. A minimum sample size of 100 vehicles was observed during each spot speed study. A summary of the results of the driver behavioral study is provided here:

- The presence of steady burn warning lights on work zone channelizing drums did not significantly impact the center lane positioning of drivers. Drivers traveling through work zones with steady burn warning lights on drums spent slightly less time in the center lane position, on average, compared to drivers at locations without steady burn warning lights on drums. This finding suggests that steady burn warning lights on drums may not influence nighttime driver behavior in work zones.

- The presence of a steady burn warning light on the drums had a marginal increase on the tendency of drivers to travel in close proximity to the drums.

Drivers traveling through work zones with steady burn warning lights on drums spent a slightly higher percent of time in the lane position closest to the drums as compared to drivers at locations without steady burn warning lights on drums. However, this difference was not statistically significant.

- The presence of a steady burn warning light on the drums caused a significant increase in the rate of steering reversals. Drivers traveling through work zones with steady burn warning lights on drums had a higher steering reversal rate than the drivers at work zone locations without steady burn warning lights on drums.

- Freeway locations with steady burn warning lights on the drums exhibited higher nighttime mean speeds compared to freeway locations without steady burn warning lights. Mean, median, and 85th percentile speeds were 3.9 mph, 3.1 mph, and 3.1 mph higher at locations with steady burn warning lights as compared to locations without warning lights. The standard deviation (or variance) of travel speeds was not significantly different between the locations with and without steady burn warning lights. These results may be indicative of drivers exercising greater caution when traveling through work zones without steady burn warning lights. However, the effects of other uncontrolled factors such as work zone layout, roadway geometry, and the presence of workers may have also contributed to this result.

- In work zone locations without steady burn warning lights, 14.1 percent of drums were found to be damaged, while 16.1 percent of drums were found to be damaged at those locations with steady burn warning lights. These findings suggest that drivers may be more likely to veer from the travel lane and strike a drum in work zones with steady burn warning lights.

To what degree do steady burn warning lights affect the luminance of drums as drivers approach work zones in Michigan?

In addition to examining the impacts of steady burn warning lights on driver performance, additional research was undertaken to explore the relative differences in the nighttime visual characteristics between drums with and without steady burn warning lights used in a variety of work zone scenarios. The objectives of this research are as follows:

- Examine nighttime luminance characteristics of commonly used work zone drums with and without steady burn warning lights in a controlled environment.
- Examine nighttime luminance characteristics of work zone channelizing drums with and without steady burn warning lights during real life operation in a sample of work zone scenarios within the State of Michigan.

All steady burn warning lights on drums observed in the luminance evaluations were of the 360-degree type. The instrument used for all luminance measurements was a Konica/Minolta LS-100, which utilizes a flareless fixed aperture single-lens-reflex optical system with a 1 degree acceptance angle. To validate the results of the field study, the research team performed a nighttime luminance measurement of several drum scenarios at the top of a large parking structure on the campus of Wayne State University. This allowed for the presence/absence of a steady burn warning light to be evaluated in a controlled environment from a stationary vehicle. Three sample drums were utilized in this evaluation, each with a different sheeting type and/or condition. The sheeting on each of these drums met or exceeded MDOT's in-service work zone sheeting standards. All drums were MDOT standard size, measuring 36 inches tall with a top diameter of 18 inches. The 360 degree amber steady burn warning light was 4.25 inches tall (exclusive of the base) and 3.25 inches in diameter. Including the non-illuminated base, the light added 10 inches to the height of the drum. Each of the 24 drum scenarios was measured three times during the controlled evaluation for a total of 72 luminance measurements.

The field evaluations allowed for a determination of differences in field-measured luminance levels of work zone drums with and without steady burn warning lights. Fifteen work zones in 10 counties throughout Michigan were randomly selected for use in this evaluation. All of the work zones utilized in the study were on limited-access freeways under the jurisdiction of MDOT. The field luminance measurements were performed between the hours of 10:30 PM and 4:00 AM on dry nights in late-May and early-June of 2010. The luminance meter operator was seated in the front passenger seat with the meter mounted on a tripod to ensure stability during measurement. All measurements were performed from the same 2010 Toyota Corolla using only the low beam headlamps. At least 20 luminance measurements were obtained from randomly selected individual drums at each of the 15 study work zones. The field evaluation yielded a total of 372 nighttime drum luminance measurements obtained from the 15 work zone locations – an average of 24.8 measurements per location. Luminance measurements were recorded for 287 drums with high intensity sheeting and 85 drums with prismatic sheeting. Drums with steady burn warning lights accounted for 145 of the luminance measurements, while drums without the lights accounted for the remaining 227 measurements. Again, all field luminance measurements were performed from the passenger seat of a slow moving vehicle at a distance of approximately 200-ft away from the drum. The results of the controlled and field experiments revealed the following:

- 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. When measured at a distance of 200-ft, the addition of a steady burn warning light increased the average luminance by 0.165 cd/m^2 (2.6 percent) and 0.50 cd/m^2 (3.9 percent) for the high intensity drums and prismatic drums, respectively, when measured in the controlled environment. Similar results were obtained during the field evaluation, as drums with steady burn warning lights measured at a distance of approximately 200-ft had average luminance values that were 0.36 cd/m^2 (7.3 percent) greater and 0.04 cd/m^2 (0.3 percent) lower than drums without steady burn warning lights for high intensity drums and prismatic drums, respectively.

- Prismatic sheeting materials provide the largest improvement to drum luminance. Compared to drums with high intensity sheeting, prismatic sheeting had average luminance measurements that were 10.26 cd/m^2 (203.6 percent) greater when measured in the field and 8.45 cd/m^2 (177.1 percent) greater when measured in a controlled environment.

- 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.

- The average luminance for each of the evaluated drum conditions was greater than the minimums of 2.3 – 3.2 cd/m^2 that have been recommended in the literature for sign legibility purposes [*32,33,34,35*]. Additionally, only 8.7 percent (25 out of 287) of the high intensity drums measured in the field evaluation had luminance values that were lower than 2.4 cd/m^2, which was the most commonly referenced minimum luminance threshold. Most of these occurrences were due to the presence of dirt and grime or a general lack of maintenance of the drums. None of the prismatic drums observed in the field measured lower than 2.4 cd/m^2.
- Drum luminance can be accurately measured in the field from a slow moving vehicle, which had not previously been confirmed in the literature.

How do the costs compare between the use of drums with and without steady burn warning lights?

The costs associated with the use of drums with and without steady burn waning lights were compared in order to determine the additional costs introduced by the use of the warning lights. In order to accomplish this, the costs of materials, installation, maintenance, and disposal were considered. Based solely upon drum costs, those drums with steady burn warning lights are 130 percent greater on a per-unit basis. On a per-mile basis, the materials and battery maintenance costs (equivalent uniform annual cost) were found to be between \$5,744 and \$7,157 higher for drums with steady burn warning lights. In addition to these tangible costs, the drums with steady burn warning lights also introduce additional intangible costs due to the disposal of both the steady burn warning light fixtures and the used batteries.

What were the ultimate conclusions regarding the use of steady burn warning lights?

This research evaluated the relative differences between drums with steady burn warning lights compared to drums without steady burn warning lights for several measures of effectiveness. Based on a synthesis of all results, 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 microprismatic sheeting materials. This conclusion is similar to those found in previous research on this topic. Thus, it was concluded that steady burn warning lights demonstrate little to no additional value to work zone safety when used on channelizing drums in work zones. Drums with high intensity sheeting that is in good condition will typically provide adequate nighttime brightness for work zone channelization regardless of whether a steady burn warning light is attached. However, if additional nighttime brightness is desired, 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.

1.0 INTRODUCTION AND BACKGROUND

Roadway work zones have become increasingly commonplace in the United States over the past several decades. By the 1980's, most of our nation's roadway system had been built and an increasing percentage of road work involved the maintenance and repair of the existing roadway infrastructure, as the roadways built during the previous decades began deteriorating. Maintenance and repair work on an existing roadway presents the challenge of either maintaining traffic on the roadway or rerouting traffic to other facilities while work is being performed. Capacity limitations and/or lack of alternate routes often necessitate that traffic be maintained on the existing roadway while work is also being performed. Although most road work in Michigan is typically performed during the day, the type and duration of the work being performed often requires that the work zone traffic control remain in place at all times.

From 1997 to 2002, the number of work zone fatalities in the United States increased by nearly 55 percent [*1*]. In response to this trend, work zone safety became a high priority issue for road agencies as several national initiatives were launched aimed at reducing the frequency of work zone crashes, injuries, and fatalities, such as the Federal Highway Administration (FHWA) Work Zone Safety Program. Such programs have aided in reducing the number of work zone fatalities in the United States from 1,063 in 2004 to 720 in 2008 [*2*]. In the State of Michigan, the number of work zone crashes has decreased by over 24 percent over the past 5 years, from 6,583 to 4,977 as shown in Table 1. Similarly, the number of injuries has decreased from 1,828 in 2004 to 1,278 in 2008 while the number of fatalities has also decreased gradually.

TABLE 1. Michigan Work Zone Crash Statistics, 2004 to 2008 [*2*]

	WORK ZONE CRASHES BY YEAR					
	2004	2005	2006	2007	2008	AVERAGE ANNUAL CRASHES
Crashes	6,583	6,545	5,216	5,499	4,977	5,764
Injuries	1,828	1,811	1,450	1,420	1,278	1,557
Fatalities	22	20	18	20	13	18.6

These recent safety gains in Michigan can be attributed to various safety-conscious decisions made by MDOT and other road agencies during the past decade. While these improvements have been substantial, work zone safety remains an issue.

In most work zones, the width of pavement available to motorists is reduced, resulting in either a decrease in the number of available lanes or a reduction in lane widths, which often creates an unanticipated change in the path of travel. Additionally, the shoulder which often provides a recovery area for motorists may not be available in a work zone, further reducing the margin of error required for safe navigation. In such instances, optimal work zone safety can be achieved through the provision of clear and positive guidance through the use of temporary traffic control (TTC) devices, including warning signs, pavement markings, and channelizing devices such as drums, cones, tubular markers and barricades. The Manual on Uniform Traffic Control Devices (MUTCD) indicates that no one set of temporary traffic control devices is appropriate to ensure the safety of motorists, workers, emergency personnel, and equipment protection under all project conditions.

Primary function of TCC is:

"To provide for the reasonably safe and efficient movement of road users through or around TTC zones"

MUTCD Section 6B.01

When designing TCC zones:

"The goal should be to route road users through such zones using roadway geometrics, roadside features, and TTC devices as nearly as possible comparable to those for normal highway situations"

MUTCD Section 6b.01

A typical work zone consists of four distinct areas, each of which requires a specific set of traffic control devices to provide necessary message(s) to drivers. These areas and associated message(s) include:

- **Advance Warning Area**
  To inform motorists regarding the approaching work zone.
- **Transition Area**
  Where drivers may need to change thesis path and speed.
- **Activity Area**
  Location where work activities are or may be conducted and motorists need to avoid.
- **Termination Area**
  Where motorists will be allowed to resume a normal driving path and speed.

One of the most important traffic control requirements, in both the transition area and activity area of the work zone, is clear delineation of the edge of the traveled way, a function that is typically achieved using channelizing devices. Channelizing devices in work zones provide critical information about an upcoming lane or shoulder closure, taper, lane shift, narrowing of the traveled way, separation of opposing traffic, or other required maneuvers related to the work zone. Channelizing devices are particularly important in assisting drivers with tasks such as lane selection, lateral positioning within a particular lane, and speed control. Due to the dynamic nature of work zones, channelization is typically provided by lightweight and easily movable temporary traffic control devices, including drums, cones, or vertical panels.

To help avoid additional congestion due to work zones, roadway agencies often require road work to be performed during off-peak periods, sometimes at night. Maintaining traffic through nighttime work zones pose increased delineation challenges due to diminished visibility. To help overcome these nighttime visibility issues, the Manual on Uniform Traffic Control Devices (MUTCD) requires traffic control devices, including those in work zones, to be retroreflective or internally illuminated [*3*]. Although the 2009 MUTCD provides minimum in-service retroreflectivity values for road signs, such standards are not provided for other devices commonly utilized in work zones, such as pavement markings, delineators, or channelizing devices [*3*]. However, because such portable traffic control devices are often reused multiple times in various work zones, the MUTCD states in Section 6F that work zone devices that are damaged or have lost a significant amount of their retroreflectivity shall be replaced [*3*]. Steady burn warning lights on work zone traffic control devices have been used by many road agencies in the United States to increase nighttime visibility. Initial deployment of the steady burn warning lights on traffic control devices occurred many years ago to supplement the limited retroreflectivity provided by the Engineer's grade sheeting that was commonly used at that time on drums and barriers. However, roadway agencies across the U.S. now require either high intensity (i.e., ASTM Type III) or microprismatic (i.e., ASTM Types IV and above) sheeting materials for work zone traffic control devices, which has prompted the investigation of the value of auxiliary warning lights given the improved visibility that such sheeting materials provide.

2.0 PROBLEM STATEMENT AND STUDY OBJECTIVES

Until recently, plastic drums with steady burn warning lights have been the primary channelizing device utilized in work zones throughout the State of Michigan for several years. However, MDOT has discontinued the use of lights on drums in work zones for all projects let on or after August 6th, 2009. This change in policy provides an opportunity to re-evaluate the effectiveness of steady burn warning lights as a delineation device under real-life situations. This is possible since work zones with and without steady burn lights are often controlling work zone traffic at different sections of the same highway in the same region and maybe in the same city or county. This is happening because one part of the roadwork started prior to August 2009 and the other part after that date.

The primary goal of this research is to evaluate the safety and mobility impacts associated with the elimination of steady burn warning lights on drums in roadway work zones and provide objective state-of-the-art data to MDOT to assist them in making safety and mobility conscious decision with regard to use or non-use of steady burn warning lights on work zone channelizing devices. The specific objectives of this study included:

- Perform a literature review on work zone channelizing devices.
- Conduct a current practices survey and benchmark review of the state departments of transportation (DOTs) in the United States with regard to the use of steady burn lights on drums for work zone traffic control.
- Investigate crash trends in a sample of states where data is available that has eliminated the steady burn warning lights from work zone drums.
- Investigate the work zone crash experience in Michigan for locations with and without steady burn warning lights on drums.
- Conduct a field experiment of driver behavior through work zones with and without steady burn warning lights on drums on Michigan roadways.
- Determine differences in nighttime photometric characteristics of drums with and without steady burn warning lights.
- Conduct a Cost/Benefit analysis.
- Determine the overall impact of the elimination of lights on drums.
- Prepare a final report.

3.0 STUDY METHODOLOGY

Various research tasks were performed in order to achieve the study objectives. These tasks are illustrated in the methodological flow chart presented in Figure 1, which outlines the sequence of tasks and related activities conducted as a part of this study. The study began with a comprehensive review of the current state-of-the-art and state-of-the-practice as documented in research reports and published literature regarding the use of drums in construction work zones, both with and without the presence of steady burn warning lights. This was followed by the implementation of a national state-of-the-practice survey of state Departments of Transportation (DOTs) to determine previous and current practices related to the use of steady burn warning lights on drums and other devices for the purpose of work zone channelization. The next tasks involved a comparison of work zone crash trends, both among states with varying policies on the use of steady burn warning lights, as well as a detailed investigation of crash data for work zones within the State of Michigan. In addition to examining crash trends, a series of field studies were performed to provide a more in-depth evaluation of differences in driver behavior and performance as it relates to the use of steady burn warning lights. In addition to these field studies, a series of luminance tests were also conducted, both in the field and in a controlled environment, in order to gauge the impacts of steady burn warning lights on visibility at various distances. The data from the crash comparison, behavioral studies, and luminance tests were analyzed using appropriate statistical techniques to determine the impacts of steady burn warning lights on various measures of effectiveness (MOEs). When designing the studies to compare these MOEs, sampling procedures were utilized to determine target sample sizes. The data was collected for each study component under a variety of representative field conditions, which included different types of roadways, levels of ambient lighting, work zone geometry, weather conditions, and other factors. Appropriate statistical procedures were utilized for each of the study components to determine whether specific MOEs were significantly different between those work zones with and without steady burn warning lights. Finally, a cost comparison was conducted in order to determine the economic impacts of utilizing drums with or without steady burn warning lights. This analysis examined both tangible, as well as intangible factors, in determining the economic consequences of the installation, maintenance, replacement, removal, and disposal of drums both with and without steady burn warning lights.

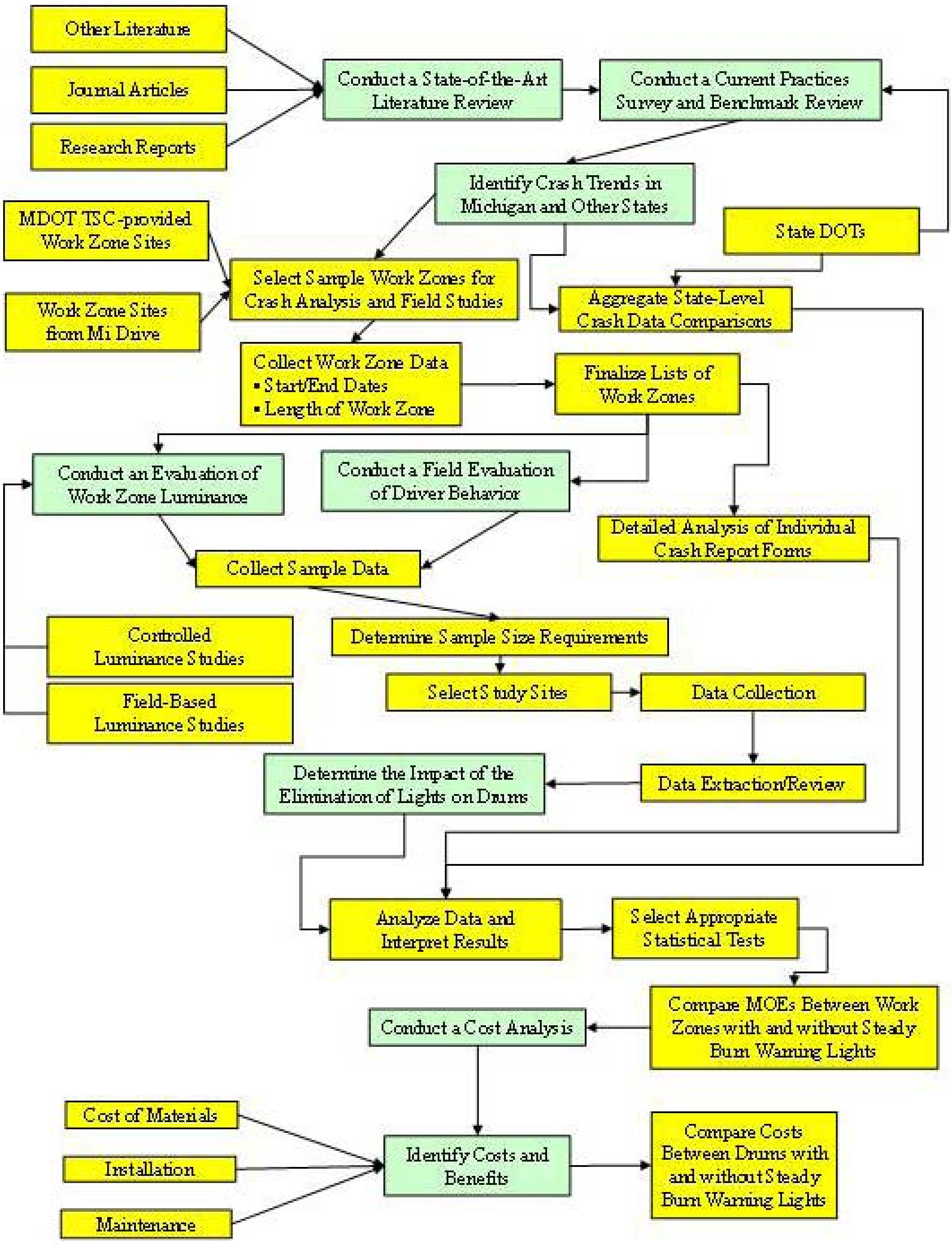

FIGURE 1. Study Methodology

The tasks conducted as a part of this study are summarized in this section of the report and a complete description of the work performed specific to each task is provided in the corresponding Chapters of this report.

- **Conduct a State-of-the-Art Literature Review.** The study began with a comprehensive state-of-the-art literature review of past research and practices pertaining to the use of steady burn warning lights on drums, as well as other relevant factors. This included a review of technical reports, journal articles, and other technical publications. The result of this task was a synopsis of relevant studies and a summary of key findings from this review are presented in Chapter 4.
- **Conduct a Current Practices Survey and Benchmark Review.** To supplement the results of the literature review, a questionnaire survey was developed and disseminated to all state DOTs with regard to their use of steady burn lights on drums for work zone traffic control. The survey was initially distributed via email with telephone follow-ups where necessary. Further details of this state-of-the-practice survey are provided in Chapter 5.
- **Investigate Crash Trends in Michigan and Other States.** Chapter 6 presents details of statewide work zone crash information for Michigan and other states, where available, including the states that currently use or have used steady burn warning lights on drums in their work zones. Michigan work zone crash data was extracted through a manual review of the Michigan State Police UD-10 crash report forms. The UD-10 forms for all crashes that occurred within the boundaries of the selected work zones during the project periods were thoroughly analyzed to determine whether the crash occurred during nighttime hours, what type(s) of traffic control was in place at the time of the crash, and whether the delineation/channelization may have influenced the crash.
- **Perform a Field Evaluation of Driver Behavior.** Due to the relative infrequency of work zone crashes, as discussed previously, additional surrogate measures of safety were also evaluated through a series of behavioral-related field experiments

to assess the effectiveness of steady burn warning lights on channelizing drums. The evaluations were performed at several work zones on MDOT roadways in Michigan that collectively represented a variety of different work zone channelization scenarios. The behavioral evaluations included: assessment of the lateral lane positioning and steering reversals of vehicles tracked through work zones, measurement of vehicular speeds in work zones, and assessment of drum condition. Results of these field studies are presented in Chapter 7.

- **Evaluate Work Zone Luminance.** Chapter 8 documents the results of the evaluation of the luminance properties of drums (with and without lights) that were performed to assess the relative visual impacts of steady burn warning lights on drums. This task involved two separate evaluations: 1) Measurement of drum luminance in a controlled environment and 2) Field measurement of drum luminance at a sample of work zones on MDOT roadways.
- **Determine the Impact of the Elimination of Lights on Drums.** Once the historical crash data, driver behavioral data, and luminance data were collected, appropriate statistical analysis techniques were identified and used to assess whether the differences of each selected MOE were significant at a 95-percent confidence level. Each of the MOEs were analyzed individually as described in Chapters 5 through 8.
- **Perform a Benefit/Cost Analysis.** An analysis was conducted to determine the economic impacts of using steady burn warning lights on channelizing drums in work zones. This included a comparison of the material, installation, maintenance, and disposal costs required in the utilization of drums with and without steady burn warning lights. Details of the benefit-cost analysis are provided in Chapter 9.

