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Evaluating the use of steady burn warning lights on drums for workzone safety

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EVALUATING THE USE OF
STEADY BURN WARNING LIGHTS ON DRUMS
FOR WORK ZONE SAFETY

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DISSERTATION

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DEDICATION

I hereby dedicate all my educational and professional achievements to my father

Mr. Nannapaneni Venkateshwara Rao,

who has been a constant source of support and encouragement throughout my education. I extend my deepest gratitude to my mother

Mrs. Nannapaneni Pavana Kumari,

for all her selfless sacrifices in my upbringing. I consider myself as one of the few blessed individuals on this earth, as I have the support of my family, friends, advisors, and well-wishers.

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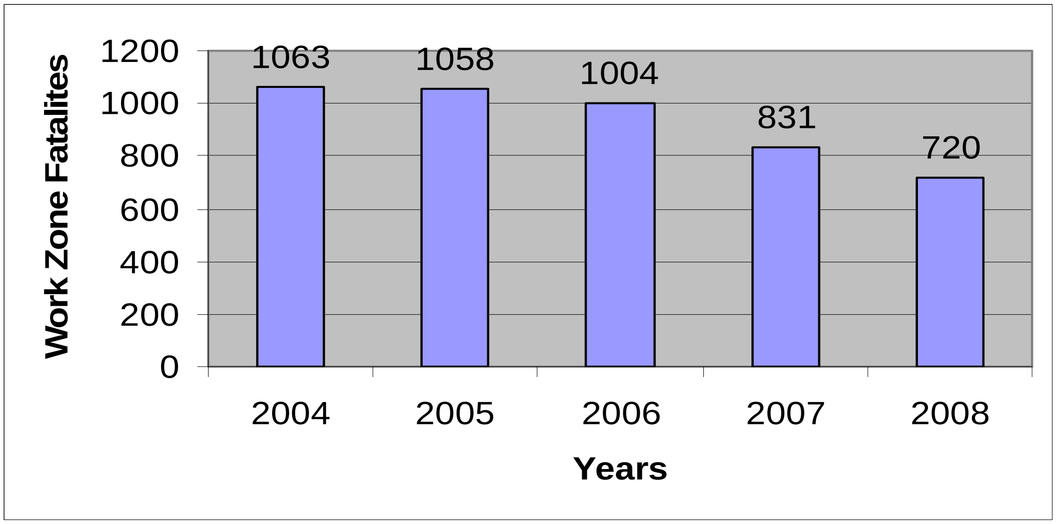
CHAPTER 1: Introduction and Background

Roadway maintenance and repair has become increasingly commonplace in the United States over the past several decades as our roadway infrastructure has continued to age and deteriorate. Maintenance and repair work on an existing roadway often presents the challenge of maintaining traffic on the existing roadway while work is being performed, thereby necessitating the use of roadway work zones. It is estimated that more than 20% of the National Highway System (NHS) is under construction during the peak construction season. Motorists can expect to encounter an active work zone in one out of every 100 miles driven on the NHS. Work zones on freeways are estimated to account for nearly 24% of non-recurring delay, and 10% of overall delay. More than 60 million vehicles per hour of capacity is lost to work zones each day during the peak construction period (1). As our aging infrastructure continues to require increasing maintenance and repair in the years to come, the number of work zones will continue to increase, which will undoubtedly impact roadway safety.