4.0 LITERATURE REVIEW

A comprehensive literature review of past research and practices pertaining to the use of steady burn warning lights on drums was performed. Relevant research reports and journal articles were identified using database queries and bibliographical reviews from relevant reports. The applicable documents were then retrieved and critically reviewed to identify information that is relevant to this research. The specific topical areas included:

- Work zone crashes,
- Field studies of driver behavior in work zones,
- Older driver issues,
- Photometric characteristics related to work zone drums, and
- Visibility requirements of drivers with respect to work zone channelization.

The following sections present a brief summary of the relevant research papers reviewed for the topics mentioned above.

4.1 Work Zone Crash Evaluations

Several studies have investigated the characteristics of crashes occurring in work zones. A study performed in Virginia by Garber et al [*4*] indicated that the activity area is the predominant location of work-zone crashes and rear-end crashes are the predominant crash type, likely due to the stop-and-go traffic flow patterns often found within the activity area. The transition area was found to have a disproportionately high proportion of sideswipe-same-direction crashes compared to the advance warning area, due to driver misjudgment of the need to merge. The activity area also had disproportionately higher fixed object crashes.

Research conducted by Ha and Nemeth [*5*] identified the type and injury level of crashes in Ohio work zones between 1982 and 1986. Similar to the Garber et al study, during daytime driving conditions, rear-end crashes were predominant, while during nighttime driving conditions, fixed object crashes were higher. Single vehicle crashes occurred predominately at night, while two-car crashes were predominant during daytime hours.

Mohan et al [*6*] studied the characteristics of work zone crashes. Two general classes of crashes were found to occur in highway work zones: 1) those that involve construction workers, which accounted for 30% of the crashes and 2) those that involve motorists outside the work area, which accounted for 70% of the crashes. Similar to the Garber et al study, rear-end collisions were found to be the most common work zone crash type (31%), followed by "hit-small-object" collisions (11%).

Khattak et al [*7*] evaluated the differences between crash rates while the work zone was in place compared to the period prior to the work zone being in place for 36 roadway segments in California. Similar to the findings in other research, this study found that rear-end and sideswipe crashes occur more frequently in work zones compared to non-work zone areas. Furthermore, crashes in work zones are typically less severe than those occurring in non-work zone areas. The total crash rate observed in the pre-work zone period was 0.65 crashes per million vehicle kilometers, compared to 0.79 crashes per million vehicle kilometers while the work zone was in place, representing an increase of 21.5 percent. A t-test showed that the two crash rates were not statistically different at a 90 percent confidence level. It should be noted that the analysis assumed that traffic volumes remained the same while the work was being performed compared to prior conditions. This assumption is likely not valid as work zones often reduce the roadway capacity thereby diverting a certain percentage of drivers onto alternate routes which will likely result in an underestimation of the crash rate calculated for the period while the work zone was in place.

The impact of work zones on crash severity has also been evaluated in previous research. A 1978 study by Graham et al [*8*] investigated work zone crashes both while the work zone was in place and prior to the work zone being in place at 79 work zone locations in seven states representing a broad range of work activities and work zone layouts. The overall crash rate was found to increase by 7.5 percent when the work zone was in place, although this increase varied by state and type of work being performed.

A study performed for the Georgia Department of Transportation by Daniel et al [*9*] found that fatal crashes in work zones are more likely to involve another vehicle than non-work-zone fatal crashes. Additionally, fatal crashes in work zones are less influenced by changes in horizontal and vertical alignment than non-work-zone crashes.

Datta and McAvoy [*10*] performed a crash study in Michigan comparing crashes before and during the work zone being in place at locations both with and without steady burn warning lights on drums. At all locations, crash data was collected during the construction period, and one year prior to the construction period. The results showed no difference between the crash rates before and during the installation of a work zone for locations regardless of whether steady burn warning lights were used on the drums.

4.2 Field Studies of Driver Behavior in Work Zones

The safety benefits provided by improving the visibility/conspicuity of traffic control devices can only truly be assessed through the direct measurement of the devices' impact on crashes. However, nighttime work zone crashes are generally rare events primarily due to the relatively short duration and/or length of most work zones coupled with drivers' perception of elevated risk when traveling through work zones. Furthermore, the transient nature of work zones makes it difficult to identify causal relationships between various work zone characteristics and crash occurrences. To overcome difficulties associated with determining the impact on crashes, non-crash measures of effectiveness related to driver behavior and/or performance are often utilized to serve as intermediate measures of effectiveness (MOEs) to assess the safety effectiveness of a treatment. Common driver behavioral/performance MOEs related to work zone safety include:

- Lateral placement of vehicles within the travel lane,
- Erratic maneuvers (i.e., rapid alignment changes or avoidance maneuvers),
- Steering reversals (i.e., changes in lateral placement),
- Encroachment onto the centerline or edgeline, and
- Vehicular speeds.

The literature search produced a number of driver behavior/performance studies that investigated the effectiveness of steady burn warning lights used on various channelization and/or delineation devices in work zones. These evaluations provided valuable guidance to this research by providing information pertaining to experimental design, field data collection methods, measures of effectiveness, and data analysis, in addition to the effectiveness of steady burn warning lights.

In the late-1970's, Pain et al [*11*], performed a field study of driver behavior to determine the impact of steady burn warning lights on driver behavior when used on an array of Type 1 barricades with engineering-grade sheeting. The steady burn warning lights were found to increase detection distances to the devices, but were found to provide no statistically significant changes in driver behavioral MOEs, including mean speed, lateral placement, or point of lane change upstream of the work zone. These results should be viewed cautiously, as they apply to warning lights on Type 1 barricades with engineering grade sheeting – neither of which are currently being used by MDOT for channelization in work zones.

Shepard [*12*] performed a study to investigate vehicle guidance through work zones by comparing the effectiveness of the steady burn warning lights versus experimental vertical panels with high-intensity sheeting when used on top of temporary concrete barriers on Interstates and four-lane highways. The study recommended that for tangent sections, steady burn warning lights on temporary concrete barricades should be replaced with reflectorized panels with high-intensity sheeting. For areas where the roadway alignment changes, it was recommended that closely spaced retroreflective raised pavement markers be used as a supplement to existing pavement markings.

Pant et al [13] performed a driver behavior study to determine the effects of steady burn warning lights used in conjunction with high-intensity retroreflective sheeting on drums in construction work zones for the Ohio Department of Transportation in 1989. The drums were evaluated on tangent sections of rural, unlighted, four-lane divided highways under dry, rainy and foggy weather conditions both day and night. One-hundred thirty-two subject drivers ranging from 16 to 75 years of age drove an instrumented vehicle along one of three rural work zones with speed limits of 65 or 55 miles per hour. A video camera installed on the roof of the automobile was used to collect the data. Several types of data were collected, including speed, speed variance, lateral placement, acceleration frequency and steering reversal data. The data for the right versus left lane closures and daytime versus nighttime conditions were analyzed separately. The data was also categorized by weather condition, age of subjects, gender and subjects that noticed the removal of the steady burn warning lights. The authors concluded that the steady burn warning lights had little to no effect on driver performance in tangent sections of rural unlighted divided highways. The authors also concluded that the research indicated that the high-intensity retroreflective sheeting outperformed the steady burn warning lights. The presence or absence of steady burn warning lights had little impact on the subjects' speed, lateral placement, acceleration frequency or steering reversals. The study recommended discontinuing the use of steady burn warning lights along tangent sections of construction work zones on rural divided highways.

A second study by Pant et al [*14*] in 1991 provided an expanded examination of the effectiveness of steady burn warning lights on drums with high-intensity sheeting. This study expanded on the previous study by including both divided and undivided roadways and vertical and horizontal alignment changes, such as curves, ramps, tapers, and crossovers. Both lighted and dark roadways were included and both right and left lane closures were utilized. Again, an instrumented vehicle was used and 107 human subjects drove the vehicle through a 0.75 mile long work zone during daytime and nighttime conditions with and without the steady burn warning lights. The measures of effectiveness included speed, lateral placement, acceleration frequency, erratic maneuver rate, lane change location upstream of the work zone, and driver observation of the lighted drums – the latter three of which were not utilized in the previous study. The results showed that steady burn warning lights had no impact on driver behavior regarding speed, lateral placement, acceleration frequency, erratic maneuver rate, or lane change location upstream of the work zone. It was concluded that high-intensity sheeting on drums in conjunction with the lighted arrow panel at the beginning of the taper had a stronger effect on drivers, as compared to the steady burn warning lights on channelizing devices. This study recommended discontinuing the use of steady burn warning lights on drums with high-intensity sheeting when a flashing arrow panel is used.

KLD Associates [*15*] reported on the results of a field experiment that investigated the effects of steady burn warning lights mounted on vertical panels with high intensity sheeting. The field experiment consisted of 30 passenger subjects who were driven through 16 simulated work zones on a clear night along a closed section of roadway. Although older and younger drivers were included in this study, a breakdown of the number of subjects in each group was not provided in the report. The simulated work zone configurations included both right and left lane closures and shoulder closures. The test vehicle would approach the simulated work zone at 30 mph. At one of six predetermined distances upstream of the work zone, the test subjects (passengers) were asked to record the current driving action required. The correct response percentage at each of the six distances was used as the primary measure of effectiveness for this study. The aggregated results showed virtually no difference in the correct response percentages at viewing distances of 1,020ft or less. At viewing distances of 1,330-ft and above greater correct response percentages were observed when the vertical panels were lighted.

Datta and McAvoy [*10*] investigated the effectiveness of work zone drums with and without the use of steady burn warning lights in Michigan. A nighttime field experiment was also conducted at 15 construction work zone sites on MDOT major arterial roadways and freeways throughout the State of Michigan. Collectively, the sites possessed a variety of geographical, environmental, and traffic conditions. Driver behavior data that was covertly collected at each site included: vehicular speeds, vehicular lateral lane placement, and steering reversal frequency. The lateral placement of randomly selected subject vehicles traveling through the work zone was recorded using a digital video camera mounted inside a survey vehicle that was following the target vehicle. Several passes through each work zone were performed. The percent of time spent in each of the three lateral positions was computed for each subject vehicle. Acceptable lateral placements were considered to be the two positions furthest away from the drums, which differed slightly from previously mentioned lateral placement studies that defined acceptable lateral placement by center placement only. The steering reversal frequency data was also extracted from the videos for each subject vehicle. Steering reversals were counted when a vehicle shifted from one lateral position to another. The rate of steering reversals observed per vehicle per minute was computed by dividing the number of steering reversals observed by the total time that the vehicle was tracked. The results showed that the average percent of time that each vehicle spent in acceptable lane position for lighted drum sites and unlighted drum sites was 92 percent and 94 percent, respectively, which essentially did not show a significant difference. The differences were similar for arterial and freeway sites. The average steering reversals per minute for all lighted drum sites was 2.54 compared to 1.84 for unlighted drum sites, which were also statistically similar. No differences in the mean or 85th percentile speeds were detected between the locations with lighted drums and unlighted drums. The authors concluded that no differences in vehicular lateral placement, steering reversal rate, or speed were detected in work zones regardless of whether or not steady burn warning lights were used on the channelizing drums.

4.3 Older Driver Issues

The fastest growing age groups in the United States are those which include older persons. In the year 2000, people over the age of 65 accounted for approximately 12 percent of the United States population [*16*]. By the year 2050, it is estimated that people over the age of 65 will account for 25 percent of the United States population. Not only is the percentage of older adults increasing, they are increasingly more mobile and are driving much later in life [*17*].

As humans age, their sensory, perceptual, cognitive, and physical functions tend to degrade. It is recognized that vision begins to deteriorate significantly with age starting in the late forties and early fifties, including: loss of acuity, trouble focusing, loss of depth perception, degradation of peripheral vision and color recognition. In addition, older drivers need greater illumination to see objects clearly and are more likely to be affected by glare than younger drivers [*17*]. Age-related visual deficiencies are generally not fully correctable by lenses and are much more of a problem during nighttime driving. Degradation of peripheral vision and depth perception makes it more difficult for older drivers to judge gap sizes and interpret traffic control devices, resulting in an increased involvement in intersection and lane change-related accidents. Loss of color sensitivity contributes to greater accident involvement at curves and intersections because of the diminished ability to recognize traffic control devices [*17*].

Although older drivers are often aware of their deficiencies and tend to drive more cautiously, they still present a safety concern especially as their numbers and traffic exposure increase. Older persons have historically had a tendency to "self test" off the system by acknowledging their physical deficiencies and making a personal decision to reduce driving, especially nighttime driving. For example, many older persons recognize their deficient night vision and cease or reduce driving at night, eliminating themselves as a safety hazard. However, it is not clear that the baby boomer generation of older drivers will be as willing to "test off" voluntarily even if they are aware of such driving performance deficiencies [*17*]. Furthermore, a significant portion of older adults live in suburban or rural areas, which are most often not served by public or alternative transportation. Older drivers are also much less likely to make voluntary risky maneuvers while driving compared to their younger counterparts. In addition, older drivers involved in fatal crashes had the lowest proportion of intoxication of all adult drivers [*18*].

Beginning in the late 1980's and continuing through this decade, a concerted effort was put forth by both researchers and transportation agencies to determine cost-effective treatments and programs for the older driver traffic safety problem. This initiative first began at the national level as included in the publication of TRB Special Report 218, *Transportation in an Aging Society* [*19*] and led to the development of the "Action Plan for Older Drivers" in 1989 and later the "Improved Highway Travel for an Aging Population" program that involved piloting roadway safety improvements for older drivers in many states [*20*]. The *Highway Design Handbook for Older Drivers and Pedestrians* [*21*] was developed by the FHWA as the culminating effort aimed at handling older driver-related issues by enhancing all facets of the roadway design process. Included in this handbook are ways to engineer the roadway to fit the needs of the older driver, including making signs more legible, providing simpler sign and signal messages, providing brighter pavement markings, etc.

Recent research has evaluated older driver performance in work zones. Heaslip et al [22] evaluated the effectiveness of various work zone design features designed in accordance with the *Highway Design Handbook for Older Drivers and Pedestrians [21]*. A field study was performed along a rural segment of Interstate 91 in western Massachusetts. Several work zone design features were evaluated, including: 1) lane closure/lane transition practices; 2) portable changeable message signing practices; and 3) channelization practices and delineation of crossovers/alternate travel paths. In addition, a focus group study was conducted to gauge an opinion of the work zone configuration employed. The major findings of the evaluation included: 1) Older drivers' speeds approaching the work zone tend to be lower and have more variance than other drivers; 2) older drivers have a less uniform merging pattern, making more conservative early merges; 3) portable changeable message signs in advance of work zones are effective in reducing speeds among older drivers and other drivers; and 4) the combination of the arrow board and static signage appears to provide drivers with information needed to make safe merges. The results of the field study suggest that these design features are effective at changing driver expectancy and consequently may lead to increased safety within the work zone.

4.4 Photometric Characteristics Related to Work Zone Drums

Luminance is the characteristic that describes the physical measure of brightness and is defined as the luminous intensity of a surface in a given direction per unit of projected area [23]. In other words, luminance is the total amount of visible light leaving a point on a surface in a given direction. The light leaving the surface can be due to reflection, emission, and or transmission. In the case of the work zone drum, reflection is provided both by 1.) retroreflection of the vehicle's headlamp illumination from the retroreflective sheeting material affixed to the drum and 2.) diffused reflection of ambient light. Emission is provided by an attached light source, if present, such as a steady burn warning light. Transmission of light through a drum is negligible as the drums are opaque. Typical units for luminance are candelas per square meter (cd/m^2) (SI units), although luminance is sometimes reported in foot-lamberts (English units). It is important not to confuse luminance with other common photometric characteristics, such as illuminance and retroreflectivity. Where luminance is the amount of light ***leaving*** a surface, illuminance (i.e., illumination) is the amount of light ***striking*** the surface [*23*]. Illuminance is expressed in lumens per unit area, commonly referred to as lux or footcandles.

Retroreflectivity is defined as the coefficient of retroreflected luminance, which is the ratio of the retroreflected luminance to the perpendicular headlamp illuminance. It is essentially a measure of the "efficiency" of a material, such as sheeting or pavement markings, to reflect vehicle headlight illumination back to the driver's eye. Retroreflectivity is measured based on a standard viewing geometry, which is defined by ASTM and differs for measurement of sign sheeting versus pavement markings. The ASTM sign sheeting retroreflectivity measurement relates to a viewing geometry of 200 meters [*24*], while the pavement marking retroreflectivity measurement relates to a 30 meter viewing geometry [*25*]. Sign sheeting is nearly always more retroreflective than pavement markings and the retroreflectivity unit for signs is $cd/lux/m^2$ and pavement markings is $mcd/m^2/lux$. The 2009 MUTCD now specifies minimum in-service levels for sign retroreflectivity, but no retroreflectivity minimums are given for pavement markings [*3*]. Table 2 summarizes the basic photometric units typically used in photometric characteristics-related research.

It is important to note that retroreflectivity is not an appropriate measurement for light emitting sources, such as a light affixed to a work zone drum – it is only for materials designed to *reflect* light. Luminance is the appropriate photometric unit of measurement for light emitting sources and is equally as appropriate for measurement of retroreflective sources as it is a general measurement of brightness. Luminance was utilized in previous work zone-related research by Fontaine et al in Texas for measurement of the brightness of work zone garments [*26*].

TABLE 2. Photometric Units of Measurement Related to Traffic Control Devices

QUANTITY	UNIT	ABBREVIATED UNIT	NOTES
Luminous flux	lumen (cd·steradian)	lm	Total light output from a lamp
Luminous intensity	candela (lm/steradian)	cd	SI base unit, also termed candle, candlepower
Luminance	candela per square meter; foot-lamberts	cd/m^2; fl	Luminous intensity per unit area reflected from an illuminated surface or emitted from a non-illuminated surface, i.e., “brightness”. May also be measured in foot-lamberts (foot-lambert = (1/pi)*candela/ft^2). 1 cd/m^2 = 0.292 foot-lamberts
Illuminance	lumen per square meter (lux); lumen per square foot (footcandles)	lx; fc	Light incident on a surface or plane, i.e., “light level” 1 lx = 0.093 footcandles
Retroreflectivity (Signs)	candela per lux per square meter	$cd/lx/m^2$	Ratio of retroreflected luminance to the perpendicular headlamp illuminance. Sensitive to viewing geometry. ASTM E1709-08 [*24*] specifies a standard geometry for measurement under a viewing geometry of 200 m, with an observation angle = 0.2° and entrance angle = -4.0°.
Retroreflectivity (Pavement Markings)	millicandela per square meter per lux	$mcd/m^2/lx$	Ratio of retroreflected luminance to the perpendicular headlamp illuminance. Sensitive to viewing geometry. ASTM E1710-05 [*25*] specifies a standard geometry for measurement under a viewing geometry of 30-meters, which corresponds to a driver eye height = 1.2 m, headlight height = 0.65 m, observation angle = 1.05° and entrance angle = 88.76°.

4.5 Driver Visibility Requirements for Work Zone Channelization

Due to the dynamic nature of work zones, temporary traffic control devices, such as drums and other channelizing devices, are typically used to delineate the edge of the traveled way. These channelizing devices provide critical information about an upcoming taper, lane shift, or other required maneuver related to the work zone traffic control and operation. To be effective, work zone drums must be visible both day and night far enough in advance of a given situation to allow for sufficient reaction time for the drivers. Nighttime visibility of the work zone drums is of particular importance due to the lack of visual guidance information from other sources. The ability for a driver to visually detect a work zone drum at night is dependent on many factors, including:

- Amount of light actually striking the drum from headlights or ambient lighting
- Retroreflective characteristics of the sheeting material attached to the drum,
- Any auxiliary light sources affixed to the drum,
- Location of the driver with respect to the drum, and
- Visual sensing characteristics of the driver.

4.5.1 Minimum Preview Time/Distance

For work zone drums to be effective, they must be visible far enough in advance to allow drivers sufficient time to perform all of the necessary guidance-related tasks including:

- Detect the drums,
- Recognize the message being conveyed by the drums (i.e., taper, lane shift).
- Decide on the appropriate reaction,
- Initiate response, and
- Complete the vehicle maneuver.

A technical report produced by the International Commission on Illumination (CIE) suggested a 3.0 second **minimum preview time** is necessary to maintain proper lane positioning [*27*]. Zwahlen and Schnell utilized a 3.65 second minimum preview time as the basis for determining the minimum retroreflectivity required by in-service pavement markings, which included the 3.0 seconds recommended by CIE plus an additional 0.65 seconds to account for the time it takes for a driver's eye to fixate on a target [*28,29*]. They claimed that a minimum preview time of 3.65 seconds allows for delineation-related tasks to be performed while still providing for some margin of driver error and driver comfort. Recent research by Deballion et al [*30*] sought to develop minimum levels of pavement marking retroreflectivity, suggesting that a minimum preview time of 2.2 seconds was necessary to satisfy the nighttime delineation visibility needs of a 62 year old driver. Deballion et al also noted that the 3.65 second preview time suggested by Zwahlen and Schnell was one of the longest preview times recommended in the literature for delineation-related tasks. As work zone channelizing devices provide delineation information that is similar to that provided by pavement markings, minimum preview times ranging from between 2.2 to 3.65 seconds, as suggested by CIE, Zwahlen and Schnell, and Deballion et al [*27*,*28*,*29*,*30*], were deemed appropriate for channelizing drums in work zones. The minimum necessary preview *distance* provided by work zone drums (or other delineators) can simply be determined by multiplying the minimum preview time by speed. For example, at 65 mph, a 2.2 second minimum preview time relates to approximately 210 feet of minimum preview distance of the roadway ahead.

McGee et al [*31*] conducted a study with an objective to develop a performance requirement or standard for the detection and recognition of retroreflective traffic devices used for work zone channelization. The minimum visible distance was established based on decision sight distance and was determined to be 900 feet when illuminated by the low beams of standard automobile headlights at night under normal atmospheric conditions when traveling at 55 mph. McGee et al noted that this value assumes that all driver information is provided solely by the channelizing devices, thereby ignoring the fact that other devices, such as warning signs and arrow panels, are typically placed in advance of the work zone to alert drivers of the approaching required maneuver [*31*]. While decision sight distance may be appropriate for advance warning devices in work zones, such as warning signs and arrow panels, it is not necessarily appropriate for channelizing or delineating devices as these devices provide a steady and simple to interpret stream of information to aid drivers in proper lane positioning.

4.5.2 Minimum Luminance Requirement

While there currently exists no established minimum luminance (or "demand" luminance) requirement for work zone traffic control devices, research has explored the issue with respect to sign legibility, such as detecting a letter “C” or reading simple text. An extensive review of several human factors studies by Sivak and Olson in 1983 found that the geometric mean of the minimum luminance values was computed by the authors to be 2.4 cd/m^2 [*32*]. The minimum luminance recommendation of 2.4 cd/m^2 for traffic control devices was referenced by Chrysler [*33*] and later supported in a 2003 FHWA report, which based on new human factors research, recommended a minimum luminance value of 2.3 cd/m^2 for reading guide signs with EModified font legends [*34*]. Schnell et al [*35*] suggested slightly higher minimum luminance levels of 3.2 cd/m^2 for reading guide signs and street name signs. Schnell et al also suggested that 2.3 cd/m^2 represents the absolute minimum luminance value for in-service guide signs and street name signs and that signs should be replaced prior to reaching such levels.

It must again be noted that these recommended minimum luminance values relate to the tasks of identifying letters or simple words (i.e., legibility), which relates to a more complex cognitive task compared to detection of a situational characteristic, such as delineation or channelization.Thus, minimum luminance values of 2.3 cd/m^2 to 3.2 cd/m^2 were deemed conservatively appropriate when applied to the case of work zone channelization, where legibility is not required. Drums also provide the advantage of being a much larger target when compared to the text on guide signs and street name signs. Furthermore, the color contrast between the white and orange retroreflective striping on the drums also aids drivers in recognition of the work zone.

Other research projects have focused on the determination of minimum pavement marking retroreflectivity levels necessary to satisfy the preview time requirement for older and younger drivers. Zwahlen and Schnell found that on a fully marked high-speed roadway, a 62 year old driver requires approximately twice the retroreflectivity as a 22 year old driver in order to have the same detection distances [*29*]. Similarly, younger drivers have been shown to possess detection distances that are on average 55 percent longer than older drivers [*36*]. The range of acceptable levels of pavement marking retroreflectivity ranged from 400 to 515 mcd/m^2/lx for older drivers traveling at 70 mph on unlit highways [*29*]. As retroreflectivity is directly related to luminance, these results can be directly translated to suggest that older drivers require twice the luminance from pavement markings as drivers in their early 20's.

4.6 Summary of Literature Review Findings

The following list presents a concise summary of the literature review findings:

1. Work zones tend to cause an increase in crashes on roadways. The overall crash rate for a sample of highways was found to increase between 7.5 percent and 21.5 percent when the work zone was in place [*7,8*]. Rear-end crashes are the predominant work zone crash during daylight hours, while fixed object crashes are predominant at night [*4,5*]. The use or non-use of steady burn warning lights on drums was found to have no significant impact on work zone crashes [*10*].

2. Nighttime work zone crashes are generally rare events. As a result, researchers typically utilize other intermediate measures of effectiveness, such as those related to nighttime driver behavior/performance, to assess potential safety-related benefits of work zone traffic control devices. Several driver behavior/performance evaluations have investigated the effectiveness of steady burn warning lights on various channelization and/or delineation devices in work zones were found in the literature review [*10,11,12,13,14,15*]. The behavioral/performance-related MOEs utilized in these evaluations included:

   - Lateral placement of vehicles within the travel lane,
   - Erratic maneuvers (i.e., rapid alignment changes or avoidance maneuvers),
   - Steering reversals (i.e., changes in lateral placement),

- Encroachment onto the centerline or edgeline, and
- Vehicular speeds.

3. Steady burn warning lights on **Type 1 barricades with engineering-grade sheeting** provide significant increases in the detection distance of the devices [*11*]. However, the steady burn warning lights did not produce changes in driver behavioral MOEs, including mean speed, lateral placement, or point of lane change upstream of the work zone. These results should be viewed cautiously, as they apply to warning lights on Type 1 barricades with engineering-grade sheeting – neither of which is commonly used by MDOT for channelization in work zones.

4. Steady burn warning lights on **vertical panels with high intensity sheeting** provided no differences in the percentage of correct driver action responses in work zones when viewed at distances of 1,020-ft or less [*15*]. At viewing distances of 1,330-ft and above, greater correct response percentages were observed when the vertical panels included steady burn warning lights. However, because channelizing devices provide greater assistance in lane-positioning guidance rather than advance warning, viewing distances over 1330-feet are not necessarily applicable for determining the effectiveness of steady burn warning lights on channelizing devices.

5. Steady burn warning lights on drums had little impact on driver behavioral MOEs, including vehicular speed, lateral placement, acceleration frequency, steering reversals, erratic maneuver rate, or lane change location upstream of the work zone [*10*,*13*,*14*]. It appears that the use of 1.) high-intensity sheeting on drums and 2.) a lighted arrow panel at the beginning of the taper provides a desirable work zone delineation [*14*].

6. Human vision begins to deteriorate significantly with age starting in the late forties and early fifties. Older persons often have visual difficulty when driving at night as they require greater illumination to see objects clearly and are more likely to

be affected by glare than younger drivers [*17*]. For example, a 62 year old driver requires approximately twice the amount of pavement marking retroreflectivity as compared to a 22 year old for the same detection distances to the marking [*29*].

7. Luminance is a general measure of "brightness" and represents the quantity of visible light leaving a point on a surface in a given direction [*23*]. Luminance measurement is the most appropriate measurement unit for devices with both light emitting components (such as steady burn warning lights) and retroreflective components (such as sheeting materials) because it is a general measurement of brightness.

8. Research has suggested that at least **2.2 to 3.65 seconds** of preview time is necessary for drivers (including older drivers) to maintain proper lane positioning while still providing some margin of driver error and comfort [*27,28,29,30*]. Because the primary function of work zone drums is to channelize and delineate the edge of the travel way, the drums assist in providing lane-positioning guidance to drivers.

9. There currently exists no established minimum luminance requirement for work zone traffic control devices. Minimum luminance recommendations for basic sign legibility (i.e., recognition of a single letter or reading a simple word) have been investigated with a range of **2.3 cd/m^2 to 3.2 cd/m^2** being recommended [*32,33,34,35*]. Minimum luminance values within this same range are conservative for the detection of work zone channelization, such as that provided by channelizing drums.

5.0 CURRENT PRACTICE SURVEY

A questionnaire survey was developed and distributed to representatives at each state DOT (excluding Michigan). This survey included questions pertaining to the types of traffic control used for delineation/channelization in work zones. The survey sought to obtain detailed information pertaining to standard work zone applications for each state, including the use of drums with or without warning lights and alternative channelization devices specific to both daytime and nighttime operations. The survey questionnaire is included in Appendix A. The survey was initially distributed via email. Telephone follow-ups were performed, as necessary, in order to obtain information from agencies that did not respond to the initial email survey, as well as to receive clarification on responses that were unclear or ambiguous.

Survey responses were received from 41 state departments of transportation. Thus, including Michigan, information pertaining to the use of warning lights on drums was obtained for 42 states. Eight states did not respond to the survey. Full survey responses from each of the responding DOTs are summarized in the table included in Appendix B. Figure 2 displays the use of warning lights on drums, as reported by each state DOT responding to the survey. The following list presents a summary of the current practices survey results:

- Fifteen (15) of the 42 responding states (35.7 percent), currently or had very recently, utilized steady burn warning lights on drums or other devices to some degree. Of these 15 states using steady burn warning lights:
  - Three states (Florida, Illinois, and Oklahoma) reported current and frequent use (i.e., ≥ 30 percent of work zones) of drums with steady burn warning lights as a part of the work zone channelization. The State of Arizona also reported frequent use of steady burn warning lights, but this use was mostly for vertical panels rather than drums. The State of Michigan had previously used lights frequently until discontinuing their use as of August 6, 2009.

  - Ten states (Colorado, Indiana, Maryland, Missouri, Montana, New York, Pennsylvania, Texas, Washington, and Wisconsin) reported infrequent use of

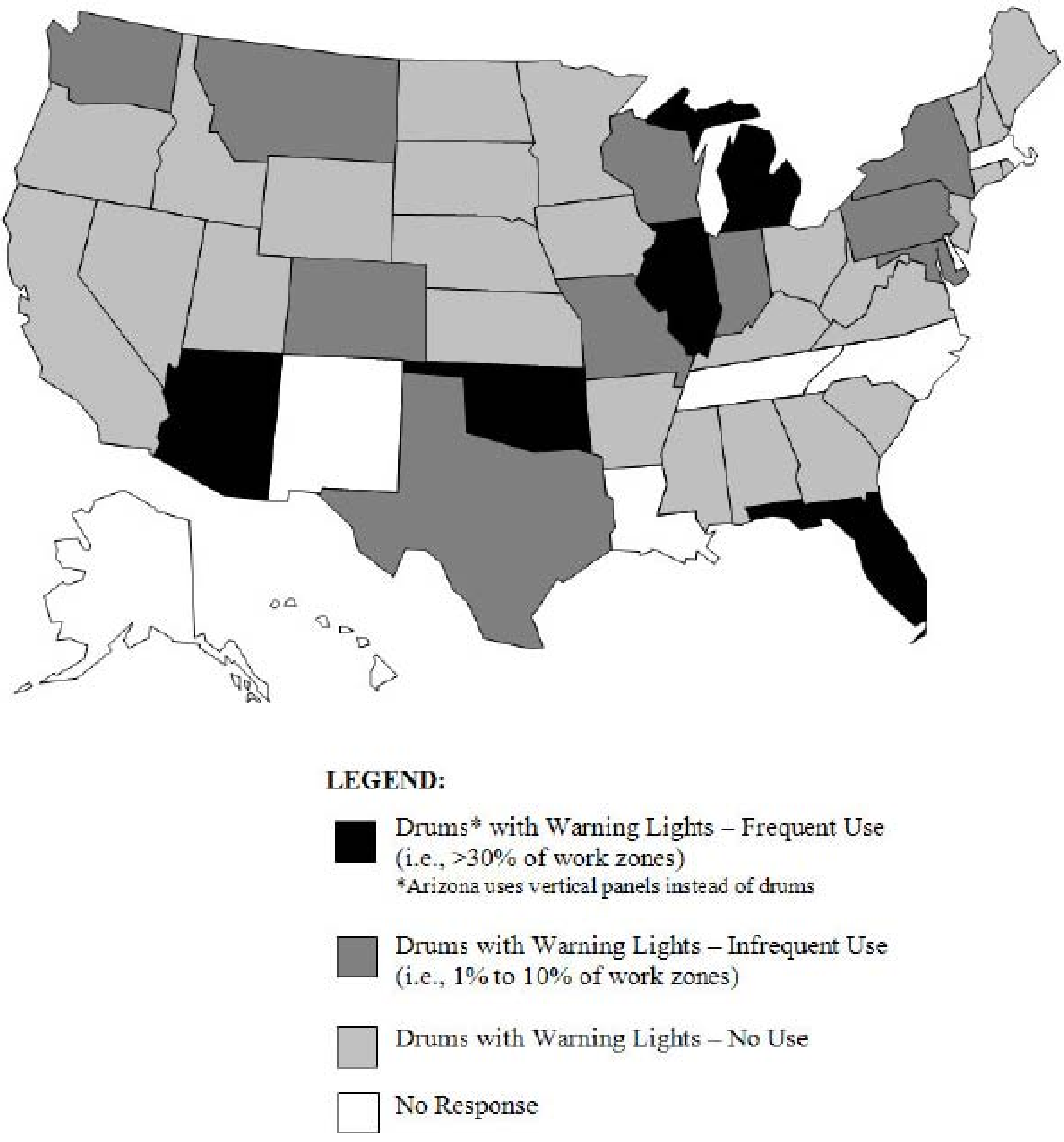

FIGURE 2. State-of-the-Practice Pertaining to the Use of Warning Lights on Channelizing Drums in Work Zones

steady burn warning lights on drums, ranging from 1 percent to 10 percent of all work zones. In general, those agencies which infrequently used lights on drums indicated that lights are/were used for very specific applications, including at spot hazards, tapers, lane shifts, and crossovers.

- The remaining 27 of the 42 responding states (64.3 percent) do not use steady burn warning lights on drums, but instead use drums or other types of channelizing devices without warning lights, such as cones (including grabber cones), vertical panels, or tubular markers.
- All states except Nebraska specify either 4-inch or 6-inch wide retroreflective alternating orange and white sheeting bands on the channelizing devices to provide adequate nighttime retroreflectivity. Nebraska specifies larger sheeting widths, with tape widths ranging from 6 to 8 inches for work zone applications.
- Of the states which indicated the grade of retroreflective sheeting used on drums and other work zone channelizing devices:
  - Eight states (Arizona, Idaho, Illinois, Maryland, New Jersey, New York, Rhode Island, and Utah) specify microprismatic sheeting.
  - Eleven states (Alabama, Connecticut, Florida, Georgia, Iowa, Michigan, New Hampshire, North Dakota, Pennsylvania, Washington, and Wyoming) specify high-intensity retroreflective sheeting with microprismatic sheeting given as an option.
  - Thirteen states (Arkansas, Colorado, Mississippi, Missouri, Montana, Nebraska, Nevada, South Carolina, Texas, Vermont, Virginia, West Virginia, and Wisconsin) specify high-intensity retroreflective sheeting only.
  - **No states specify engineer-grade sheeting for work zone drums.**

- Seven states had performed studies on the effectiveness of steady burn warning lights on drums (Florida, Michigan, New Jersey, Ohio, Texas, Utah, and Wisconsin). Of these, four states have subsequently ceased using steady burn warning lights, including Michigan. It is important to note that the New Jersey DOT had documented incidents where the warning light assembly(s) went through the windshields of vehicles. The States of Florida, Texas, and Wisconsin are still using steady burn warning lights on drums to a certain degree.

As a part of this study, work zone crash data was examined at the statewide level for Michigan and other states where such data was available. This allowed for a comparison of crash trends over time and a determination of whether the use of steady burn warning lights tend to have a substantive effect on such trends. This comparison was supplemented by an in-depth study of crash data for specific work zones within the State of Michigan. The results of these statewide and location-specific comparisons are presented in this Chapter.

6.1 Work Zone Crashes in Other States

During the state-of-the-practice survey, additional data was collected pertaining to each state's population, vehicle miles traveled (VMT), percentage of construction projects with lights on drums and no lights on drums, total crashes, and number of crashes which occurred within work zones. Additional data searches were conducted to identify other relevant sources of information that were available for each state. Data was requested for the period from 2006 through 2008. Complete information was obtained for all of the requested data categories from 26 states.

These 26 states were divided into three groups based upon the percentage of statewide work zones that utilized steady burn warning lights on drums for delineation/ channelization, as follows:

- **Group 1:** States that do not use lights on drums for any construction work zones.
- **Group 2:** States that use lights on drums in at least 30 percent of construction work zones (i.e., frequent use of lights on drums).
- **Group 3:** States that use lights on drums in between 1 and 10 percent of construction work zones (i.e., infrequent use of lights on drums).

The average annual crash rates (based on statewide total VMT in millions) for both total crashes and work zone crashes were determined for each of the states individually and for each of the three groups. The percent of total crashes that occurred in work zones was also compared between the three groups to determine if the state policy regarding the use of steady burn warning lights had a meaningful impact on the rate of work zone crashes.

Only slight differences were observed between the crash rates for each of the three groups for both total crashes and work zone crashes. Group 2 (i.e., frequent use of lights on drums) had the highest crash rate of any of the three groups for both total crashes (2.927 per Million VMT) and work zone crashes (0.059 per MVMT). Group 3 (i.e., infrequent use of lights on drums) had the lowest crash rates of any of the three groups for both total crashes (1.823 per MVMT) and work zone crashes (0.034 per MVMT). The crash rates for Group 1 (i.e., no use of lights on drums) fell in between the rates for Groups 2 and 3 for both total crashes (2.243 per MVMT) and work zone crashes (0.038 per MVMT). No discernable differences were observed between any of the three groups when considering work zone crashes as a percent of total crashes as all groups ranged between 1.7 percent and 2.0 percent. Both the raw crash data and crash rates are shown in Table 3.

These aggregate data do not show the degree to which steady burn warning lights are utilized to have a significant impact on the rate of work zone crashes. It must be noted that utilizing total VMT as the primary exposure factor for the computation of work zone crash rates assumes an equal proportion of work zone VMT to total VMT for each state. As VMT data for work zones are generally not available on a statewide or project-specific level, total VMT was used as the primary crash exposure factor in lieu of work zone data.

TABLE 3. State Work Zone Crash Data and Associated Crash Rates

GROUP BASED ON LIGHTS ON DRUM USE	STATE	AVERAGE OF 3 YEARS (2006-2008)				CRASH RATES		WORK ZONE CRASHES PCT. OF TOTAL CRASHES
		POPULATION	VMT (MILLIONS OF MILES)	TOTAL CRASHES	WORK ZONE CRASHES	TOTAL CRASHES (PER MILLION VMT)	WORK ZONE CRASHES (PER MILLION VMT)	
Group 1: No Lights on Drums	Alabama	4,625,353	60,376	133,009	2,336	2.203	0.039	1.8%
	Idaho	1,493,715	15,410	25,226	258	1.637	0.017	1.0%
	Kansas	2,778,594	29,997	67,302	1,728	2.244	0.058	2.6%
	Kentucky	4,234,998	47,780	125,112	644	2.619	0.013	0.5%
	Maine	1,315,070	14,879	32,011	640	2.151	0.043	2.0%
	Mississippi	2,918,787	42,849	77,201	1,226	1.802	0.029	1.6%
	Nebraska	1,770,895	19,341	34,420	441	1.780	0.023	1.3%
	North Dakota	638,613	7,851	15,903	165	2.026	0.021	1.0%
	Ohio	11,473,980	109,970	327,941	5,609	2.982	0.051	1.7%
	Oregon	3,735,526	34,567	43,791	543	1.267	0.016	1.2%
	Rhode Island	1,054,305	8,374	43,762	526	5.226	0.063	1.2%
	South Dakota	795,754	9,053	15,952	235	1.762	0.026	1.5%
	Utah	2,663,501	26,257	57,933	3,067	2.206	0.117	5.3%
	Vermont	620,738	7,613	14,230	57	1.869	0.007	0.4%
	Virginia	7,698,737	81,817	144,126	2,210	1.762	0.027	1.5%
Group 1 Average		**3,187,904**	**34,409**	**77,195**	**1,312**	**2.243**	**0.038**	**1.7%**
Group 2: Lights on Drums ≥ 30%	Arizona*	6,343,951	62,353	133,385	4,412	2.139	0.071	3.3%
	Illinois	12,829,015	106,810	413,235	7,956	3.869	0.074	1.9%
	Michigan	10,045,697	103,541	318,518	5,231	3.076	0.051	1.6%
	Oklahoma	3,606,205	48,253	74,378	1,468	1.541	0.030	2.0%
Group 2 Average		**8,206,217**	**80,239**	**234,879**	**4,767**	**2.927**	**0.059**	**2.0%**
Group 3: Lights on Drums 1-10%	Indiana	6,335,593	71,222	201,057	3,723	2.823	0.052	1.9%
	Maryland	5,618,251	55,943	99,393	2,180	1.777	0.039	2.2%
	Missouri	5,874,327	68,753	84,423	2,546	1.228	0.037	3.0%
	Montana	956,497	11,128	21,997	301	1.977	0.027	1.4%
	Pennsylvania	12,418,755	108,275	128,109	1,625	1.183	0.015	1.3%
	Washington	6,453,088	56,338	126,912	2,466	2.253	0.044	1.9%
	Wisconsin	5,598,455	58,784	122,701	1,760	2.087	0.030	1.4%
Group 3 Average		**6,179,281**	**61,492**	**112,084**	**2,086**	**1.823**	**0.034**	**1.9%**

*Arizona uses vertical panels rather than drums.

6.2 Work Zone Crashes on MDOT Roadways

Though significant differences were not observed in the evaluation of statewide work zone crash trends, a more detailed analysis of Michigan work zone crashes was conducted in order to gain further insight into the potential impacts of the use/non-use of steady burn warning lights. Data for crashes occurring in sample groups of work zones in the State of Michigan were obtained in order to compare work zones with and without steady burn warning lights on drums. The specific work zone locations and other relevant information, such as the project time periods and work zone boundaries, were identified based on information obtained from the MDOT website, as well as through information provided by MDOT Transportation Service Centers (TSC). Work zones that were either shorter than 1/2 mile, or did not include drums (some sites just used cones), were not used in the crash study.

Tables 4 and 5 present the characteristics of the sample group of work zones used in the crash analysis for locations with and without steady burn warning lights, respectively. These work zones were selected from two sources: (1) the Mi Drive website (http://www.michigan.gov/drive), which provides an up-do-date list of all current and upcoming construction projects, and (2) project lists obtained from MDOT Transportation Service Centers. The work zones that included drums with steady burn warning lights include projects that were let prior to August 6, 2009. Table 4 shows that the work zone start dates occurred after this date for eleven projects, though steady burn warning lights were present as the **letting date occurred prior to the MDOT moratorium**. The locations without steady-burn warning lights were selected from among those projects that were let on or after August 6, 2009. Thirty-one (31) work zone locations used drums with steady burn warning lights, while 25 work zone locations used drums without steady burn warning lights as shown in Tables 4 and 5, respectively. The locations without steady burn warning lights typically provided a smaller data collection period due to the fact that the policy eliminating the use of warning lights on drums only went into effect in August 2009.