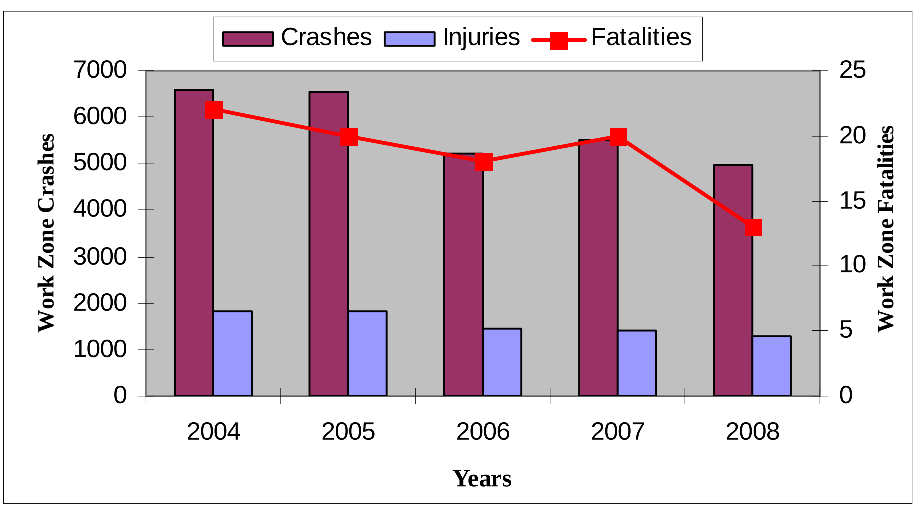
Significant improvements have been made in the field of road safety over the past several decades. In 2007, the fatality rate on roadways in the United States (U.S.) was 1.37 fatalities per 100 million miles of travel, which was down significantly from 5.50 fatalities per 100 million miles of travel in 1966. Nevertheless, in 2008, nearly 2.4 million people were injured and 37,261 people died on our nation's roadways (2). Of these 37,261 fatalities, 720 fatalities occurred in work zones.

Like the overall fatality rate, the work zone fatality rate has decreased considerably over the years. A look at the most recent five years shows a down trend of total fatal crashes related to work zones both in the U.S. and in Michigan, as shown in Figures 1 and 2, respectively. It is important to note, however, that work zone safety continues to be a significant problem that needs attention from engineering, enforcement, and other areas. According to the FHWA (1), each year more than 40,000 people are injured as a result of motor vehicle crashes in work zones. One work zone fatality occurs every 10 hours and one work zone injury occurs every 13 minutes (1). According to AAA, the societal cost of crashes is nearly two and a half times greater than congestion (3).



Source: Fatality Analysis Reporting System (FARS) – ARF, NHTSA

Figure 1: Work Zone Fatality Trend in the United States



Source: Criminal Justice information Center

Figure 2: Michigan Work Zone Crash Trend

Work zone driving conditions differ from normal driving conditions and typically demand more attention from drivers. Therefore, to help motorists while driving through the work zones, various traffic control devices are used, which include: signs; pavement markings; and channelizing devices. The Manual on Uniform Traffic Control Devices (MUTCD), 2009 Edition, states “the primary function of temporary traffic control (TTC) is to provide for the reasonably safe and effective movement of road users through or around TTC zones while reasonably protecting road users, workers, responders to traffic incidents, and equipment” (4).

“Most TTC zones are divided into four areas: the advance warning area, the transition area, the activity area, and the termination area” (4). The advance warning area is the section of highway where road users are informed about the upcoming work zone. Road users are redirected out of their normal path during the transition area. The activity area is the section of the highway where the work activity takes place and it is comprised of the work space, the traffic space, and the buffer space. The termination area is the section of the highway where road users are returned to their normal driving path.

Out of these four areas, the most crash prone area would be the transition area. This is due to the vehicle being forced to deviate from its original path accompanied by a change in speed and other operating conditions. It has been estimated that 42% of work zone crashes occur in the transition zone *prior* to the work area (5).

In the transition area, the function of the channelizing devices is most crucial. The channelizing devices, according to the MUTCD, are intended to warn motorists of the impending work activities ahead in or near the roadway and to guide motorists to follow a safe speed and path by demarking the edge of the travel way. Channelizing devices, such as cones, tubular markers, vertical panels, drums, and barricades, provide for a smooth and gradual transition of traffic flow from one lane to another. In work zones of prolonged duration, drums are commonly used as traffic control devices to channelize traffic through the work zone due to their visibility, good target value, and the respect they command from motorists. The type and duration of the work being performed often requires that these channelizing devices remain in place at all times day and night.