TABLE 4. MDOT Work Zone Locations WITH Steady Burn Warning Lights on Drums

ROUTE	COUNTY	ROADWAY TYPE	CRASH DATA COLLECTION PERIOD			LENGTH OF WORK ZONE (MILES)	TOTAL CRASHES FOR THE PERIOD
			WORK ZONE START DATE	END DATE	TOTAL MONTHS		
M-13	Saginaw	Arterial	5/4/2009	7/31/2010	15.1	1.1	33
M-43	Ingham	Arterial	3/25/2010	7/31/2010	4.3	7.5	8
M-17	Washtenaw	Arterial	4/1/2010	7/31/2010	4.0	1.5	71
I-94 BL	Berrien	Arterial	5/4/2009	7/31/2010	15.1	2.1	35
M-89	Allegan	Arterial	6/15/2009	10/30/2009	4.6	1.5	5
M-25	Bay	Arterial	10/13/2008	7/31/2010	21.9	1.3	19
M-50/M-99	Eaton	Arterial	7/20/2009	7/31/2010	12.5	2	26
M-13/M-46	Saginaw	Arterial	7/20/2009	7/31/2010	12.5	2.3	28
I-94	Calhoun	Freeway	5/6/2009	12/19/2009	7.6	2.3	67
I-94	Calhoun	Freeway	4/13/2009	5/30/2010	13.7	1.7	129
I-675	Saginaw	Freeway	6/30/2009	7/31/2010	13.2	6.2	80
I-696	Macomb	Freeway	1/1/2010	5/31/2010	5.0	9.2	120
I-94	Washtenaw	Freeway	1/1/2010	7/31/2010	7.0	7.5	152
I-94	Berrien	Freeway	8/3/2009	6/25/2010	10.9	9.7	245
I-96	Ottawa	Freeway	6/15/2009	7/31/2010	13.7	2	275
I-96	Wayne	Freeway	2/15/2010	7/31/2010	5.5	8	330
I-196	Allegan	Freeway	5/26/2009	5/31/2010	12.3	2.5	67
I-96	Ingham	Freeway	7/20/2009	12/31/2009	5.5	6.6	125
I-94	Kalamazoo	Freeway	5/25/2009	7/31/2010	14.4	2.7	381
US-131	Kalamazoo/Allegan	Freeway	7/6/2009	5/14/2010	10.4	3.7	399
US-31	Berrien	Freeway	4/19/2009	5/15/2010	13.0	1.5	17
US-127	Isabella	Freeway	1/1/2010	7/31/2010	7.0	3	107
I-96	Kent	Freeway	11/7/2008	6/29/2009	7.8	4.5	64
I-196	Kent	Freeway	9/1/2009	5/21/2010	8.7	5	103
US-131	Kent	Freeway	10/17/2009	7/31/2010	9.6	4.9	106
I-69	Lapeer/Genesee	Freeway	4/13/2009	7/31/2010	15.8	1.1	143
US-10	Midland	Freeway	3/17/2008	7/31/2010	28.9	7.5	308
M-59	Oakland	Freeway	9/18/2009	6/15/2010	9.0	1.5	67
M-59	Oakland	Freeway	9/2/2009	7/31/2010	11.1	2.1	109
M-59	Macomb	Freeway	9/2/2009	7/31/2010	11.1	1.5	50
I-96	Oakland	Freeway	6/30/2009	12/31/2009	6.1	1.3	88
TOTAL							**3,757**

TABLE 5. MDOT Work Zone Locations WITHOUT Steady Burn Warning Lights on Drums

ROUTE	COUNTY	ROADWAY TYPE	CRASH DATA COLLECTION PERIOD			LENGTH OF WORK ZONE (MILES)	TOTAL CRASHES FOR THE PERIOD
			WORK ZONE START DATE	END DATE	TOTAL MONTHS		
US-24 BL	Oakland	Arterial	4/16/2010	5/31/2010	1.5	1.1	11
M-40	Allegan	Arterial	1/1/2010	7/31/2010	7.0	7.5	16
M-72	Leelanau	Arterial	4/20/2010	7/16/2010	2.9	1.5	1
US-24	Oakland	Arterial	3/2/2010	3/14/2010	0.4	2.1	15
M-1	Wayne	Arterial	4/5/2010	7/31/2010	3.9	1.5	20
US-12	Wayne	Arterial	4/5/2010	7/10/2010	3.2	1.3	39
M-40	Van Buren	Arterial	4/19/2010	7/31/2010	3.4	2	10
M-204	Leelanau	Arterial	10/19/2009	4/29/2010	6.4	2.3	9
M-22	Leelanau	Arterial	10/29/2009	4/29/2010	6.1	2.3	5
M-39	Wayne	Arterial	10/6/2009	7/31/2010	9.9	1.7	198
US-12	St. Joseph	Arterial	10/10/2009	6/25/2010	8.6	6.2	22
US-131	Traverse/Kalkaska	Arterial	10/5/2009	6/17/2010	8.5	9.2	18
US-131	Allegan	Freeway	4/1/2010	5/31/2010	2.0	7.5	
I-275	Wayne	Freeway	3/5/2010	6/15/2010	3.4	9.7	21
I-75	Monroe	Freeway	1/1/2010	7/31/2010	7.0	2	41
I-75	Monroe	Freeway	3/10/2010	7/31/2010	4.8	8	19
I-75	Monroe	Freeway	3/31/2010	4/9/2010	0.3	2.5	53
US-131	Kalamazoo	Freeway	4/5/2010	4/30/2010	0.8	6.6	0
I-94	Jackson	Freeway	4/10/2010	7/30/2010	3.7	2.7	5
I-75	Saginaw/Bay	Freeway	3/19/2010	5/28/2010	2.3	3.7	26
I-75	Wayne	Freeway	5/1/2010	7/30/2010	3.0	1.5	6
I-94	Macomb	Freeway	4/10/2010	7/31/2010	3.7	3	40
I-196	Kent	Freeway	10/2/2009	7/31/2010	10.1	4.5	103
I-75	Ogemaw	Freeway	9/12/2009	12/11/2009	3.0	5	169
I-96	Eaton/Clinton	Freeway	8/27/2009	12/31/2009	4.2	4.9	6
TOTAL							**920**

A total of 3,757 crashes occurred in the 31 work zones that utilized drums **with steady burn warning lights.** This includes all crashes that occurred within the work zone limits during the time period between the construction start date and the construction end date for completed project or between the construction start date and July 31, 2010 for continuing projects. Similarly, a total of 920 crashes occurred in the 25 work zones that included drums **without steady burn warning lights**. These crashes were identified using the Michigan Traffic Crash Facts (MTCF) Data Query Tool, as well as MDOT's Traffic Crash Reporting System (TCRS) and Transportation Management System (TMS).

The individual UD-10 traffic crash report forms were downloaded for each of these 4,677 crashes and a detailed review was conducted in order to identify:

1. **Crashes which occurred during nighttime (i.e., dark lighting) conditions** – This determination was made by examining both the lighting condition reported by the officer, as well as the time of day during which the crash occurred. Crashes where the officer coded a nighttime lighting condition (dark-lighted, dark-unlighted, dawn, or dusk) were identified as nighttime crashes. If the lighting condition field was left blank, the time of day was referred to and compared to season sunrise and sunset times in order to make this determination.

2. **Crashes which occurred in the presence of drums** – Once it was established that a crash had occurred during nighttime conditions, the narrative and diagram portions of the UD10 forms were examined to determine whether drums were present in the immediate vicinity of the crash. All forms which included drums either in the diagram or which mentioned drums in the police officer narrative were identified as having occurred in the presence of drums.

3. **Crashes which may have been influenced by the presence of the drums** – For those crashes which occurred both during nighttime conditions and in the presence of drums, a further review was conducted in order to identify those crashes which may have been influenced by the presence of drums as opposed to some other factors. This includes crashes which occurred in the taper area, transition area, activity area, or termination area of the work zone. Crashes were determined not to have been influenced by the presence of drums if they: (a) were caused by deer or other animals in the roadway; (b) were caused by other objects, such as struck drums or debris, that were within the travel lane; or (c) involved rear-end collisions due to stopped traffic.

Once each crash had been categorized using the previously described procedure, a comparison was made between the crash data for the locations with and without steady burn warning lights. Since the work zones within each group were of varying lengths and durations, as well as the fact that traffic volume data was unavailable for the period during which the work zones were in operation, the crash frequencies cannot be directly compared between the two groups. For example, though a total of 3,757 crashes occurred at the sites **with steady burn warning lights** and 920 crashes occurred at the sites **without steady burn warning lights**, these data cannot be compared directly due to non-availability of work zone traffic volume data and lengths of time are different for the work zones in these two groups. As such, a more appropriate method for assessing whether the presence of steady-burn warning lights has a significant impact on work zone safety is to compare the following two proportions:

1. The proportion of total work zone crashes that occurred during nighttime conditions – If the steady burn warning lights have an impact on work zone safety, it is expected

that the proportion of total work zone crashes occurring at night will be different between those work zones with and without lights.

2. The proportion of work zone crashes occurring at night in the presence of drums that may have been influenced by the drums – If the steady burn warning lights have an impact, these proportions are also expected to differ between those work zones with and without lights.

Table 6 shows that of the 3,757 total crashes experienced in the work zones with steady burn warning lights, 1,484 (39.5%) occurred at night. Of the 920 crashes experienced in the work zones without steady burn warning lights, 281 (30.5%) occurred at night. The Z-test statistic in Table 6 shows that a significantly lower proportion of crashes occurred at night in the work zones **without steady burn warning lights**.

When focusing only upon those crashes which occurred in the presence of drums, 30 of the 139 such crashes (21.6%) may have been influenced by the presence of the drums at the sites where **steady burn warning lights** were present. At the locations where **steady burn warning lights were not used**, it was found that 10 of the 49 crashes which occurred in the presence of drums may have been influenced by the drums (20.4%). Table 6 shows that, although a lower percentage of crashes occurred in work zones which did not use steady burn warning lights, this difference was not statistically significant.

Collectively, these data indicate that the presence of steady burn warning lights was not found to significantly influence the proportion of crashes occurring at night. The locations **without steady burn warning lights** experienced a lower proportion of crashes at night in comparison to those locations **with steady burn warning lights**. When examining only those crashes that occurred in the presence of drums, there was virtually **no difference** in the proportion of crashes that may have been influenced by the drums, regardless of whether steady burn warning lights were in use or not.

TABLE 6. Work Zone Crashes versus Steady Burn Warning Light Presence

<table>
<tr><th rowspan="2">MEASURES OF EFFECTIVENESS</th><th colspan="2">CRASHES IN WORK ZONE GROUPS</th><th rowspan="2">Z-TEST STATISTIC</th><th rowspan="2">CRITICAL Z-VALUE @ 95% LOC</th><th rowspan="2">SIGNIFICANT DIFFERENCE?</th></tr>
<tr><th>WITH STEADY BURN WARNING LIGHTS</th><th>WITHOUT STEADY BURN WARNING LIGHTS</th></tr>
<tr><td>Total work zone crashes</td><td>3,757</td><td>920</td><td rowspan="3">4.99</td><td rowspan="3">1.96</td><td rowspan="3">Yes</td></tr>
<tr><td>Nighttime work zone crashes</td><td>1,484</td><td>281</td></tr>
<tr><td>Percent of work zone crashes occurring at night</td><td>39.5%</td><td>30.5%</td></tr>
<tr><td>Total nighttime work zone crashes occurring in the presence of drums</td><td>139</td><td>49</td><td rowspan="3">0.03</td><td rowspan="3">1.96</td><td rowspan="3">No</td></tr>
<tr><td>Nighttime work zone crashes that may have been influenced by the presence of drums</td><td>30</td><td>10</td></tr>
<tr><td>Percentage of crashes influenced by presence of drums as compared to nighttime crashes in presence of drums</td><td>21.6%</td><td>20.4%</td></tr>
</table>

In addition to comparing these proportions, crash data for the same time periods prior to the start of construction were examined to determine whether the number of overall crashes and nighttime crashes within the project boundaries had increased or decreased during the work period. For example, the number of crashes that occurred over the duration of a project that began on April 20th and was completed on July 16th were compared to the number of crashes that occurred the previous year during this same time period. Table 7 presents these comparisons for the locations **with steady burn warning lights** while Table 8 presents similar data for the work zones **without steady burn warning lights**.

TABLE 7. Comparison of Crashes at MDOT Work Zone Locations WITH Steady Burn Warning Lights on Drums

ROUTE	LOCATION OF PROJECT	MILEAGE (MILES)	# OF MONTHS	PERIOD PRIOR TO CONSTRUCTION		CONSTRUCTION PERIOD		% CHANGE DURING CONSTRUCTION	
				TOTAL	NIGHT TIME	TOTAL	NIGHT TIME	TOTAL	NIGHT TIME
M-13	Holland to Jane	2	15.1	17	1	33	4	-94.1%	-300.0%
M-43	Pine to Walnut	0.5	4.3	16	2	8	0	50.00%	100.00%
M-17	Carpenter to Golfside	1	4.0	35	5	71	10	-102.9%	-100.0%
I-94BL	Fair Ave to River St	2	15.1	53	16	35	11	34.0%	31.3%
M-89	Jefferson to Wilmott	1.2	4.6	11	0	5	0	54.5%	0.0%
M-25	Johnson St. to Livingston Ave.	1	21.9	53	12	19	3	64.2%	75.0%
M-50/M-99	Kimbark to M-50 Junction	1	12.5	23	7	26	6	-13.0%	14.3%
M-13/M-46	Hess to M-46 and M-46 Harris to Lincoln Street	1.2	12.5	38	11	28	7	26.3%	36.4%
I-94	MM 104 to MM 110	6.1	7.6	93	49	67	48	-38.8%	-2.1%
I-94	MM 95 to MM 99	4.8	13.7	128	45	129	56	-0.8%	-24.4%
I-675	I-75N to I-75S	7.9	13.2	135	47	80	23	40.7%	51.1%
I-696	I-94 to Hayes	2	5.0	114	31	120	19	-5.3%	38.7%
I-94	Baker to Jackson Co. Line	13	7.0	136	62	152	61	-11.8%	1.6%
I-94	Indiana to MM 23	23	10.9	316	148	245	121	22.5%	18.2%
I-96	M-104 to Ottawa Co. Line	16	13.7	293	153	275	154	6.1%	-0.7%
I-96	Beech Daly to I-94	12	5.5	278	93	330	81	-18.7%	12.9%
I-196	71st to 118th	11	12.3	149	74	67	19	55.0%	74.3%
I-96	US-127 to Meridian	12	5.5	132	62	125	67	5.3%	-8.1%
I-94	Oakland to Portage	9	14.4	484	206	381	136	21.3%	34.0%
US-131	B avenue to 146th	31	10.4	269	132	399	170	-48.3%	-28.8%
US-31	Indiana to US-12	3.3	13.0	23	10	17	10	26.1%	0.0%
US-127	Shepherd to 127BR junction	5	7.0	40	20	107	62	-167.5%	-210.0%
I-96	Over Grand River	1.5	7.8	75	48	64	24	14.7%	50.0%
I-196	Ottawa/Kent to M-11	4.5	8.7	154	68	103	41	33.1%	39.7%
US-131/44th Street	36th to 54th	2.3	9.6	197	66	106	40	46.2%	39.4%
I-69	M-15 to M-24	10.2	15.8	164	91	143	64	12.8%	29.7%
US-10	Sanford Lake to Midland/Bay County Line	13.3	28.9	281	139	308	139	-9.6%	0.0%
M-59	Opdyke to Woodward	2.1	9.0	74	16	67	20	9.5%	-25.0%
M-59	Dequindre to Crooks	4.5	11.1	182	65	109	45	40.1%	30.8%
M-59	Mound to Dequindre	2	11.1	56	22	50	18	10.7%	18.2%
I-96	East of Beck to Novi Road	3.5	6.1	160	50	88	25	45.0%	50.0%
TOTALS		**209.9**	**337.3**	**4,179**	**1,751**	**3,757**	**1,484**	**10.1%**	**15.2%**

TABLE 8. Comparison of Crashes at MDOT Work Zone Locations WITHOUT Steady Burn Warning Lights on Drums

ROUTE	LOCATION OF PROJECT	MILEAGE (MILES)	# OF MONTHS	PERIOD PRIOR TO CONSTRUCTION		CONSTRUCTION PERIOD		% CHANGE DURING CONSTRUCTION	
				TOTAL	NIGHT TIME	TOTAL	NIGHT TIME	TOTAL	NIGHT TIME
US-24 Bus (Cass)	Chavez to Woodward	1.1	1.5	9	1	11	2	-22.2%	-100.0%
M-40	S. Allegan Co Line to M-89	7.5	7.0	30	15	16	8	46.7%	46.7%
M-72	Cedar Run and Goodrick Rd.	1.5	2.9	1	0	1	0	0.0%	0.0%
US-24	12 Mile to 13 Mile	2.1	0.4	12	3	15	1	-25.0%	66.7%
M-1	Chandler to Tuxedo	1.5	3.9	18	4	20	3	-11.1%	25.0%
US-12	Outer Driver to Brady St.	1.3	3.2	44	7	39	3	11.4%	57.1%
M-40	St. Joseph to Chicago/Plant Road	2	3.4	15	3	10	0	33.3%	100.0%
M-204	Between Suttons Bay and Lake Leelanau	2.3	6.4	6	5	9	7	-50.0%	-40.0%
M-22	Near Lime Lake Road	2.3	6.1	9	6	5	4	44.4%	33.3%
M-39	Porter St. to Pinecrest Ave.	1.7	9.9	232	48	198	49	14.7%	-2.1%
US-12	Franks to Branch Co. Lin	6.2	8.6	24	14	22	14	8.3%	0.0%
US-131	M-113 to Boardman	9.2	8.5	39	13	18	9	53.8%	30.8%
US-131 SB, Wayland	120th Ave to 135th	7.5	2.0	25	15	21	8	16.0%	46.7%
I-275	I-94 to Monroe County	9.7	3.4	20	6	41	14	-105.0%	-133.3%
I-75	I-127 to Nadeau	2	7.0	17	3	19	10	-11.8%	-233.3%
I-75	Laplaisance to Sandy Creek	8	4.8	30	12	53	14	-76.7%	-16.7%
I-75	MM1 to MM3	2.5	0.3	0	0	0	0	0.0%	0.0%
US-131	Center Ave to Flowerfield Road	6.6	0.8	7	2	5	1	28.6%	50.0%
I-94	Sargent to Race	2.7	3.7	21	9	26	5	-23.8%	44.4%
I-75	I-675 to M-84	3.7	2.3	6	2	6	3	0.0%	-50.0%
I-75	Rouge River Bridge	1.5	3.0	14	5	40	11	-185.7%	-120.0%
I-94	10 Mile to 12 Mile	3	3.7	100	30	103	13	-3.0%	56.7%
I-196/Baldwin	I-96 to US-131	4.5	10.1	184	52	169	58	8.2%	-11.5%
I-75	From Arenac/Ogemaw Co. Line to Lehman/Boehm Rd	5	3.0	8	6	6	4	25.0%	33.3%
I-96	M-43 to Wacousta	4.9	4.2	79	52	67	40	15.2%	23.1%
TOTALS		**100.3**	**110.1**	**950**	**313**	**920**	**281**	**3.2%**	**10.2%**

These results show that fewer crashes were experienced on average at both the work zones **with and without steady burn warning lights**. The locations with steady burn warning lights experienced 10.1 percent fewer total crashes and 15.2 percent fewer work zone crashes in comparison to the same time period prior to construction. The locations without steady burn warning lights experienced 3.2 percent fewer crashes and 10.2 percent fewer nighttime crashes.

The **age of the drivers** involved in the nighttime crashes that occurred in the presence of drums, were also examined to determine whether older drivers were more likely to be crash-involved in either setting. However, only **two** of the crashes in the work zones **with steady burn warning lights** involved drivers age 65 and above and only **one** of the crashes in the work zones **without steady burn warning lights** involved such drivers. This difference was also not statistically significant.

Given the limited crash data related to older drivers, aggregate crash statistics for the five-year period from 2004 to 2009 in the State of Michigan were also examined to assess how frequently drivers of age 65 and above were involved in nighttime work zone crashes. Table 9 presents data regarding the percentage of crashes under various categories that involved drivers age 65 and above. When examining all police-reported traffic crashes in the State of Michigan, 7.4 percent of all crash-involved drivers were found to be 65 years of age or older. When examining nighttime crashes, only 4.4 percent of crash-involved drivers were age 65 and above. While age-specific travel data are not directly available, this may reflect the fact that older drivers tend to drive less at night. Similarly, while older drivers are slightly overrepresented in work zone crashes (7.7 percent of all work zone crashes involve older drivers, compared to 7.4 percent of all crashes), they are slightly underrepresented in nighttime work zone crashes (4.2 percent of drivers in nighttime work zone crashes versus 4.4 percent of drivers in all nighttime crashes). Collectively, these data do not indicate that nighttime work zones are particularly problematic for drivers 65 years of age and above in the State of Michigan.

TABLE 9. Statewide Crash Data for Drivers Age 65 and Above in Comparison to All Drivers, 2004 to 2009

CRASH CATEGORY	ALL DRIVERS	DRIVERS AGE 65 AND ABOVE	PERCENT OF ALL DRIVERS AGE 65 AND ABOVE
Total Crash-Involved Drivers	3,289,611	241,846	7.4%
Crash-Involved Drivers during Nighttime	1,088,234	47,661	4.4%
Crash-Involved Drivers in Construction/ Maintenance or Utility Work Zones	64,326	4,977	7.7%
Crash-Involved Drivers in Construction/ Maintenance or Utility Work Zones at Night	13,213	554	4.2%

7.0 FIELD EVALUATION DRIVER BEHAVIOR

Due to the relatively infrequent and random nature of work zone crashes, particularly those that may be influenced by the presence of drums, additional studies were conducted in order to determine whether various aspects of driver behavior and performance differed between work zones with and without steady burn warning lights on drums. Specifically, a nighttime field evaluation was performed at several work zones on MDOT roadways throughout the State of Michigan to assess the driver behavior-related characteristics with respect to the presence (or absence) of steady burn warning lights on channelizing drums. A comparative parallel study design was utilized as the data was collected concurrently at separate work zone locations, some of which included **drums with steady burn warning lights**, while others included **drums without steady burn warning lights**.

There exists an inherent relationship between specific driver behavior/performance characteristics and the risk of a crash. Because work zone channelization assists drivers in tasks such as maintaining a safe speed and path through the work zone, it follows that the channelization-related crash risk would be associated with behavioral characteristics related to the ability of drivers to maintain a safe lane position and speed control while traveling through the work zone. Thus, the behavioral/performance related characteristics used in this evaluation were carefully selected to provide an indication of the relative crash risk associated with the work zone channelization. Five measures of effectiveness (MOEs) were assessed as a part of this evaluation, which were similar to those utilized in previous research by Pant et al [*13,14*] and Datta and McAvoy et al [*10*], including:

- Percent of time subject vehicles spent in the center lane position - The center lane position represents the safest lateral position within the lane. Vehicles that are positioned too closely to the drums risk collision with the drums, workers, or equipment, while vehicles that are in the farthest position from the drums risk collision with other vehicles or running off the road. Thus, a higher percentage of time spent in the center lane position represents a traffic safety benefit, while a lower percentage of time spent in the lane position closest to the drums also represents a traffic safety benefit;

- Percent of time subject vehicles spent in the lane position closest to the drums – Similarly, a higher percentage of time spent in the lane position closest to the drums presents a greater opportunity for a driver to strike a drum and, thus, represents a potential negative safety impact;
- Rate of steering reversals for subject vehicles, per minute - Steering reversals relate to a driver's inability to safely maintain a consistent lane position. Thus, a lower rate of steering reversals also represents a traffic safety benefit;
- Percent of drums that were damaged - Similarly, lower percentages of damaged drums indicate fewer vehicular intrusions into the work area; and
- Vehicular speed characteristics - Vehicular speeds may also be indicative of safety benefits. In particular, as the variance in travel speeds is reduced, the likelihood of traffic crashes is also reduced. Other vehicle characteristics, such as the 85th percentile speed, provide evidence of additional differences in work zone driver behavior and performance.

7.1 Sample Size Determination

Data was collected regarding five specific MOEs: (1) the percent of time vehicles spent in the center lane position; (2) the percent of time vehicles spent in the lane position closest to the drums; (3) the rate of steering reversals per minute; (4) the mean vehicular speed, and (5) the percent of drums that were damaged. Selection of the appropriate statistical sample size equation is dependent on the characteristics of the data used to compute the MOE. For example, if the data is reported as proportions or percentages, the following formula can be used to estimate the number of vehicles that should be observed within each of the two groups (with and without lights) in order to detect a specified difference between the MOEs computed for the two groups:

$$n = \frac{[z_{\alpha/2}\sqrt{(p_1 + p_2)(q_1 + q_2)/2}\,]^2}{(p_1 - p_2)^2}$$

where:

n = number of vehicles to be observed in each group (i.e., drums with lights versus drums without lights)

$z_{\alpha/2}$ = standard normal value assuming a significance level of α percent

p_1 = mean proportion or percent for group 1

p_2 = mean proportion or percent for group 2

$q_1 = 1 - p_1$

$q_2 = 1 - p_1$

Similarly, if the data is reported as rates or naturally occurring measurements, the following formula can be used to calculate the number of vehicles that must be observed within each group in order to detect a specific difference between the MOEs computed for the two groups:

$$n = \frac{(z_{\alpha/2})^2(\sigma_1^2 + \sigma_2^2)}{(\overline{X}_1 - \overline{X}_2)^2}$$

where:

n = number of vehicles to be observed in each group (i.e., drums with lights versus drums without lights)

$z_{\alpha/2}$ = standard normal value assuming a significance level of α percent

$\overline{X}_1$ = sample mean for group 1

$\overline{X}_2$ = sample mean for group 2

σ_1 = standard deviation of data for group 1

σ_2 = standard deviation of data for group 2

Using sample data from one particular location and assuming a significance level (α) of 0.05 (based upon standard statistical practices), the minimum number of subject vehicles required to detect a statistically significant difference in each MOE was determined as a part of this study. The following sample estimates were utilized to determine target sample sizes for each of the five MOEs under consideration:

- Percent of Time Spent in Center Lane Placement = 24.8
- Percent of Time Spent in Position Closest to Drums = 9.9
- Steering Reversals per Minute: Mean = 4.0, St. Dev. = 2.89
- Vehicular Speed (mph): Mean = 61.1, St. Dev. = 6.3
- Percent of Damaged Drums = 12.1

Table 10 displays the minimum number of vehicles that must be observed within each group of locations in order to detect specific differences for the particular MOE, based on the assumed sample estimates. The researchers determined that detection of a 5 percent difference would be acceptable for proportion data, while a difference of 0.5 steering reversals and 1.0 mph in mean speed would be acceptable differences for the respective MOEs. Based on the minimum sample size estimates shown in Table 10, the researchers determined that a minimum sample of 532 vehicles would be tracked through the work zone locations both with and without steady burn warning lights on the drums. This would allow for detection of a minimum difference between the two groups (i.e., drums with lights vs. drums without lights) of 0.50 steering reversals per minute and a 5-percentage point difference for the lateral lane position MOEs. Furthermore, a minimum of 305 vehicular speed samples were necessary per group to detect a 1.0 mph difference in mean speeds and a minimum of 267 drum observations were necessary to detect a 5-percentage point difference in drums that were damaged.

TABLE 10. Sample Size Requirements for Study Measures of Effectiveness

MEASURE OF EFFECTIVENESS (MOE)	MINIMUM NUMBER OF VEHICLES REQUIRED PER GROUP			
	SIZE OF DETECTABLE DIFFERENCE			
	5%	10%	15%	20%
Percent of Time Spent in Center Lane Placement	**532**	121	49	24
Percent of Time Spent in Position Closest to Drums	**210**	36	8	-
Percent of Damaged Drums	**267**	51	15	4
MEASURE OF EFFECTIVENESS (MOE)	**MINIMUM NUMBER OF VEHICLES REQUIRED PER GROUP**			
	SIZE OF DETECTABLE DIFFERENCE			
	0.50	**1.00**	**1.50**	**2.00**
Steering Reversals per Minute	**257**	64	29	16
Mean Vehicular Speeds (mph)	1,220	**305**	136	76

7.2 Site Selection

A total of 28 work zones in 15 counties throughout the lower peninsula of Michigan were utilized for the driver behavioral study. Each work zone was located on an MDOT roadway. Each study location included one or more sections of channelizing drums that were at least ½ mile in length, which was established as the minimum distance necessary to effectively assess driver behavior. The study locations were randomly selected from a list of eligible work zone sites in Michigan. The work zones selected for use in this study collectively represented a broad range of work zone scenarios, including:

- Drums with and without steady burn warning lights,
- Single lane closures, double lane closures, and shoulder closures,
- Roadway lighting and no roadway lighting,
- Arterials and freeways,
- Drums on the left and drums on the right, and
- Various drums offset from the edge of the lane.

All steady burn warning lights on drums observed in the field evaluations were of the 360 degree type. The characteristics for each of the 28 study work zones are presented in Table 11.

TABLE 11. Characteristics of Work Zone Sites for Field Study of Driver Behavior

STEADY BURN WARNING LIGHTS ON DRUMS	SITE	COUNTY	LENGTH OF WORK ZONE	ROADWAY LIGHT	ROADWAY TYPE
No	M-59	Oakland	2.1	Yes	Freeway
	M-39	Wayne	1.7	Yes	Arterial
	US-24	Oakland	1	Yes	Arterial
	I-275	Wayne	9.7	No	Freeway
	I-75	Monroe	2	No	Freeway
	I-75	Monroe	8	No	Freeway
	M-1	Wayne	1.5	Yes	Arterial
	I-75	Monroe	2.5	No	Freeway
	US-131	Kalamazoo	6.6	No	Freeway
	US-12	Wayne	1.3	Yes	Arterial
	I-94	Jackson	2.7	No	Freeway
	I-75	Bay/Saginaw	3.7	No	Freeway
	US-24 Business	Oakland	1.1	Yes	Arterial
	I-75	Wayne	1.5	Yes	Freeway
	I-196	Kent	2.5	No	Freeway
	I-94	Macomb	3	Yes	Freeway
	M-40	Van Buren	1.6	Yes	Arterial
	I-696	Macomb	4	Yes	Freeway
Yes	M-59	Oakland	6.5	Mixed	Freeway
	I-96	Wayne	12	Yes	Freeway
	I-675	Saginaw	7.9	Mixed	Freeway
	I-696	Macomb	4	Yes	Freeway
	I-94	Kalamazoo	0.5	No	Freeway
	I-94	Washtenaw	13	No	Freeway
	I-196	Allegan	6.7	No	Freeway
	I-96	Ottawa	15.3	No	Freeway
	I-94 Business	Berrien	1.5	Yes	Arterial
	I-94	Berrien	19	No	Freeway

Demographic information, including population and driver licensing data, was relatively consistent between each of the 15 counties utilized in this study. The overall percentage of licensed drivers over the age of 65 for the 15 study counties was 15.3 percent, which was slightly lower than that for the State of Michigan (16.6 percent). Crash involvement of older drivers was also comparable across the sample counties. As the study sites were randomly selected from all candidate work zones, it is reasonable to assume that the driving populations were also comparable between the work zones with and without steady burn warning lights.

7.3 Field Data Collection Procedures

Driver behavioral data collection was performed at the study sites during periods of darkness between January and May of 2010. The studies were conducted from early evening (after dark) hours until well after midnight. As such, a wide range of traffic volumes were observed, as well as a diverse sample of driver types and ages. Data was only collected during dry weather conditions as it was not possible to accurately assess the lane positioning of vehicles during wet weather conditions using the procedures described herein.

The nighttime driver behavior data collection was performed from a survey vehicle by covertly recording the movements of randomly selected subject vehicles as they were followed through the work zone by the survey vehicle. Each pass through the work zone would typically begin several hundred feet upstream of a section of channelizing drums. As the survey vehicle approached the section of drums, the driver would position the vehicle directly behind the selected subject vehicle. If multiple travel lanes were available in the work zone, only vehicles traveling in the lane closest to the channelizing drums were observed. The survey vehicle driver made reasonable attempts to maintain a 4 to 8 second spacing from the rear of the subject vehicle throughout the entire work zone.

The behavior of the subject vehicle was covertly recorded as it was followed through the work zone using a high definition video camera mounted on a tripod inside the vehicle. The camera was positioned in a consistent manner for each subject vehicle such that the field-of-view was centered on the rear of the vehicle and that the view included a substantial distance beyond the left and right lane markings, including the channelizing drums. The passenger in the survey vehicle held the tripod in place to ensure that the desired camera view was maintained throughout each pass. Adjustments to the camera position were only made if absolutely necessary to maintain a uniform field-of-view. After following the subject vehicle through the entire work zone, the driver would turn around at the nearest exit, crossroad, or driveway and the survey process was repeated for the opposite travel direction, assuming that the work zone was two-directional. If the work zone only existed for a single direction, the survey vehicle simply proceeded back to the start of the work zone to resume the survey for another randomly selected subject vehicle. The data collection procedure was repeated for a minimum of 20 passes through each work zone. The videos were also utilized for assessment of drum condition.

Nighttime road work was active during data collection at six (6) of the 28 study locations. Extensive work activity was being performed in the closed lane(s) at three (3) of these six (6) locations, while localized bridge repair work was being performed at the remaining three (3) locations. Driver behavioral data was not collected in the proximity of the work activity area as the presence of workers and/or equipment introduces a potentially confounding effect on driver behavior.

Occasional nuances were encountered during the tracking of subject vehicles. In the event that a subject vehicle exited from the lane nearest to the drums prior to the end of the work zone, the survey vehicle driver would take reasonable measures to reposition the data collection vehicle behind the next closest vehicle, provided that a sufficient length of drums was still present. In the event that another vehicle merged between the data collection vehicle and the subject vehicle, the survey vehicle driver would make necessary adjustments and continue to follow the new subject vehicle instead.

Nighttime spot speed measurements were also performed at a randomly selected sample of work zone locations. Only freeway sites were utilized for the spot speed study. This was because freeway locations had consistent work zone speed limits (i.e., 60 mph when no workers were present and 45 mph when workers were present), while the work zone speed limits at arterial locations varied widely. The data collectors selected a suitable vantage point from an overpass located in the middle of a long section of channelizing drums. Spot speeds for randomly selected free-flowing vehicles (i.e., minimum 5 second headways) were then measured from the parked data collection vehicle using a radar gun. A minimum sample size of 100 vehicles per work zone was desired, but not always attainable due to either low traffic volumes or congestion.

7.4 Data Extraction

Videos were obtained from more than 1,200 total passes of the survey vehicle through the study work zones. The videos were immediately transferred to a computer for review upon return to the office. A team of trained technicians reviewed the videos to extract the necessary driver behavioral data. The reviewer first recorded basic information about the work zone conditions, including:

- Presence/absence of steady burn warning light on drums,
- Position of the drums (right or left),
- Approximate distance from the edge of the travel lane to the near edge of the drums,

- Horizontal alignment (straight or presence of one or more curves),
- Roadway type (arterial or freeway), and
- Presence/absence of roadway lighting.

Each pass through the work zone was reviewed and specific characteristics of the behavior for each subject vehicle was assessed. Both passenger and commercial vehicles were observed. The reviewer began assessing the behavior of the subject vehicle at the start of the lane or shoulder closure (i.e., after the taper). The behavior of the subject vehicle was continuously assessed throughout the entire section of the work zone. The following information was obtained for each subject vehicle during the review:

- Time spent in left-of-center lane position,
- Time spent in center lane position,
- Time spent in right-of-center lane position,
- Total tracking time, and
- Frequency of lane position changes (i.e., steering reversals).

Each MOE was computed such that equal weighting was given to all subject vehicles, regardless of the amount of time that each vehicle was tracked. The following example provides an explanation of the procedure by which each MOE was computed for a subject vehicle. A review of the video for one particular run found the subject vehicle to have spent the initial 9 seconds in the left-of-center position, the next 14 seconds in the center position, the next 15 seconds right-of-center, and the final 18 seconds in the center position. The total tracking time for this subject vehicle was 9+14+15+18 = 56 seconds. A total of three steering reversals were observed, as follows: 1) left to center, 2) center to right, and 3) right to center. Thus, the rate of steering reversals was computed as (3/56)*60 = 3.21 steering reversals per minute. The percent time spent in the center lane position was computed as (14+18)/56*100 = 57.14 percent. The channelizing drums were on the left-side of the lane. As such, the percent time spent in the position closest to the drums (i.e., left-of-center position) was (9/56)*100 = 16.07 percent. Similar calculations were repeated for each of the 1,236 vehicles included in the data set.

To provide consistent boundary definitions for each of the three lateral positions, the video reviewers were instructed to fixate their view on the position of the vehicle's license plate with respect to the center of the lane, provided that the license plate was centered on the vehicle. A vehicle was considered in center lateral position if any portion of the license plate was positioned over the center of the lane. A vehicle was considered to be positioned left or right of center if the entire license plate had shifted laterally beyond the center of the lane. Examples of the three lateral lane positions are shown in Figure 3. If the license plate was missing or off-center, the reviewer would utilize a secondary distinguishing feature on the center of the vehicle to determine the lateral position.

The amount of time spent in each lateral position was determined using the clock embedded in the video review window. All times were recorded

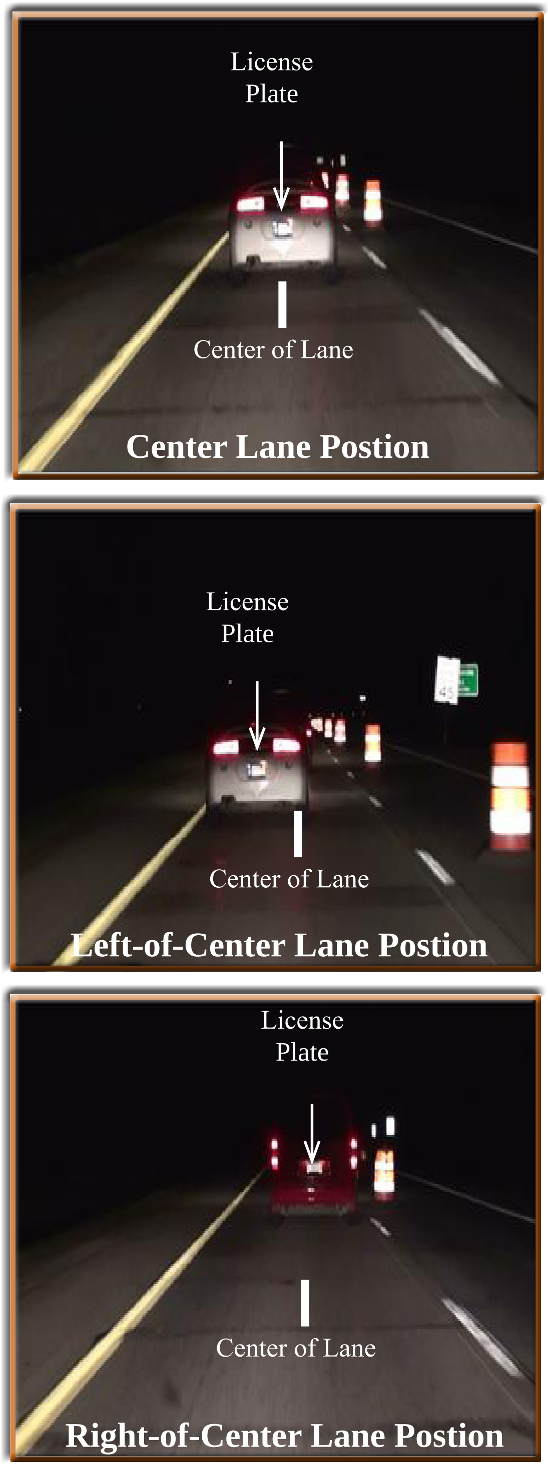

FIGURE 3. Example of Vehicular Lateral Lane Position Assessment

to the nearest second. The total tracking time was equal to the sum of the time spent in each of the three lateral positions. Data was collected only for vehicles that were tracked for a minimum of 10 seconds, as this was assumed as the minimum duration for which an accurate driver behavioral assessment could be made. After the videos were reviewed, the data was tabulated and coded into a single data set for analysis.

The videos were also utilized to extract information pertaining to the drum conditions as viewed during nighttime driving conditions. For each work zone location, the video for a single pass through the entire section of channelizing drums was reviewed and assessment of the condition of each drum was performed. If a work zone existed for both directions of travel, an assessment of drum condition was performed independently for each direction. The following damage condition assessment was performed for each channelizing drum observed in the videos:

- Scuffed,
- Dented,
- Knocked over/leaning,
- Missing, or
- Undamaged.

7.5 Results of Driver Behavior/Performance Studies

Sample data for each measure of effectiveness (MOE) was examined to determine the appropriate statistical analyses techniques by which to compare these data between those locations with and without steady burn warning lights.

Data expressed in terms of percentages are compared using the two-sample Z-test of proportions, which is calculated by the following general formula:

$$Z = \frac{P_{with} - P_{without}}{\sqrt{P_{total}(1 - P_{total})\left(\frac{1}{n_{with}} + \frac{1}{n_{without}}\right)}}$$

where:

Z = calculated Z-test statistic

P_{with} = the proportion corresponding to work zones with steady burn warning lights

$P_{without}$ = the proportion corresponding to work zones without steady burn warning lights

P_{total} = the proportion corresponding to all work zones combined

n_{with} = the sample size corresponding to work zones with steady burn warning lights

$n_{without}$ = the sample size corresponding to work zones without steady burn warning lights

If the calculated Z-statistic is greater than the critical value (±1.96) obtained from the cumulative standard normal distribution table, the difference in proportions is statistically different at the prescribed level of confidence (95 percent).

Those MOEs that are expressed in terms of a continuous random variable, such as a rate, are compared using a test of equality of means. Such tests include Student's t-Test, Welch's t-Test, or the Mann-Whitney U Test. The appropriate test among these is determined based upon whether the underlying data was normally distributed and whether the variances in the MOEs between the groups with and without steady burn warning lights are significantly different from one another. If the data was normally distributed with equal variances, Student's t-Test is appropriate; if the data was normally distributed with unequal variances, Welch's t-Test is appropriate; and if the data was not normally distributed, the Mann-Whitney U Test is appropriate. The normality assumption was assessed using the one-sample Kolmogorov-Smirnov test while the equality of variances was assessed using the Levene test for homogeneity of variance.

For those MOEs that may be influenced by other variables (in addition to the presence/absence of steady burn warning lights), the three aforementioned tests can be generalized by conducting ether a multi-factor analysis of variance (as an alternative to the tTest) or using the Kruskal-Wallis Test (as an alternative to the Mann-Whitney U Test). For example, the lane positioning data was analyzed using a multi-factor analysis of variance (ANOVA). Main factor effects and interactions of the main factor effects were included in the ANOVA. The independent factors entered into the ANOVA for each of the vehicle-tracking based MOEs (i.e., lateral placement, steering reversals) included:

- Steady burn warning light on drums (presence or absence),
- Horizontal alignment (straight or at least one horizontal curve),
- Drum side (left or right), and
- Drum distance from edge of the lane (less than 1-ft or at least 1-ft).

7.5.1 Lateral Positioning and Steering Reversals

Data for a total of 1,236 subject vehicles was extracted during the video review process, representing an average of 44.1 vehicles per study site. Of the total sample, 664 of these vehicles were observed in work zones without steady burn warning lights on drums, while the remaining 572 vehicles were observed in work zones with steady burn warning lights on drums. Thus, the minimum sample size requirement of 532 vehicular observations was achieved for each group. Passenger vehicles comprised 97.1 percent of the data set, while commercial vehicles made up the remaining 2.9 percent.

The presence of a steady burn warning light on the drums had very little impact on the center lane positioning tendencies of drivers. The average percent time spent in the center lane position was 38.41 and 38.95 for locations without and with steady burn warning lights on drums, respectively. This difference was not statistically significant. The results of this test are shown in Table 12 along with the results of the tests for the other MOEs.

TABLE 12. Summary of Driver Behavior Impacts Associated with Steady Burn Warning Lights on Drums

MEASURE OF EFFECTIVENESS	STEADY BURN WARNING LIGHT PRESENCE/ABSENCE	OVERALL SAMPLE MEAN	DIFFERENCE	SIGNIFICANT DIFFERENCE?
Percent of Time Spent in Center Lane Position	Drums Without Light	38.41	+ 0.54	No
	Drums With Light	38.95		
Percent of Time Spent in Lane Position Closest to Drums	Drums Without Light	8.37	+ 2.76	No
	Drums With Light	11.13		
Number of Steering Reversals per Minute	Drums Without Light	4.18	+ 0.75	Yes
	Drums With Light	4.93		

Notes: These data represent 664 vehicles observed in work zones without steady burn warning lights on drums and 572 vehicles observed in work zones with steady burn warning lights on drums. Statistical testing was performed at a 95-percent confidence level.

The presence of a steady burn warning light on the drums had a marginal impact on drivers' tendency to travel in close proximity to the drums. The average percent time spent in the position nearest to the drums was 8.37 and 11.13 for locations without and with steady burn warning lights on drums, respectively. This difference is not statistically significant.

The presence of a steady burn warning light on the drums had **a significant** impact on the rate of steering reversals. The average number of steering reversals per minute was 4.18 and 4.93 for locations without and with steady burn warning lights on drums, respectively.

The impacts of the other roadway or work zone related factors that were included in the analyses were also investigated for each of the three MOEs. Several statistically significant differences in the MOEs were observed and the ANOVA results for the additional factors are reported in Table 13. Note that these factors were tested simultaneously along with the presence or absence of the warning light factor in the ANOVA model. As such, these results control for the effects of each of the other factors.

TABLE 13. ANOVA Results for Additional Factors Related to the Roadway or Work Zone

FACTOR	LEVEL	NO. OF VEHICLES	PCT. TIME IN CENTER LANE POSITION		PCT. TIME IN LANE POS. CLOSEST TO DRUMS		STEERING REVERSALS PER MINUTE	
			MEAN	SIGNIFICANT DIFFERENCE?*	MEAN	SIGNIFICANT DIFFERENCE?*	MEAN	SIGNIFICANT DIFFERENCE?*
Horizontal Alignment	Straight	534	39.45	No	9.01	No	4.25	No
	Curved	702	38.06		10.14		4.74	
Drum Side	Left	708	44.01	Yes	12.89	Yes	4.97	Yes
	Right	528	31.48		5.31		3.93	
Drum Dist. from Edge of Lane	<1-ft	391	39.40	No	8.42	No	4.21	No
	≥1-ft	845	38.31		10.22		4.68	

* Based on a 95-percent confidence level

The drum side (e.g., left or right) factor was found to have a statistically significant impact on all of the lane positioning MOEs. Drums positioned on the left side elicited a significantly higher rate of both center lane positioning and positioning closest to the drums compared to drums on the right side. This is likely due to drivers possessing greater confidence in the ability to judge their vehicle's distance from the drums accurately when the drums are positioned on the left side of the vehicle. Drivers are less confident of their positioning when the drums are positioned on the right, resulting in drivers "shying" away from the drums. Steering reversals occurred at a higher rate when drums were positioned on the left side compared to the right side. Neither the horizontal alignment of the roadway nor the drum distance from the edge of the lane had a significant impact on any of the three lane positioning related MOEs, although slight differences were observed.

7.5.2. Vehicular Speeds

Spot speed studies were conducted at seven locations without steady burn warning lights and six locations with steady burn warning lights. These sites included various combinations of shoulder and lane closures and different work zone lengths. All spot speed studies were conducted during nighttime conditions using a radar gun. Data was collected covertly by an observer who was positioned above the roadway on a freeway overpass, at a location that was approximately half-way through a series of channelizing drums in a particular work zone. Free-flowing vehicles (i.e., minimum headways of 5 seconds) were selected at random and, if the work zone was operating in both directions, speed data was collected in both directions. Data was only collected under dry pavement conditions and only in work zones where no work was being performed at the time of the study. Only freeway sites were utilized for the spot speed study because these locations had consistent work zone speed limits (i.e., 60 mph when no workers were present) while the work zone speed limits at arterial locations varied widely.