Maintaining traffic through nighttime work zones poses increased risks for drivers and roadway workers due to the lack of ambient light. To help overcome nighttime visibility issues, the 2009 MUTCD requires work zone traffic control devices to be retroreflective or internally illuminated. To help supplement retroreflectivity, Section 6F.81 of the 2009 MUTCD allows for the use of auxiliary steady burn warning lights (SBWL) on work zone channelizing devices. Steady burn warning lights on work zone channelizing devices have been used by roadway agencies throughout the United States for many years, although the use of brighter sheeting materials has prompted investigation into the value and effectiveness added by such lights. As a result, research was undertaken to explore the impacts associated with the use of steady burn warning lights on channelizing drums considering a variety of work zone scenarios.

CHAPTER 2: State-of-the-Art Literature Review

A comprehensive literature review of past research and practice related to the use of steady burn warning lights on drums was performed in the early stages of this research. Pertinent journal articles and research reports were identified using database queries and bibliographical reviews from key reports. Documents that were useful to this research were then carefully identified and thoroughly reviewed to extract information on various topics of interest. These topics included:

- Work Zone Safety and Work Zone Crashes
- Traffic Control Devices Used in Work Zones
- Steady Burn Warning Lights
- Field Evaluation Methodologies
- Photometric Properties and Standards for Work Zone Devices

A brief summary of the key research papers that were reviewed for the above mentioned topics is presented in the following sections.

2.1 Work Zone Safety and Work Zone Crashes

The Federal Highway Administration (FHWA) published a document entitled "Work Zone Impacts Assessment: An Approach to Assess and Manage Work Zone Safety and Mobility Impacts of Road Projects" (6). The intent of this document was to provide guidance to the road agencies in assessing and managing the work zone impacts within their jurisdictions. In September 2004, the FHWA published updates to the work zone regulations at 23 CFR 630 Subpart J. The updated Rule is referred to as the Work Zone Safety and Mobility Rule (Rule) and applies to all state and local governments that receive Federal-aid highway funding.

Transportation agencies are required to comply with the provisions of the Rule by October 12, 2007. The changes made to the regulations broaden the former Rule to better address the work zone issues of today and the future. To help address the issues of maintaining work zone safety and mobility, the Rule provides a decision-making framework that facilitates comprehensive consideration of the broader safety and mobility impacts of work zones across project development stages, and the adoption of additional strategies that help manage these impacts during project implementation. At the heart of the Rule is a requirement for agencies to develop an agency-level work zone safety and mobility policy. The policy is intended to support systematic consideration and management of work zone impacts across all stages of project development. Based on the policy, agencies will develop standard processes and procedures to support implementation of the policy. These processes and procedures shall include the use of work zone safety and operational data, work zone training, and work zone process reviews. Agencies are also encouraged to develop procedures for work zone impact assessment. The third primary element of the Rule calls for the development of project-level procedures to address the work zone impacts of individual projects. These project level procedures include identifying projects that an agency expects will cause a relatively high level of disruption (referred to in the Rule as significant projects) and developing and implementing transportation management plans (TMPs) for all projects.

The Michigan Department of Transportation (MDOT) established the "Work Zone Safety and Mobility Manual" (7) to improve safety and mobility in work zones by reducing congestion and traffic incidents. Specific processes, procedures and guidelines to support implementation of the policy are developed and communicated through this manual. This manual also includes methods for the analysis of crash data, mobility analysis, work zone training requirements by classification and work zone process review procedures. All projects require that a Transportation Management Plan (TMP) be developed and implemented. For projects that are considered significant, those that exceed the mobility analysis thresholds, an in depth transportation management plan will be required. A transportation management plan consists of three primary components: 1) a temporary traffic control plan that addresses traffic safety and control through the work zone, 2) a transportation operations plan outlining strategies that will be used to mitigate work zone impacts, and who 3) a public information plan containing strategies to inform those affected by the work zone impacts and the changing conditions.

A study performed by Garber et al (8) investigated the characteristics of work-zone crashes that occurred in Virginia from 1996 through 1999. The information on each crash was obtained from police crash records. Each crash was located in one of five areas of the work zone: (*a*) advance warning; (*b*) transition; (*c*) longitudinal buffer; (*d*) activity; and (*e*) termination. The percentage distributions were analyzed relative to crash location, crash severity, collision type, and highway type. The proportionality test was used to determine significant differences at the 5% significance level. The results indicate that the activity area is the predominant location of work-zone crashes regardless of highway type, and rear-end crashes are the predominant crash type. The results also indicate that the proportion of sideswipe-in-same-direction crashes in the transition area is significantly higher than that in the advance warning area.