A comparison of the resultant speed data between these groups of locations showed that the median, mean, and 85th percentile speeds tended to be an average, between 3.1 and 3.9 mph higher in the work zones where steady burn warning lights were utilized. Work zones on freeways without steady burn warning lights on the drums had nighttime median, mean, and 85th percentile speeds of 59.5 mph, 57.8 mph and 63.8 mph, respectively. Work zones on freeways with steady burn warning lights on the drums exhibited a median, mean, and

85th percentile speed of 63.4 mph, 60.9 mph, and 66.9 mph, respectively. These speed differences between the two groups (i.e., drums with lights vs. drums without lights) were **statistically significant**. In addition to comparing the differences in speed characteristics, the average standard deviation (or variance) in travel speeds were also compared between the two groups. The standard deviation of travel speeds was slightly higher at the locations without steady burn warning lights (standard deviation of 5.9 mph compared to 5.7 mph at locations with steady burn warning lights), although this difference was not statistically significant. The summary of the speed data is shown in Table 14.

TABLE 14. Spot Speed Measurements at Work Zones on Freeways

SITE	WARNING LIGHTS ON DRUMS	WORK ZONE POSTED SPEED LIMIT (MPH)*	NO. OF SPEED MEAS.	MEAN SPEED (MPH)	MEDIAN SPEED (MPH)	85TH % SPEED (MPH)	STD DEV (MPH)
US-131 (Center to Flowerfield)	No	60/45	106	57.9	55.8	61.4	5.9
I-94 (Sergeant to Race)	No	60/45	100	59.6	57.3	61.6	5.0
I-196 (Fuller to M-37)	No	60/45	101	54.0	50.5	57.0	4.4
I-94 (10 Mile to 12 Mile)	No	60/45	101	63.2	60.9	66.5	5.4
I-696 (I-94 to Hayes)	No	60/45	100	60.3	58.3	64.7	6.6
I-275 (Sibley to Huron River)	No	60/45	100	59.2	57.7	63.3	4.8
I-75 (MM5 to MM11)	No	60/45	100	62.6	60.6	65.7	3.7
LOCATIONS WITHOUT STEADY BURN WARNING LIGHTS			**708**	**59.5**	**57.8**	**63.8**	**5.9**
I-94 (US 131 to Westnedge)	Yes	60/45	100	63.3	60.2	65.5	4.3
I-94 (Baker to Jackson Co.)	Yes	60/45	100	60.1	58.1	62.5	5.7
I-96 (48th to 68th)	Yes	60/45	101	68.0	65.3	70.2	4.0
I-94 (US-12 to I-94 BR)	Yes	60/45	106	65.4	62.0	68.5	4.3
M-59 (Mound to Van Dyke)	Yes	60/45	100	61.1	59.2	65.3	6.0
M-59 (Adams to Dequindre)	Yes	60/45	100	62.2	60.4	66.2	5.6
LOCATIONS WITH STEADY BURN WARNING LIGHTS			**607**	**63.4**	**60.9**	**66.9**	**5.7**

* Workers not-present/workers present

7.5.3 Drum Condition

The nighttime drum condition assessment found relatively minor differences between the percent of damaged drums at work zone locations with versus without steady burn warning lights on drums. Work zone locations without steady burn warning lights had 14.1 percent of the drums damaged or missing, while locations with steady burn warning lights had 16.1 percent of the drums damaged or missing. The z-test of proportions showed that the difference between the two groups was statistically significant at a 95 percent level of confidence. The drum condition assessment data is shown in Table 15.

TABLE 15. Nighttime Drum Condition Assessment

SITE	DRUM SIDE	WARNING LIGHTS ON DRUMS	DAMAGED/ MISSING		UNDAMAGED		TOTAL DRUM COUNT
			COUNT	%	COUNT	%	
I-196 (M-37 to Fuller)	Left	No	22	9.0%	223	91.0%	245
I-275 (I-94 to Monroe Co. Line)	Left	No	136	18.8%	588	81.2%	724
I-75 (675 to M-84)	Right	No	27	6.2%	410	93.8%	437
I-75 (MM1 to MM3)	Right	No	9	17.6%	42	82.4%	51
I-75 (Nadeau to I-275)	Right	No	20	37.0%	34	63.0%	54
I-75 (Rouge River Bridge)	Left	No	8	9.1%	80	90.9%	88
I-94 (10-mile to 12-mile)	Left	No	10	11.0%	81	89.0%	91
M-1 (Chandler to Tuxedo)	Right	No	22	13.7%	139	86.3%	161
M-39 (I-94 to I-75)	Left	No	17	12.1%	124	87.9%	141
M-40 (St. Joseph to Chicago)	Both	No	31	10.0%	278	90.0%	309
M-59 (Woodward to I-75)	Right	No	23	28.4%	58	71.6%	81
US-12 (Outer Dr. to Brady)	Right	No	40	29.4%	96	70.6%	136
US-131 (Center to Flowerfield)	Right	No	27	19.0%	115	81.0%	142
US-24 (12-mile to 13-mile)	Left	No	31	41.3%	44	58.7%	75
US-24 BL (Chavez to Woodward)	Left	No	11	9.3%	107	90.7%	118
I-75 (LaPlaissance to Sandy Creek)	Left	No	0	0.0%	69	100.0%	69
I-94 (Sergeant to Race)	Right	No	3	1.7%	178	98.3%	181
LOCATIONS WITHOUT STEADY BURN WARNING LIGHTS			**437**	**14.1%**	**2,666**	**85.9%**	**3,103**
I-196 (71st to 118th)	Left	Yes	36	24.0%	114	76.0%	150
I-675 (Tittabwassee to I-75)	Both	Yes	59	23.6%	191	76.4%	250
I-696 (I-94 to Hayes)	Left	Yes	23	22.8%	78	77.2%	101
I-94 (Baker to Jackson Co.)	Both	Yes	43	8.5%	465	91.5%	508
I-94 (US-12 to I-94 BR)	Left	Yes	112	18.0%	510	82.0%	622
I-94 (US-131 to Westnedge)	Left	Yes	3	1.8%	162	98.2%	165
I-94 BR (Fair to 2nd)	Right	Yes	4	2.9%	136	97.1%	140
I-96 (48th to 68th)	Left	Yes	117	20.6%	450	79.4%	567
I-96 (Wyoming to Grand)	Right	Yes	38	24.1%	120	75.9%	158
M-17 (Carpenter to Golfside)	Right	Yes	5	4.9%	97	95.1%	102
M-43 (Pine to Walnut)	Left	Yes	31	38.3%	50	61.7%	81
M-59 (Ryan to Adams)	Both	Yes	10	6.9%	134	93.1%	144
LOCATIONS WITH STEADY BURN WARNING LIGHTS			**481**	**16.1%**	**2,507**	**83.9%**	**2,988**
Calculated Z-Statistic for Difference in Proportions =			**2.20**				
Critical Z-Statistic =			**1.96**				
Significant Difference?			**Yes**				

8.0 LUMINANCE EVALUATION FOR DRUMS WITH AND WITHOUT STEADY BURN WARNING LIGHTS

In addition to examining the impacts of steady burn warning lights on driver performance, additional research was undertaken to explore the relative differences in the nighttime visual characteristics between drums with and without steady burn warning lights used in a variety of work zone scenarios. The objectives of this research are as follows:

- Examine nighttime luminance characteristics of commonly used work zone drums with and without steady burn warning lights in a controlled environment.
- Examine nighttime luminance characteristics of work zone channelizing drums with and without steady burn warning lights used in several work zones scenarios within the State of Michigan.

It was important to select a photometric unit of measurement that describes the overall "brightness" of the drum including both the retroreflective sheeting and a steady burn warning light attached to the drum. Luminance was determined to be the most appropriate unit of measurement for comparing the relative brightness of drums with and without steady burn warning lights as it describes the physical measure of brightness regardless of whether the light is reflected from the sheeting or emitted from the steady burn warning light. Please refer to the literature review for further description of luminance and other related photometric characteristics. It is again important to note that retroreflectivity is not an appropriate unit of measurement for determining the brightness of drums with steady burn warning lights as it is only applicable to reflective surfaces and not to light emitting sources.

All steady burn warning lights on drums observed in the luminance evaluations were of the 360-degree type. The instrument used for all luminance measurements was a Konica/Minolta LS-100, which utilizes a flareless fixed aperture single-lens-reflex optical system with a 1 degree acceptance angle.

8.1 Sample Size Determination

Sample size calculations were conducted in order to determine a sufficient amount of luminance data to be collected for the purposes of both the controlled and field evaluations. The following formula was used to estimate the target number of luminance measurements within each of the two groups (with and without lights) that would be necessary in order to detect a specified difference in luminance between the two groups:

$$n = \frac{(z_{\alpha/2})^2(\sigma_1^2 + \sigma_2^2)}{\delta^2}$$

where:

n = number of vehicles to be observed in each group (i.e., drum lights versus no drum lights)

$z_{\alpha/2}$ = standard normal value assuming a significance level of α percent

d = mean difference in luminance between group 1 and group 2

σ_1 = standard deviation of luminance among group 1

σ_2 = standard deviation of luminance among group 2

Using sample data from one particular location and assuming values of 0.05 for α (selected based upon standard statistical practices), the minimum number of luminance measurements required to detect a statistically significant difference between the two groups can be determined. The following sample estimates were utilized to determine sample sizes for both the field luminance data and the controlled (parking lot) luminance data:

- Mean parking lot luminance = 4.54 cd/m^2
- Standard deviation parking lot luminance = 0.32 cd/m^2
- Mean field-measured luminance = 5.06 cd/m^2
- Standard deviation field-measured luminance = 2.09 cd/m^2

Table 16 displays the number of luminance measurements that must be obtained within each group in order to detect specific differences in each of the three MOEs, based on the assumed sample estimates. Measurements of luminance in a controlled environment produce very little variability in the measurements for each drum, thereby leading to a very small minimum sample size requirement for a given drum scenario. For example, only 3 measurements are required to detect a 0.5 cd/m^2 difference in luminance when measured in a controlled environment. Conversely, luminance measurements tend to be more variable in a field setting due to external factors, such as the amount of ambient light and the condition of the drums. The sample data for the field luminance study indicate that approximately 34 field measurements must be performed per group in order to detect a difference of 1.0 cd/m^2 while 134 field measurements per group will allow for the detection of a difference of 0.5 cd/m^2 at a 95 percent confidence level.

TABLE 16. Sample Size Calculations for Study Measures of Effectiveness

STUDY SETTING	NUMBER OF MEASUREMENTS PER GROUP REQUIRED TO DETECT DIFFERENCE IN LUMINANCE OF BETWEEN 0.5 AND 2.0 cd/m^2			
	0.5 cd/m^2	1.0 cd/m^2	1.5 cd/m^2	2.0 cd/m^2
Parking Lot (Controlled)	3	1	1	1
Field Measured	134	34	15	8

Based on the minimum sample size estimates shown in Table 16 the researchers determined that a minimum of 3 luminance measurements would be conducted for each drum scenario evaluated in the parking lot study. This would allow for sufficient precision to detect a difference of 0.5 cd/m^2 in luminance. For the field study, a minimum of 134 drum luminance measurements would be obtained for locations both with and without steady burn warning lights on the drums to provide a similar level of precision (0.50 cd/m^2).

8.2 Controlled Evaluation of Drum Luminance

To validate the results of the field study, the research team performed a nighttime luminance measurement of several drum scenarios at the top of a large parking structure on the campus of Wayne State University. This allowed for the presence/absence of a steady burn warning light to be evaluated in a controlled environment from a stationary vehicle. Three sample drums were utilized in this evaluation, each with a different sheeting type and/or condition. The sheeting on each of these drums met or exceeded MDOT's in-service work zone sheeting standards. All drums were MDOT standard size, measuring 36 inches tall with a top diameter of 18 inches. The 360 degree amber steady burn warning light was 4.25 inches tall (exclusive of the base) and 3.25 inches in diameter. Including the non-illuminated base, the light added 10 inches to the height of the drum.

Drum luminance was measured under several predefined conditions, which included:

- Sheeting Type
  - New high intensity sheeting
  - Used high intensity sheeting
  - Used microprismatic sheeting
- Drum lighting condition
  - Steady burn warning light on drum
  - No light on drum
- Lateral offset to the near edge of the drum from the center of the vehicle
  - 6 ft right (represents 0-ft offset from the right edge of a 12-ft lane)
  - 10 ft right (represents 4-ft offset from the right edge of a 12-ft lane)
- Vehicles
  - 2002 Oldsmobile Alero
  - 2008 Ford E-Series Cargo Van

A full factorial ANOVA was performed, meaning that each drum condition was measured under each of the other conditions. Thus, a total of 3*2*2*2 = 24 drum scenarios were measured during the controlled evaluation.

Prior to data collection, the first vehicle was carefully positioned at a marked location with the center of the vehicle aimed straight ahead to ensure consistent headlamp alignment between the two vehicles. The vehicle was not moved until all measurement scenarios had been completed. Consequently, each of the predefined drum scenarios was formed by moving or modifying the drums at marked locations. The vehicle's low beam headlamps were utilized during all measurements.

All drum scenarios were measured from the passenger seat of the vehicle at a distance of 200-ft. The 200-ft measurement distance was utilized as it represented the approximate field measurement distance, which corresponds to the distance that the drum (and steady burn warning light, if attached) maximized the 1-degree aperture measurement circle on the luminance meter. To provide consistency between measurements for drums with and without steady burn warning lights, the measurement circle was positioned identically for all drums, regardless of whether or not a light was attached. Three drum luminance measurements were recorded for each scenario after which the next scenario was prepared. Figure 4 provides photographs of various drums with and without lights viewed at a distance of 200-ft.

To ensure a consistent level of background luminance, the drum technician wore black clothing and stood behind the drum during measurement. It should be noted that some amount of ambient lighting was present for all measurements, as it was not possible to extinguish or effectively block the parking lot lighting as can be seen in Figure 4. However, the drums were positioned as far away from the light sources as possible and were approximately 50 feet from the base of the nearest lamp post. As the drums were placed in identical positions during each test, the amount of ambient light was constant between each measurement for all scenarios.

(a) Used prismatic drum

(b) Used high intensity drum

FIGURE 4. Example Drum Scenarios Used in the Controlled Evaluation (Photographs taken from the 2002 Olds Alero at 200-ft with a 6-ft lateral offset)

8.3 Results of Controlled Evaluation

Each of the 24 drum scenarios were measured three times during the controlled evaluation for a total of 72 luminance measurements. The descriptive statistics for nighttime drum luminance measured during the controlled evaluation are shown in Table 17.

TABLE 17. Descriptive Statistics for Controlled Luminance Evaluation

LATERAL OFFSET	SHEETING TYPE	STEADY BURN WARNING LIGHT	MEAN (cd/m^2)	STANDARD DEVIATION (cd/m^2)	NUMBER OF MEASUREMENTS
6-ft right	New High Intensity	Drums Without Light	9.28	0.13	6
		Drums With Light	9.22	0.40	6
		ALL	9.25	0.29	12
	Used High Intensity	Drums Without Light	5.22	0.97	6
		Drums With Light	5.53	0.88	6
		ALL	5.38	0.90	12
	Used Prismatic	Drums Without Light	14.12	2.15	6
		Drums With Light	14.72	1.45	6
		ALL	14.42	1.77	12
10-ft right	New High Intensity	Drums Without Light	7.20	0.31	6
		Drums With Light	7.48	0.25	6
		ALL	7.34	0.31	12
	Used High Intensity	Drums Without Light	4.09	0.51	6
		Drums With Light	4.24	0.54	6
		ALL	4.17	0.51	12
	Used Prismatic	Drums Without Light	11.81	1.59	6
		Drums With Light	12.21	1.34	6
		ALL	12.01	1.42	12
ALL	New High Intensity	Drums Without Light	8.24	1.11	12
		Drums With Light	8.35	0.96	12
		ALL	8.30	1.02	24
	Used High Intensity	Drums Without Light	4.66	0.94	12
		Drums With Light	4.88	0.97	12
		ALL	4.77	0.94	24
	Used Prismatic	Drums Without Light	12.97	2.17	12
		Drums With Light	13.47	1.87	12
		ALL	13.22	2.00	24

Notes: The data have been combined for the two vehicles used in the study.
Average background luminance = 0.116 cd/m^2

Again, all luminance measurements were taken through the windshield from the front passenger seat of a parked vehicle at a distance of 200-ft from the drum. For display purposes, the luminance data in Table 17 have been combined for the two vehicles used in the study.

The luminance data from the controlled evaluation were analyzed using a full-factorial analysis of variance (ANOVA). All statistical inferences were based on a 95 percent level of confidence. The independent variables included:

- Presence/absence of steady burn warning light,
- Sheeting type,
- Drum lateral offset, and
- Vehicle type.

The ANOVA model had an adjusted R2 of 0.994. The ANOVA results indicated that drum light, sheeting type, lateral offset, and vehicle type each had a statistically significant impact on drum luminance at a 95 percent confidence level. Similar to the field evaluation results, sheeting type had, by far, the most significant impact on luminance, as indicated by the relative magnitude of the F-statistic. The average luminance of the prismatic drum (considering all scenarios) was 4.92 cd/m2 (59.3 percent) greater than the new high intensity drum and 8.45 cd/m2 (177.1 percent) greater than the used high intensity drum. Steady burn warning light presence had relatively little impact on luminance. The addition of a steady burn warning light to the drum increased the average luminance by 0.11 cd/m2 (1.3 percent) and 0.22 cd/m2 (4.7 percent) for the new and used high intensity drums, respectively and 0.50 cd/m2 (3.9 percent) for the prismatic drum. Although small in magnitude, the luminance increases associated with the steady burn warning light were statistically significant for each of the sheeting types. However, when compared to each of the other evaluated factors, including sheeting type, drum offset, and vehicle type, the presence of a steady burn warning light was found to have the smallest relative impact on drum luminance. The lateral offset of the drum also significantly impacted luminance, as the average luminance decreased by 1.56 cd/m2 (21.3 percent) for the two high intensity drums and 2.41 cd/m2 (16.7 percent) for the prismatic drums when moved from a 6-ft lateral offset to a 10-ft lateral offset.

8.4 Field Evaluation of Drum Luminance

The purpose of the field evaluation was to determine differences in the field-measured luminance levels of work zone drums with and without steady burn warning lights when used as channelizing devices. Fifteen work zones in 10 counties throughout Michigan were randomly selected for use in this evaluation. All of the work zones utilized in the study were on limited-access freeways under the jurisdiction of the Michigan Department of Transportation. The work zones selected for use in this study collectively represented a broad range of work zone scenarios, including:

- Drums with and without steady burn warning lights,
- Drums with high intensity sheeting and drums with prismatic sheeting,
- Locations with roadway lighting and locations with no roadway lighting,
- Locations with drums on the left and locations with drums on the right, and
- Urban and rural environments.

Table 18 presents the characteristics of the work zones utilized in this study. The field luminance measurements were performed between the hours of 10:30 PM and 4:00 AM on dry nights in late-May and early-June of 2010. The luminance meter operator was seated in the front passenger seat with the meter mounted on a tripod to ensure stability during measurement. All measurements were performed from the same 2010 Toyota Corolla using only the low beam headlamps. At least 20 luminance measurements were obtained from randomly selected individual drums at each of the 15 study work zones. Depending on the length of the work zone and traffic volumes, multiple passes through the work zone were sometimes necessary to obtain the target sample size.

TABLE 18. Characteristics of Work Zone Sites for Field Study of Luminance

SITE	BEGIN AND END	COUNTY	STEADY BURN WARNING LIGHTS ON DRUMS	ROADWAY LIGHTING
M-59	Ryan to Adams	Oakland	Yes	Yes
M-59	Woodward to I-75	Oakland	No	Yes
I-96	Grand to Southfield	Wayne	Yes	Yes
I-275	I-94 to Monroe Co. Line	Wayne	No	No
I-75	LaPlaisance to Sandy	Monroe	No	No
I-94	US 131 to Westnedge	Kalamazoo	Yes	No
US-131	Center to Flowerfield	Kalamazoo	No	No
I-94	Baker to Jackson Co. Line	Washtenaw	Yes	No
I-94	Sergeant to Race	Jackson	No	No
I-75	Rouge River Bridge	Wayne	No	Yes
I-96	48th to 68th	Ottawa	Yes	No
I-196	Fuller to M-37	Kent	No	No
I-94	US-12 to I-94 BR	Berrien	Yes	No
I-94	10-Mile to 12-Mile	Macomb	No	Yes
I-696	I-94 to Hayes	Macomb	No	Yes

Each pass began several hundred feet upstream of the work zone. The driver would proceed towards the work zone, positioning the vehicle in the travel lane closest to the channelizing drums. After entering the work zone, the driver would decelerate to a speed at or below 20 mph. The driver carefully monitored the rear-view mirror for vehicles approaching from behind. If an approaching vehicle was detected, the driver would pull onto the shoulder or behind the barrels (if possible) or accelerate to a safe operating speed. If the traffic volumes at a particular site were such that it was generally unsafe to travel at such low speeds, the luminance measurements were not performed for that site at that time.

Luminance measurements were performed by identifying a single drum at random that was several hundred feet downstream from the vehicle. The targeted drum was tracked through the eyepiece until the drum, including any steady burn light affixed on top, touched the top and bottom of the 1-degree aperture measurement circle within the eyepiece of the luminance meter. It was at this moment that the trigger was released and the final measurement was recorded. To provide consistency between measurements, the measurement circle was positioned identically for all drums, regardless of whether or not a steady burn light was attached to the top of the drum. Readings were discarded if stray light from opposite direction vehicular headlamps, ambient lighting sources, or other drums were in the target measurement area when the reading was taken. Based on the fixed 1-degree aperture circle of the luminance meter and the drum height, the measurements were taken when the vehicle was approximately 200 feet upstream of the targeted drum. Each measurement was verbally recorded into the microphone of a high definition video camera that had been positioned in the center console of the vehicle. The video camera provided both an audible record of the luminance readings and a visual record of the entire work zone scene during each measurement. The video was also utilized to visually identify whether the study location utilized drums with high intensity sheeting or prismatic sheeting, as this characteristic is apparent to the naked eye. Figures 5a and 5b provides examples of the luminance measurement area at a distance of approximately 200 feet for drums with and without steady burn warning lights.

Figure 5a. Luminance measurement of drums without steady burn warning lights, unlit freeway, prismatic sheeting

Figure 5b. Luminance measurement of drums without steady burn warning lights, unlit freeway, high intensity sheeting

Luminance data was only collected for continuous sections of channelizing drums that were parallel to the travel lane on level, straight sections of roadway. All luminance data was measured from the travel lane that was adjacent to the drums. Drums were positioned no more than 4-ft from the edge of the travel lane. To help eliminate potentially biasing factors, luminance measurements were not taken under any of the following conditions:

- Taper sections – Readings were only obtained on drums that were parallel to the travel lane to ensure that the headlight beams were consistently striking the drums at a similar angle;
- Roadway segments with excessive horizontal or vertical curvature – Changes in horizontal or vertical alignment would also impact the angle at which the headlights reflect off of the drums, resulting in higher or lower luminance measurements as a result;
- One or more vehicles were closely following the data collection vehicle – If another vehicle was traveling closely behind the data collection vehicle, stray light from the trailing vehicle's headlamps may tend to inflate the subsequent luminance measurements;
- Opposing vehicles were present and no barrier existed to block the headlamp illumination – Measurements were also not taken if a vehicle was coming from the opposite direction and its headlights were impacting the luminance

measurements. Measurements were only taken with opposing traffic present if a median barrier of sufficient height was available to block this traffic's headlamps;

- Rough pavement sections – Measurements were not obtained on rough pavement sections as the luminance meter could not be appropriately stabilized sufficiently in order to obtain consistent measurements on such sections;
- The steady burn warning light was missing, burned out, or malfunctioning (only for drums with lights) – If the steady burn warning light was not functioning properly, the luminance measurements would be biased; or
- Drums were closely spaced such that individual drums could not be isolated in the measurement target circle on the meter – If consecutive drums were spaced too tightly together, it was not always possible to isolate only the target drum. In such cases, the second drum may result in an artificially high luminance measurement.

8.5 Results of Field Evaluation

The field evaluation yielded a total of 372 nighttime drum luminance measurements obtained from the 15 work zone locations – an average of 24.8 measurements per location. Luminance measurements were recorded for randomly selected 287 drums with high intensity sheeting and 85 drums with prismatic sheeting. Drums with steady burn warning lights accounted for 145 of the luminance measurements, while drums without the lights accounted for the remaining 227 measurements. Again, all field luminance measurements were performed from the passenger seat of a slow moving vehicle at a distance of approximately 200-ft away from the drum. The descriptive statistics for field measured luminance data are shown in Table 19.

TABLE 19. Descriptive Statistics for Field Luminance Evaluation

SHEETING TYPE	ROADWAY LIGHTING	STEADY BURN WARNING LIGHT	MEAN (cd/m²)	STANDARD DEVIATION (cd/m²)	NUMBER OF MEASUREMENTS
High Intensity	Segments Without Roadway Lighting	Drums Without Light	5.56	1.74	89
		Drums With Light	5.00	2.19	69
	Segments With Roadway Lighting	Drums Without Light	4.22	1.98	86
		Drums With Light	5.68	2.35	43
	ALL SEGMENTS	Drums Without Light	4.90	1.97	175
		Drums With Light	5.26	2.26	112
		ALL DRUMS	5.04	2.09	287
Prismatic	Segments Without Roadway Lighting	Drums Without Light	14.69	4.27	41
		Drums With Light	15.05	3.22	24
	Segments With Roadway Lighting	Drums Without Light	17.62	4.46	11
		Drums With Light	15.87	5.79	9
	ALL SEGMENTS	Drums Without Light	15.31	4.43	52
		Drums With Light	15.27	3.99	33
		ALL DRUMS	15.30	4.24	85

The field measured luminance data was analyzed using a full-factorial analysis of variance (ANOVA). The analysis was performed using PASW (formerly SPSS) version 18 using the General Linear Model command [*37*]. All statistical inferences were based on a 95 percent level of confidence. The independent variables included:

- Presence/absence of steady burn warning light,
- Sheeting type, and
- Presence/absence of roadway lighting.

The ANOVA model had an adjusted $R^2 = 0.727$. Sheeting type and roadway lighting each had a statistically significant impact on drum luminance at a 95 percent confidence level. Of the statistically significant variables, sheeting type had the most significant impact on drum luminance, as indicated by the magnitude of the F-statistic.

The presence of a steady burn warning light **did not have a statistically significant impact** on luminance for either the prismatic or drums with high intensity sheeting. High intensity drums had an average luminance of 4.90 cd/m^2 and 5.26 cd/m^2 for drums without and with steady burn warning lights, respectively. Prismatic drums had an average luminance of 15.31 cd/m^2 and 15.27 cd/m^2 for drums without and with steady burn warning lights, respectively. Thus, drums with steady burn warning lights had average luminance values that were 0.36 cd/m^2 (7.3 percent) greater and 0.04 cd/m^2 (0.3 percent) lower than drums without steady burn warning lights for high intensity drums and prismatic drums, respectively. The presence of roadway lighting had a relatively small impact on luminance, although this factor was found to be statistically significant.

8.6 Comparison of Controlled and Field Evaluations of Luminance

Another objective of this research was to compare luminance measured within actual work zones to luminance measured within a controlled environment. Although measurements performed in a controlled environment present a safer and more efficient data collection procedure, there was uncertainty as to the transferability of these luminance measurements to actual field conditions. The mean and 95 percent confidence intervals for the field-measured and controlled-measured luminance data separated by sheeting type and steady burn warning light presence are displayed in Figure 6. It shows some similarities between the measurements performed in the field compared to the controlled environment for the high intensity and prismatic drums. However, the new high intensity drum clearly displayed a higher mean luminance compared to the field measured high intensity drums. This was not unexpected, as new drums are generally not representative of a typical in-service drum.

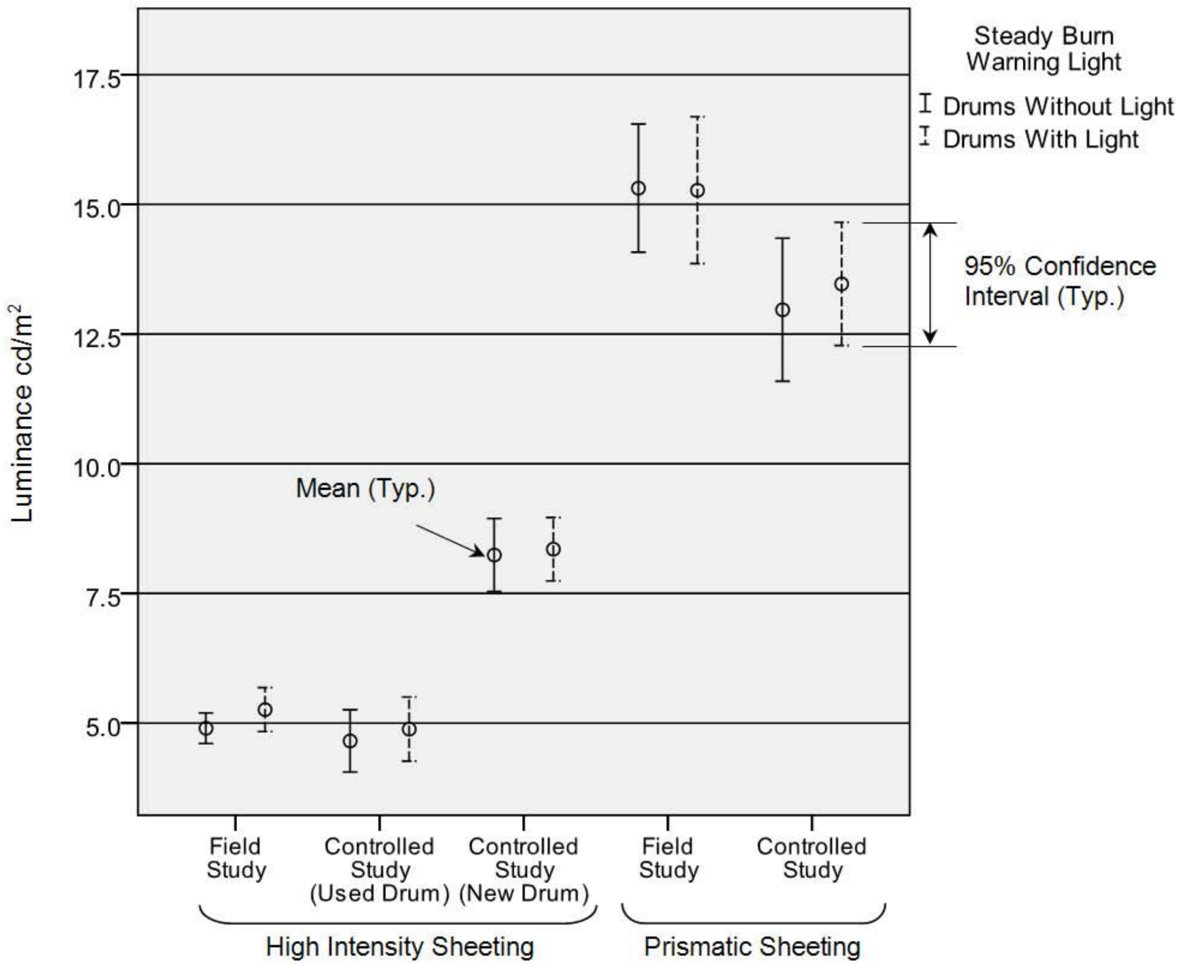

FIGURE 6. Mean and 95 Percent Confidence Interval for Drum Luminance by Evaluation Type, Sheeting Type, and Steady Burn Warning Light Presence

An independent sample t-test was performed to determine the statistical significance of the differences observed between drum luminance measured in the field versus in the controlled environment. Separate t-tests were performed for the high intensity drums and the prismatic drums. Based on the reasons stated previously, the new high intensity drum used during the controlled evaluation was excluded from the t-test. The results of the t-test are shown in Table 20.

TABLE 20. T-Test Results for Luminance Measured During the Field Evaluation Versus the Controlled Evaluation

SHEETING MATERIAL	EVALUATION	NUMBER OF MEASUREMENTS	MEAN (cd/m^2)	STANDARD DEVIATION (cd/m^2)	ABSOLUTE DIFFERENCE IN MEANS (cd/m^2)	P-VALUE	ARE THE MEANS SIGNIFICANTLY DIFFERENT?*
High Intensity	Field	287	5.04	2.09	0.27	0.243	No
	Controlled	24	4.77	0.94			
Prismatic	Field	85	15.30	4.24	2.08	0.001	Yes
	Controlled	24	13.22	2.00			

*Based on a 95 percent confidence level

The t-test confirmed that no significant difference exists between luminance measured in the controlled environment versus in the field for the high intensity drums. The average luminance for high intensity drums was 0.27 cd/m^2 (5.7 percent) greater when measured in the field versus the controlled environment. However, the average prismatic drum luminance was statistically significantly larger (2.08 cd/m^2 [15.7 percent]) when measured in the field versus the controlled environment.

9.0 COST ANALYSIS

The intent of this analysis is to examine the costs associated with the use of drums with and without steady burn warning lights. In order to accomplish this, the costs of materials, installation, maintenance, and disposal are considered.

Cost assumptions are made based upon:

"The spacing between cones, tubular markers, vertical panels, drums, and barricades should not exceed a distance in feet equal to 1.0 times the speed limit in mph when used for taper channelization, and a distance in feet equal to 2.0 times the speed limit in mph when used for tangent channelization."

MUTCD Section 6F.63

As per the MUTCD criteria shown above, the total number of drums used in a site depends on the posted speed limit. At work zone locations within the State of Michigan, the posted speed limits generally vary from 30 mph to 45 mph where workers are present. Table 21 provides details of the number of drums required for a typical one-mile long closure of a 12-ft lane, including the adjacent 12-ft shoulder, for various speed limits under such conditions. These are based upon the MUTCD criteria and, in general, MDOT work zones are designed in a more conservative nature.

TABLE 21. Drums Required Per Mile of Tangent Section Based Upon Speed Limit

WORK ZONE SPEED LIMIT	SHOULDER TAPER	TRANSITION TAPER	TANGENT PER MILE	DOWNSTREAM TAPER	TOTAL DRUMS
30	3	6	88	5	102
35	4	7	76	5	92
40	4	8	66	5	83
45	5	12	59	5	81

For example, in freeway tangent segments, drums are frequently spaced at 50-ft intervals while the MUTCD allows for a maximum spacing of 90 ft at 45 mph. As such, these values are conservative from a cost comparison standpoint.

MDOT's unit prices were used to determine the average cost of materials for drums with and without steady burn warning lights. These pay item costs are provided in Table 22.

TABLE 22. Drum Costs

DESCRIPTION	PAY ITEM	UNIT PRICE (EACH UNIT)
Plastic Drum, High Intensity, Lighted	8120102	$46.00
Plastic Drum, High Intensity	8120100	$20.00

Based solely upon drum costs, those drums with steady burn warning lights are 130 percent greater on a per-unit basis. In addition, drums with steady burn warning lights require additional maintenance to replace the lights, as well as the batteries. Data provided through various vendors in the state of Michigan indicate that the typical battery life for steady burn warning lights is 6 to 8 weeks, with each battery costing approximately two dollars. Conservatively assuming an 8-week battery life, additional maintenance costs of $13.00 will be incurred on an annual per-drum basis for battery replacement. Additional costs will be incurred for the replacement of either type of drums due to damage caused by vehicle collisions. The results of the field drum condition survey showed that 2.3 percent of drums were dented, knocked down, or missing in those work zones that utilized steady burn warning lights. Work zones without steady burn warning lights exhibited 3.1 percent of drums were in similar condition. For analysis purposes, it was assumed that this percentage of drums would require replacement on an annual basis. Further assumptions were made regarding the resources required for drum installation, maintenance, and replacement. The underlying assumptions for the cost analysis are shown in Table 23.

TABLE 23. Assumptions for Cost Analysis

ASSUMPTIONS	DRUMS WITHOUT STEADY BURN WARNING LIGHTS	DRUMS WITH STEADY BURN WARNING LIGHTS
Service Life of Drums (years)	2	2
Cost of Drums (dollars) each	20	46
Time Required for Drum Installation (person-hrs per mile)	3	3
Time Required for Replacement of Drums (person-hrs per drum)	0.5	0.5
Rate of Drums to be Replaced (percent)	3.1	2.3
Time Required for Replacement of Lights/ Batteries (person-hrs per mile)	N/A	3
Service Life of Steady Burn Warning Lights (months)	N/A	12
Cost of Steady Burn Warning Lights (dollars)	N/A	15
Service Life of Batteries (weeks)	N/A	8
Cost of Batteries (dollars)	N/A	2
Loaded Hourly Cost Rate (dollars per person-hr)	20	20
Vest Charge Rate (percent)	5	5

Using these cost data, Table 24 provides details of the life cycle equivalent uniform annual costs (EUAC) per mile of tangent section required for drums both with and without steady burn warning lights over the assumed 2-year service life with a 5 percent vest charge rate. On a per mile basis, the material and battery maintenance costs (EUAC) are between \$5,744 and \$7,157 greater per year for drums with steady burn warning lights.

TABLE 24. Typical Material and Maintenance Equivalent Uniform Annual Costs Per Mile of Tangent Section for Drums by Speed Limit

WORK ZONE SPEED LIMIT	WITHOUT STEADY BURN WARNING LIGHTS	WITH STEADY BURN WARNING LIGHTS
30	$2,342	$9,499
35	$2,124	$8,608
40	$1,928	$7,806
45	$1,884	$7,628

In addition to these tangible costs, the drums with steady burn warning lights also introduce additional intangible costs due to the disposal of both the steady burn warning lights and the used batteries. Besides comparing the cost differences between the two types of drums, potential benefits were also examined through the crash data, driver behavior, and luminance studies described previously. However, as the results of these studies did not reveal any substantive differences in safety performance between the drums with and without warning lights, there are no quantifiable benefits to include as a part of a benefit-cost analysis. As such, the increased costs associated with the use of steady-burn warning lights were not shown to be cost-effective.

10.0 CONCLUSIONS

This research evaluated the relative differences between drums with steady burn warning lights compared to drums without steady burn warning lights for several measures of effectiveness. The following conclusions associated with the use of steady burn warning lights on work zone drums were drawn from the results of the evaluations:

State-of-the-Practice for the Use of Warning Lights on Channelizing Drums

- Of the states responding to the survey, 9.5 percent (4 of 42) currently use steady burn warning lights for work zone channelization on a frequent basis (i.e., at 30 percent or more of the work zone locations statewide). These states include: Arizona, Florida, Illinois, and Oklahoma. It should be noted that Arizona uses vertical panels rather than drums. The State of Michigan had used drums on a frequent basis prior to discontinuing use for projects let on or after August 6, 2009.
- Steady burn warning lights were used on an infrequent basis (i.e., at 1 percent to 10 percent of the work zone locations statewide) by 23.8 percent (10 of 42) of the states responding to the survey. These states include: Colorado, Indiana, Maryland, Missouri, Montana, New York, Pennsylvania, Texas, Washington, and Wisconsin. Most of these states indicated that warning lights are/were used for specific types of applications, including at spot hazards, tapers, lane shifts, and crossovers.
- Of the states that responded, 64.3 percent (27 of 42) do not use steady burn warning lights on drums, but instead use either drums without warning lights or another type of channelizing device, such as cones, vertical panels, or tubular markers. These states include: Alabama, Arkansas, California, Connecticut, Georgia, Idaho, Iowa, Kansas, Kentucky, Maine, Minnesota, Mississippi, Nebraska, Nevada, New Hampshire, New Jersey, North Dakota, Ohio, Oregon, Rhode Island, South Carolina, South Dakota, Utah, Vermont, Virginia, West Virginia, and Wyoming.

- The following states did not respond to the survey: Alaska, Delaware, Hawaii, Louisiana, Massachusetts, New Mexico, North Carolina, and Tennessee.

Work Zone Crashes

- Among the work zone crash data obtained from 26 states, only slight differences were observed between the rates of work zone crashes in states with varying policies regarding the use (frequent, infrequent, or non-use) of steady burn warning lights on work zone drums. The states that frequently use lights on drums exhibited a slightly higher work zone crash rate among the three groups at 0.059 crashes per million vehicle miles traveled. 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. No discernable differences were observed between any of the three groups of states when examining work zone crashes as a proportion of total crashes.
- Work zone crash data was collected at a sample group of MDOT work zones with and without steady burn warning lights. A comparison of data between the two groups showed that both groups of work zones experienced **reductions in total crashes and nighttime crashes** in comparison to the same time periods prior to the start of construction.
- This crash data review also showed that a higher proportion of work zone crashes tended to occur during nighttime conditions at locations with steady burn warning lights (39.4%) compared to locations without steady burn warning lights (29.7%).
- A manual review of the UD-10 crash report forms showed that, 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 samples. 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 are not overrepresented in nighttime work zone crashes involving drums, regardless of the presence or absence of steady burn warning lights on drums.

Driver Behavior in Work Zones

- The presence of steady burn warning lights on work zone channelizing drums did not significantly impact the center lane positioning of drivers. Drivers traveling through work zones with steady burn warning lights on drums spent slightly less time in the center lane position, on average, compared to drivers at locations without steady burn warning lights on drums. This finding suggests that steady burn warning lights on drums may not influence nighttime driver behavior in work zones.
- The presence of a steady burn warning light on the drums had a marginal increase on the tendency of drivers to travel in close proximity to the drums. Drivers traveling through work zones with steady burn warning lights on drums spent a slightly higher percent of time in the lane position closest to the drums compared to drivers at locations without steady burn warning lights on drums. However, this difference was not statistically significant.
- The presence of a steady burn warning light on the drums caused a significant increase in the rate of steering reversals. Drivers traveling through work zones with steady burn warning lights on drums had higher steering reversal rates than the drivers at work zone locations without steady burn warning lights on drums.

- Freeway locations with steady burn warning lights on the drums exhibited higher nighttime mean speeds compared to freeway locations without steady burn warning lights. Mean, median, and 85th percentile speeds were 3.9 mph, 3.1 mph, and 3.1 mph higher at locations with steady burn warning lights as compared to locations without warning lights. The standard deviation (or variance) of travel speeds was not significantly different between the locations with and without steady burn warning lights. These results may be indicative of drivers exercising greater caution when traveling through work zones without steady burn warning lights. However, the effects of other uncontrolled factors such as work zone layout, roadway geometry, and the presence of workers may have also contributed to this result.
- The presence of a steady burn warning light on the drums had a statistically significant impact on drum condition. In work zone locations without steady burn warning lights, 14.1 percent of drums were found to be damaged, while 16.1 percent of drums were found to be damaged at those locations with steady burn warning lights. These findings suggest that drivers may be more likely to veer from the travel lane and strike a drum in work zones with steady burn warning lights.

Luminance of Channelizing Drums

- 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. When measured at a distance of 200-ft, the addition of a steady burn warning light increased the average luminance by 0.165 cd/m^2 (2.6 percent) and 0.50 cd/m^2 (3.9 percent) for the high intensity drums and prismatic drums, respectively, when measured in the controlled environment. Similar results were obtained during the field evaluation, as drums with steady burn warning lights measured at a distance of approximately 200-ft had average luminance values that were 0.36 cd/m^2 (7.3 percent) greater and 0.04 cd/m^2 (0.3 percent) lower than drums without steady burn warning lights for high intensity drums and prismatic drums, respectively.

- Prismatic sheeting materials provide the largest improvement to drum luminance. Compared to drums with high intensity sheeting, prismatic sheeting had average luminance measurements that were 10.26 cd/m^2 (203.6 percent) greater when measured in the field and 8.45 cd/m^2 (177.1 percent) greater when measured in a controlled environment.
- 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.
- The average luminance for each of the evaluated drum conditions was greater than the **minimums of 2.3 – 3.2 cd/m^2** that have been recommended in the literature for sign legibility purposes [*32*,*33*,*34*,*35*].
- Drum luminance can be accurately measured in the field from a slow moving vehicle, which had not previously been confirmed in the literature.

Based on a synthesis of all results, steady burn warning lights demonstrate 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 microprismatic sheeting materials. This conclusion is similar to those found in previous research [*10*,*12*,*13*,*14*] on this topic. Thus, it was concluded that steady burn warning lights demonstrate little to no additional value to work zone safety when used on channelizing drums in work zones. Drums with high intensity sheeting that is in good condition will typically provide adequate nighttime brightness for work zone channelization regardless of whether a steady burn warning light is attached or not. However, if additional nighttime brightness is desired, the use of prismatic sheeting provides a far greater increases in visibility compared to the addition of a steady burn warning light to the drum.

1. *Work Zone Safety Fact Sheet*, National Work Zone Awareness Week 2004, Federal Highway Administration.

2. Michigan Criminal Justice Information Center, 2004-2008 Michigan Work Zone Crash Comparison, http://michigan.gov/documents/mdot/work_zone_crash_2009_278506_7.pdf.

3. *Manual on Uniform Traffic Control Devices For Streets and Highways, 2009 Edition.* U.S. Department of Transportation, Federal Highway Administration, Washington D.C., 2009.

4. Garber, N.J. and M. Zhao. "Distribution and Characteristics of Crashes at Different Work Zone Locations in Virginia." In *Transportation Research Record 1794*, Transportation Research Board, National Research Council, Washington, D.C., 2002, pp 19 -25.

5. Ha, T.J., and Z.A. Nemeth. "Detailed Study of Accident Experience in Construction and Maintenance Zones." In *Transportation Research Record 1509,* Transportation Research Board, National Research Council, Washington, D.C., 1998, pp 38-45.

6. Mohan, S.B. and P. Gautam. "Cost of Highway Work Zone Injuries." ASCE Volume 7, Issue 2, 68 – 73.

7. Khattak, A.J. and F.M. Council. "Effects of Work Zone Presence on Injury and Non-injury Crashes." In *Accident Analysis and Prevention,* Volume 34, 2002, pp 19-29.

8. Graham, J.L., R.J. Paulsen, and J.C. Glennon. "Accident Analysis of Highway Construction Zones". In *Transportation Research Record 693*, Transportation Research Board, National Research Council, Washington, D.C., 1978, p. 25-32.