Ha et al (9) performed research and identified injury level and type of crashes in state of Ohio work zones, between 1982 and 1986. This research identified that rear-end crashes were predominant during the day time, while fixed object crashes were predominant in the night time driving conditions, similar to the findings of Garber et al study.

Mohan et al (10) studied the details of the various injury types and their cost estimates. Two types of accidents occur in highway work zones: those that involve construction workers, which account for 30% of the accidents; and those that involve motorists outside the construction area, which account for 70% of the accidents. Construction/maintenance workers suffer approximately 27,000 first-aid injuries and 26,000 lost-time injuries per year at a total annual cost of $2.46 billion dollars, and motorists suffer approximately 700 fatalities, 40,000 injuries, and 52,000 property-damage-only accidents, at a total cost of $6.2 billion dollars per year. Highway work zone fatalities, per billion dollars spent, cost at least four times more than in total U.S. construction. While the highway traffic fatality rate has been declining by approximately 3.3% per year since 1960, and construction fatalities have been decreasing by approximately 6% per year since 1970, work zone fatalities have stayed constant at around 700 deaths per year. Using available databases, it was found that 1) the average direct cost of a motorist's injury is estimated at $3,687; and 2) an overturned vehicle has the largest average cost of $12,627, followed by a rear-end collision averaging $5,541. Analysis of the causes of these traffic accidents showed that driver error was the most expensive pre-crash activity, with an average cost of $7,676, and rear-end collisions are the most common (31%) vehicle crashes, followed by "hit-small-object" collisions at 11% of the total motor vehicle crashes.

Khattak et al (11) performed a study to evaluate the differences between pre and during work zone conditions for 36 roadway segments in California. Study found that: sideswipe and rear-end crashes occur more frequently in work zones compared to non-work zones; crashes in work zones are typically less severe than those occurring in non-work zone areas; and the total crash rate observed in the pre-work zone period was 0.65 crashes per million vehicle kilometers (MVK) compared to 0.79 crashes per MVK while the work zone was in place, representing an increase of 21.5 percent. A t-test performed at 90 percent confidence level showed that the two crash rates were not statistically different. It is important to note that the analysis assumed that the traffic volumes remained same during both conditions. This assumption may not be a valid one as traffic volumes reduce when woke zone is in place compared to regular traffic conditions. This research found that after controlling for various factors, longer work zone duration significantly increases both injury and non-injury crash frequencies.

Graham et al (12) did a study to investigate crashes both while the work zone was in place and during pre-work zone conditions at 79 work zones in seven states in 1978. These 79 locations represented a broad range of work activities and work zone layouts. The study found that the overall crash rate was found to increase by 7.5 percent when the work zone was in place, however, this increase varied by state and by type of work.

Chambless et al (13) researched the crash data from the states of Alabama, Michigan and Tennessee between the years of 1996 and 1998. Their research objectives were to: perform a comprehensive analysis of computerized work zone and non work zone crash data in Alabama, Michigan and Tennessee; compare and contrast characteristics in the three states in order to determine whether problems are local or national; and construct the circumstances of a "typical" work zone crash. The study was greatly facilitated by using the Information Mining for Producing Accident Countermeasure Technology (IMPACT) module of Critical Analysis Reporting Environment (CARE) software. IMPACT compares a test subset (in this case, crashes in work zones) with a control subset (crashes outside of work zones). In Alabama, for example, 35% of work-zone crashes occur in rural areas, which exceed the 28% of non work zone crashes occurring in rural areas. Although rural crashes do not constitute a majority of work zone crashes, because the proportion of rural crashes is higher in work zones than in non work zones, rural crashes are said to be over represented in work zones. The study concluded that: 63% of the work zone crashes took place on interstate, U.S. and state roads, as compared to only 37% of non work zone crashes. It appears that work zone safety efforts focused on these highways will provide the greatest safety gains; 48% of the work zone crashes occur in 45 and 55 mph speed zones, as opposed to 34% of non work zone crashes. Drivers more than 25 miles from home are significantly over represented in work zone crashes (25% to 15%). However, concentrating efforts on 45 and 55 mph speed zones and drivers more than 25 miles from home appears to offer good opportunities to improve work zone safety; and "Misjudging stopping distance/following too closely" accounts for 27% of the "prime contributing crash circumstances" for work zone crashes as opposed to 15% for non work zone crashes. The study also observed that pedestrians are involved in work zone crashes at practically the same rate they are involved in non work zone crashes.