9. Daniel, J, K. Dixon, and D. Jared. "Analysis of Fatal Crashes in Georgia Work Zones." In *Transportation Research Record 1715*, Transportation Research Board, National Research Council, Washington, D.C., 2000, pp 18 - 23.

10. Datta, T.K. and D.S. McAvoy. *A Study of the Effectiveness of the Use of Steady Burn Warning Lights on Drums in Construction Work Zones.* Michigan Department of Transportation, Wayne State University, Detroit, Michigan, 2005.

11. Pain, R. F., H.W. McGee, and B.G. Knapp. *Evaluation of Traffic Control for Work Zones*. NCHRP Report 236, Transportation Research Board, Washington, D.C., 1981.

12. Shepard, F. D. "Improving Work Zone Delineation on Limited Access Highways"**.** In *Transportation Research Record 1352*, Transportation Research Board, National Research Council, Washington, D.C., 1990, 36 - 43.

13. Pant, P. D., and Y. Park. "Effectiveness of Steady-Burn Lights for Traffic Control in Tangent Sections of Highway Work Zones", In *Transportation Research Record 1254*, Transportation Research Board, Washington, D.C., 1992, pp 56-59.

14. Pant, P. D., X.H. Huang, and S.A. Krishnamurthy. "Steady Burn Warning Lights in Highway Work Zones: Further Results of Study in Ohio." In *Transportation Research Record 1352,* Transportation Research Board, Washington, D.C., 1992, pp 60-66.

15. "Steady-Burn Warning Lights Executive Summary." KLD Associates, Inc., Huntington Station, New York, 1992.

16. *Sixty-Five Plus in the United States*. Statistical Brief. Bureau of the Census, United States Department of Commerce, Washington, D.C., May 1995.

17. R.W. Lyles, M.R. Kane, F. Vanosdall, and F.X. McKelvey. *Improved Traffic Control Device Design and Placement to Aid the Older Driver,* Final Report. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington D.C., December 1997.

18. *Traffic Safety Facts 2000: Older Drivers.* DOT HS 809 328. National Highway Traffic Safety Administration, USDOT, Washington, D.C., 2000.

19. *Transportation in an Aging Society*, TRB Special Report 218. Transportation Research Board, National Research Council, Washington D.C., 1988.

20. Florida DOT Traffic Engineering Manual. Section 6.1 - Florida's Elder Road User Program. Florida Department of Transportation, Tallahassee, Florida, 1999.

21. *Highway Design Handbook for Older Drivers and Pedestrians.* Report FHWA/RD-01/103. Federal Highway Administration, Washington, D.C., 2001.

22. Heaslip, K., J. Collura, and M. Knodler. "Evaluation of Evaluation of Work Zone Design Features to Aid Older Drivers." Transportation Research Board 88th Annual Meeting CD-ROM. Transportation Research Board, January 2009.

23. *Merriam-Webster Online Dictionary.* Website: http://www.merriam-webster.com/dictionary. Accessed January, 2010.

24. ASTM E1709 - 08 "Standard Test Method for Measurement of Retroreflective Signs Using a Portable Retroreflectometer at a 0.2 Degree Observation Angle"

25. ASTM E1710 - 05 "Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer"

26. Fontaine, M.D., P.J. Carlson, and H.G. Hawkins. Evaluation of Traffic Control Devices for Rural High-Speed Maintenance Work Zones: Second Year Activities and Final Recommendations. Report No. FHWA/TX-01/1879-2. Federal Highway Administration, Texas Department of Transportation, Texas Transportation Institute, College Station, TX, 2000.

27. Commission Internationale de l'Eclairage (CIE). Visual Aspects of Road Markings. CIE Joint Technical Report 73-1988, World Road Association (PIARC), Vienna Austria, 1988.

28. Zwahlen, H.T. and T. Schnell. Driver Headlamp Dimensions, Driver Characteristics, and Vehicle and Environmental Factors Used in Retroreflective Target Visibility Calculations. In *Transportation Research Record 1692,* Transportation Research Board, National Research Council, Washington, D.C., 1999.

29. Zwahlen, H.T. and T. Schnell. "Minimum In-Service Retroreflectivity of Pavement Markings." In *Transportation Research Record 1715,* Transportation Research Board, National Research Council, Washington, D.C., 2000.

30. Debaillon, C., P.J. Carlson, H.G. Hawkins, Y. He, T. Schnell, and F. Aktan. "Review and Development of Recommended Minimum Pavement Marking Retroreflectivity Levels". In *Transportation Research Record 2055,* Transportation Research Board, National Research Council, Washington, D.C., 2008.

31. McGee H. W. and B.G. Knapp. "Visibility Requirements for Traffic Control Devices in Work Zones. Abridgement". In *Transportation Research Record 703*, Transportation Research Board, National Research Council, Washington, D.C., 1979, pp. 16 - 19.

32. Sivak, M. and P.L. Olson. *Optimal and Replacement Luminances of Traffic Signs: A Review of Applied Legibility Research.* Report Number UMTRI 83-43. The University of Michigan Transportation Research Institute (UMTRI), December 1983.

33. Chrysler, S. "Luminance: A Systems Approach to the Visibility of Traffic Control Devices." Paper presented at the 1996 Asia-Pacific Regional Meeting of the International Road Federation, Taipei, Taiwan, Nov., 1996.

34. Carlson, P.J. and H.G. Hawkins. *Updated Minimum Retroreflectivity Levels for Traffic Signs – Final Report.* Texas Transportation Institute, Federal Highway Administration, United States Department of Transportation, July 2003.

35. Schnell, T., L. Yekhshatyan, and R. Daiker. "Effect of Luminance and Text Size on Information Acquisition Time from Traffic Signs". In *Transportation Research Record 2122*. Transportation Research Board, National Research Council, Washington D.C., 2009, pp. 52-62.

36. Zwahlen, H.T. and T. Schnell. "Visibility of Road Markings as a Function of Age, Retroreflectivity Under Low-Beam and High-Beam Illumination at Night." In *Transportation Research Record 1692*, Transportation Research Board, National Research Council, 1998, pp. 152-162.

37. PASW Release 18. SPSS (an IBM Company), Chicago, Illinois, 2009.

38. *Manual on Uniform Traffic Control Devices For Streets and Highways, 2005 Edition.* Michigan Department of Transportation, Lansing, Michigan, 2005.

Appendix A

STATE-OF-THE-PRACTICE
SURVEY QUESTIONNAIRE

QUESTIONNAIRE SURVEY ON THE USE OF STEADY-BURN WARNING LIGHTS IN HIGHWAY CONSTRUCTION WORK ZONES

Please respond to the following questions.

1. Agency Name: ____
   Your Name and Title: ____
   Address: ____
   Telephone No.: ____
   E-Mail:____

2. Please check each channelizing device which is currently used by your agency for highway work zone traffic control applications and indicate the approximate percentage of all highway work for which each type of device is used.

   ❒ Cones
   _____%
   ❒ Drums *with* steady-burn warning lights
   _____%
   ❒ Drums *without* steady-burn warning lights
   _____%
   ❒ Tubular Markers
   _____%
   ❒ Barricades
   _____%
   ❒ Other devices *with* warning lights,
   _____%
   (please specify the type of device)_______________________
   ❒ Other devices *without* warning lights,
   _____%
   (please specify the type of device)_______________________

3. If you use **drums** as a part of work zone delineation, please provide width of the retroreflective tapes and the grade of material used:

   ____

4. Has your agency ever used drums ***without*** **steady-burn warning lights** in highway work zones?

   ❒ Yes
   ❒ No

   If Yes, over what approximate periods (dates) were steady-burn warning lights **not** used?

   ____

5. Has your agency ever used drums *with* **steady-burn warning lights** in highway work zones?

   ❒ Yes, only **two-way** steady-burn warning lights

   ❒ Yes, only **360-degree** steady-burn warning lights

   ❒ Yes, both **two-way and 360-degree** steady-burn warning lights

   ❒ No

   If Yes, over what approximate periods (dates) were steady-burn warning lights used?

   ____

   If you use steady burn lights on drums, please explain how and where they are used:

   ____

6. Does your agency currently have a policy outlining the use (or nonuse) of **steady-burn warning lights** on **drums**?

   ❒ Yes

   ❒ No

   If yes, please send a copy of this policy by e-mail or standard mail, or briefly state the policy here.

   ____

7. Has your agency conducted any studies on the effectiveness of drums *with* or *without* **steady-burn warning lights** in highway construction work zones?

   ❒ Yes

   ❒ No

   If Yes, please send a copy of the research conducted by e-mail or standard mail, or briefly state the results of your study.

   ____

8. Would you be willing to provide assistance in obtaining traffic crash data in work zones within your jurisdiction?

   ❒ Yes (Please note that we will follow-up with specific requests for data).

   ❒ No

Your participation in this survey is greatly appreciated. Please fax or e-mail your completed survey to:

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Appendix B

STATE-OF-THE-PRACTICE SURVEY RESULTS

Agency Name	Contact	Channelizing Device(s) Useded?					Width of Retroreflective Tape on Drum/Other Devices and Grade	Without Steady Burn Warning Lights		Drums with Steady Burn Warning Lights		How and Where are Steady Burn Warning Lights Used	Policy for Use/Non-Use of Steady Burn Warning Lights	Study on Effectiveness of Steady Burn Warning Lights on Drums		Willing to Provide Assistance in Obtaining Traffic Crash Data
		Cones	Drums With Lights	Drums Without Lights	Barricades	Other		Ever Used?	Approximate Dates Used	Ever Used?	Approximate Dates Used			Ever Performed?	Brief Description of Results	
Georgia Department of Transportation	Richard Marshall, rmarshall@dot.ga.gov, (404)631-1971	Yes	No	Yes	No	Vertical Panels	4" to 6" Type III or Type IV (High Intensity Reflective Sheeting, or Prismatic Sheeting)	Yes	1999-Present	Yes	Prior to 1999	In a Taper	No	No	N/A	No
Hawaii Department of Transportation	Bryan Kimura, Bryan.Kimura@hawaii.gov, (808)692-7673	DID NOT RESPOND														
Idaho Transportation Department	Harold Bleil, Harold.Bleil@itd.idaho.gov, (208)334-8564	Not Available	No	Not Avail.	Not Avail.	Not Available	Type IV or Greater (High Intensity Prismatic Sheeting or Greater)	Yes	Majority of the Time	Yes	1970's- mid 1990's	Not Available	Not Available	Not Available	Not Available	Not Available
Illinois Department of Transportation	Marshall Metcalf, Marshall.Metcalf@illinois.gov (217)782-8608	Yes	Yes - 40% used	No	Yes	Tubular Markers, Directional Indicator Barricade	At Least 2 Orange and 2 White Stripes, High Intensity Prismatic	No	N/A	Yes- Two Way	Required	Drums Used During Nighttime	Yes	No	N/A	Yes
Indiana Department of Transportation	John Pat McCarty, jmccarty@indot.in.gov, (317)234-5114	Yes	Yes/ Optional	Yes	Yes	Tubular Markers, Vertical Panels with Lights	6" Retro-Reflective Sheeting	Yes	Not Available	Yes- Two Way	Not Available	Per Indiana MUTCD	No	No	N/A	Yes
Iowa Department of Transportation	Mark Bortle, mark.bortle@dot.iowa.gov (515)239-1587	Yes	No	Yes	No	Tubular Markers, 42" Channelizers	6" Type III or IV (High Intensity Reflective Sheeting, or Prismatic Sheeting)	Yes	1995 to Present	No	N/A	N/A	Yes	No	N/A	Yes
Kansas Department of Transportation	Anthony Alrobaire, anthony@ksdot.org, (785)296-0355	No	No	No	No	Trimlines, Conical Delineators	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
Kentucky Transportation Cabinet	Vibert Forsythe, Vibert.Forsythe@ky.gov, (502)564-4780	Yes	No	Yes	Yes	None	Not Available	Yes	N/A	No	N/A	N/A	No	No	N/A	Yes
Louisiana Department of Transportation	Barry Lacy, barry.lacy@la.gov, (225)379-1584	DID NOT RESPOND														
Maine Department of Transportation	Dana Hanks, dana.hanks@maine.gov, (207)624-3574	Yes	No	Yes	Yes	No	4" to 6" Grade not Specified	Yes	Always	No	N/A	N/A	Not Available	Not Available	Not Available	Not Available
Maryland State Highway Administration	Michael L. Paylor, mpaylor@sha.state.md.us (410)787-5864	Yes	Very low use - 2%	Yes	Yes	Tall-Weighted Cones	6" Diamond Grade Sheeting	Yes	1980's to Present	Yes- Two Way	Prior to 1980's	Nighttime Spot Hazards	No	No	N/A	Not Sure
Massachusetts Department of Transportation	Michael McGrath, michael.a.mcgrath@state.ma.us, (617)973-7610	DID NOT RESPOND														
Minnesota Department of Transportation	Marvin L. Sohlo, marv.sohlo@state.mn.us, (651)234-7380	Yes	No	Yes	Yes	Warning Signs, Tubular Markers	4" Retro-Reflective Sheeting	Yes	Many Years	Yes- Two Way	Not Available	Very Rarely	No	No	N/A	No (no data)
Mississippi Department of Transportation	Steven W. Reeves, sreeves@mdot.state.ms.us, (601)978-1842	Yes	No	Yes	Yes	Tubular Markers and Signs	6" High Intensity Reflective Sheeting	Yes	Present Time	No	N/A	N/A	No	No	N/A	No

Agency Name	Contact	Channelizing Device(s) Useded?					Width of Retroreflective Tape on Drum/Other Devices and Grade	Without Steady Burn Warning Lights		Drums with Steady Burn Warning Lights		How and Where are Steady Burn Warning Lights Used	Policy for Use/Non-Use of Steady Burn Warning Lights	Study on Effectiveness of Steady Burn Warning Lights on Drums		Willing to Provide Assistance in Obtaining Traffic Crash Data
		Cones	Drums With Lights	Drums Without Lights	Barricades	Other		Ever Used?	Approximate Dates Used	Ever Used?	Approximate Dates Used			Ever Performed?	Brief Description of Results	
Missouri Department of Transportation	Daniel J. Smith, Daniel.Smith@mdot.mo.gov, (573)526-4329	Yes	Very low use - 2%	Yes	Yes	Tubular Markers, Trimlines (With and Without Lights)	4" to 6" Type III (High Intensity Reflective Sheeting)	Yes	Optional, Unless Specified	Yes	Not Available	Tapers or Nighttime Work	Yes	No	N/A	Not Available
Montana Department of Transportation	Jim Wingerter, jwingerter@mt.gov, (406)454-5897	No	Only 5%	Yes	Yes	Type II Object Markers, Portable Hazard Panels, Tubular Markers	4" to 6" Type III (High Intensity Reflective Sheeting) Retro-Reflective	Yes	Currently	Yes-Two Way	Currently	Not Available	Yes	No	N/A	Yes
Nebraska Department of Roads	Kevin Wray, Kevin.wray@nebraska.gov, (402)479-4594	Yes	No	Yes	Yes	Vertical Panels, Tubular Markers	6" to 8" High Intensity Prismatic Sheeting	Yes	Always	No	N/A	N/A	No	No	N/A	No
Nevada Department of Transportation	David Partee, dpartee@dot.state.nv.us, (775)888-7564	Yes	No	Yes	No	No	4" to 6" High Intensity Prismatic Sheeting	Yes	Early 1990's to Present	No	N/A	N/A	No	No	N/A	No
New Hampshire Department of Transportation	Lysa Bennet Crouch, Lbennet-Crouch@dot.state.nh.us, (603)271-2466	Yes	No	Very Low, <10%	Yes, <1%	Tubular Markers	4" to 6" (High Intensity Reflective Sheeting, or Prismatic Sheeting)	Yes	For the Past 20+ Years	No	N/A	N/A	No	No	N/A	No
New Jersey Department of Transportation	Lee G. Steiner, Lee.Steiner@dot.state.nj.us, (732)625-4355	Yes	No	Yes	Yes	None	6" Type VII or VIII (Microprismatic, Retroreflective Sheeting) with S2 Requirements	Yes	January 12, 1989 to Present	Yes- Two Way	Prior to January 12, 1989	N/A	Yes	Yes	Documented Incidents Where Lights Went Through Windshields	No
New Mexico Department of Transportation	Elias Archuleta, elias.archuleta@state.nm.us, (505)827-9853	DID NOT RESPOND														
New York State Department of Transportation	Joe Rutnik, jrutnik@dot.state.ny.us, (518)388-0380	Yes	Only 5%	Yes	Yes	Tubular Markers, Cone Barriers with Lights	Type IX (Diamond Grade Reflective Sheeting)	Yes	Not Available	Yes- 360 Degree	In Roadway Closures, First 2 in Tangent Section	Highlighting Road Closures/ Hazards	Not Available	Not Available	Not Available	No
North Carolina Department of Transportation	Stuart Bourne, sbourne@ncdot.gov (919)250-4159	DID NOT RESPOND														
North Dakota Department of Transportation	Phil Murdoff, pmurdoff@nd.gov, (701)328-2563	No	No	Yes	Yes	Tubular Markers	4" to 6" Type III or Type IV (High Intensity Reflective Sheeting, or Prismatic Sheeting) or Wide Angle Prismatic Flexible Reflective Sheeting	Yes	Always	No	N/A	N/A	No	No	N/A	Not Available
Ohio Department of Transportation	Kenneth E. Linger, ken.linger@dot.state.oh.us, (614)466-0139	Yes	No	Yes	No	None	4" to 6"	Yes	Last 15 Years	Not Available	Not Available	Not Available	No	Yes	15 Years ago	No
Oklahoma Department of Transportation	George Raymond, graymond@odot.org, (405)521-2561	Yes	Yes	No	Yes	Vertical Panels (with Lights), Tubular Markers	4" to 6"	Yes	Very Limited Basis	Yes- Two Way	As Long As He Can Remember	Channelizing Devices	No	No	N/A	Yes

Agency Name	Contact	Channelizing Device(s) Useded?					Width of Retroreflective Tape on Drum/Other Devices and Grade	Without Steady Burn Warning Lights		Drums with Steady Burn Warning Lights		How and Where are Steady Burn Warning Lights Used	Policy for Use/Non-Use of Steady Burn Warning Lights	Study on Effectiveness of Steady Burn Warning Lights on Drums		Willing to Provide Assistance in Obtaining Traffic Crash Data
		Cones	Drums With Lights	Drums Without Lights	Barricades	Other		Ever Used?	Approximate Dates Used	Ever Used?	Approximate Dates Used			Ever Performed?	Brief Description of Results	
Oregon Department of Transportation	Don Wence, donald.e.wence@odot.state.or.us, (503)986-3791	Yes	No	Yes	Yes	Tubular Markers	Not Available	Yes	Not Available	No	N/A	N/A	Not Available	Not Available	Not Available	No
Pennsylvania Department of Transportation	Larry Lentz, Lalentz@state.pa.us, (717)787-2806	Yes	Only 5%	Yes	Yes	Vertical Panels	4" to 6" High Intensity Reflective Sheeting, or Prismatic Sheeting	Yes	For the Life of the Project	Yes- Two Way	For Life of Project in Certain Situation	Exit Ramps, Crossovers, Shifting Traffic	No	No	N/A	Yes (New Contact)
Rhode Island Department of Transportation	Frank Corrao, III, fcorrao@dot.ri.gov, (401)222-2468x4202	Yes	No	Yes	Yes	Tubular Markers	6" Visual Impact Performance (VIP) Reflective Sheeting	Yes	Majority of the Time	No	N/A	N/A	No	No	N/A	No
South Carolina Department of Transpiration	Joe Sease, seasejc@scdot.org, (803)737-1460	Yes	No	Yes	Yes	None	6" Type III (High Intensity Reflective Sheeting) Prismatic	Yes	Since 1995	Yes- Two Way	Prior to 1995	N/A	No	No	N/A	No
South Dakota Department of Transportation	Laurie Schultz, laurie.schultz@state.sd.us, (605)773-4759	Yes	No	Yes	Yes	Tubular Markers	4" to 6", Grade is not Specified	Yes	Not Available	No	N/A	N/A	No	No	N/A	No (no data)
Tennessee Department of Transportation	Brian Egan, Brian.Egan@state.tn.us, (615)741-2414	DID NOT RESPOND														
Texas Department of Transportation	Michael Chacon, mchacon@dot.state.tx.us, (512)416-3120	Yes	Low - 10% used	Yes	Yes	Drums with Flashing Lights, Vertical Panels	4" High Intensity Sheeting	Yes	No Date Given	Yes- Both Two-Way and 360 Degree	Since the Early 1990's	Uses Lights on Drums or Approved Substitutes/ Optional	Yes	Yes	http://tti.tamu.edu	No
Utah Department of Transportation	Shawn Debenham, Sdebenham@utah.gov, (801)965-4590	Yes	No	Yes	Yes	Tubular Markers	4" to 6" Type IV (High Intensity Prismatic Sheeting) Retroreflective Bands	Yes	1970's to Present	Yes	Prior to Early 1970's	Lane Closure Taper Devices	No	Yes	In 1980's looked at higher retroreflectivity instead of lights on drums	Yes
Vermont Department of Transportation	Robert White, robertt.white@state.vt.us, (802)828-2781	Not Available	No	Yes	Not Available	Not Available	6" Type III (High Intensity Reflective Sheeting) Prismatic	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
Virginia Department of Transportation	David Rush, David.Rush@vdot.virginia.gov, (804)371-6672	Yes	No	Yes	Yes	Tubular Markers and Signs	6" High Intensity Sheeting	Yes	1999 to Present	Yes- Two Way	Prior to Early 1990's	Near Coast due to Foggy Conditions	No	No	N/A	Yes
Washington State Department of Transportation	Frank R. Newboles, newbolf@wsdot.wa.gov, (360)705-7392	Yes	Low - 10% used	Yes	Yes	Tubular Markers	4" to 6" Type III or Type IV (High Intensity Reflective Sheeting, or Prismatic Sheeting)	Yes	Always	Yes- Two Way	Case by Case	For Complex Work Zones, Enhancement	No	No	N/A	No
West Virginia Department of Transportation	Ted Whitmore, ted.j.whitmore@wv.gov, (304)558-9468	Yes	No	Yes	Yes	Tubular Markers, Channelizer Cones	6" ASTM Type III (High Intensity Reflective Sheeting)	Yes	Over 10 Years	Yes- Two Way	Stopped Over 10 Years Ago	Not Available	No	No	N/A	Yes (New Contact)
Wisconsin Department of Transportation	Tom Notbohm, thomas.notbohm@dot.wi.gov, (608)266-0982	Yes	Low - 10% used	Yes	Yes	Tubular Markers	4" High Intensity Sheeting	Yes	1990 to Present	Yes- Two Way	Currently and for many years	When deviated from expected travel path, some areas with ambient lighting	Yes	Yes	Concluded high intensity sheeting performed well, lights not necessary in all situations	No
Wyoming Department of Transportation	Joel Meena, joel.meena@dot.states.wy.us, (307)777-4374	Yes	No	Yes	Yes	Tubular Markers	6" Type III (High Intensity Reflective Sheeting) or Better	Yes	100% of Time	No	N/A	N/A	No	No	N/A	Yes