Daniel et al (14) reported the study performed by The Georgia Department of Transportation to identify the type of collision, location, and construction activity associated with fatal crashes in work zones. This study is expanded further to examine the difference between fatal crash activities within work zones, compared with fatal crashes in non work zone locations. Using data from three work zone locations in Georgia, fatal crash activity within work zones was compared with nonfatal crashes within work zones. Finally, the fatal crash activity was examined to determine the influence of work zone activity on the frequency of fatal crashes. The overall findings of the study indicate that the work zone influences the type of collision, light conditions, truck involvement, and roadway functional classification under which fatal crashes occur. The study also indicates that fatal crashes in work zones are more likely to involve another vehicle than non-work zone fatal crashes, and fatal crashes in work zones are less influenced by horizontal and vertical alignment than non-work zone crashes are.

Venugopal et al (15) conducted research to develop regression models predicting the expected number of crashes at work zones on rural, two-lane freeway segments. Crashes on approaches to work zones and those inside the work zones were analyzed separately. For developing these models, an extensive database was obtained, including freeway data, crash data, and work zone characteristics. Negative binomial models were developed with average daily traffic, the length of the work zones, and the duration of the work projects as exposure-to-risk variables. The cost of the various work projects was found to be a good substitute for some of the exposure-to-risk variables. The investigated variables included the number of on and off ramps, both on approaches and inside the work zones; the type of work; and the intensity of the road work involved. The models may be used to evaluate beforehand the expected number of crashes on the work zone, given the work zone characteristics.

Ullman et al (16) presented an analysis of work zone fatal crashes nationwide to assess possible underreporting due to differences in how information about a work zone crash is captured on standard state crash reporting forms. The possible effects of differences in crash report forms on work zone crash statistics were first identified in the mid-1990s, by using data from the Highway Safety Information System. The influence of different crash report forms on work zone crash data contained in the Fatality Analysis Reporting System (FARS) were examined. An investigation of the data contained in FARS from 1998 to 2000 indicates a statistically significant dependence between the way in which work zones are denoted on a state's crash report form and the percentage of fatalities that are coded as occurring in a work zone. From this analysis, it appears that nationally, existing data may underreport the number of fatalities that occur in work zones by as much as 10%.

Fontaine et al (17) presented the effectiveness of speed displays and portable rumble strips to reduce speeds in rural-maintenance work zones. Speed displays are radar-activated signs that dynamically display approaching vehicle speeds. These devices were tested on two-lane, low-volume and high-speed rural roads where maintenance activities were completed in a single day. Speed and volume data were collected for cars and trucks as they traveled through four work zones. These data were collected when no work zone traffic control was present, when normal work zone traffic control was set up, and when the test treatment was installed. The results for the portable rumble strips were mixed, with passenger cars experiencing less than a 3.2-km/h (2-mph) reduction in mean speed approaching the temporary traffic-control zone. The impact of the rumble strips on trucks was more pronounced, with mean speed reductions approaching the temporary traffic-control zone of up to 11.6 km/h (7.2 mph) lower than normal traffic control. The percentage of vehicles exceeding the speed limit in the advance warning area was also reduced when the rumble strips were used. The speed display was generally more effective than the rumble strips at reducing speeds in the advance warning area. Mean speeds were often reduced approaching the activity area, with speed reductions of up to 16.1 km/h (10 mph) being achieved. The percentage of vehicles exceeding the speed limit was also reduced in the advance warning area.

Wang et al (18) conducted research to identify the potential of fluorescent orange sheeting, innovative message signs, and changeable message signs with radar for reducing speeds in highway work zones. The study investigated the effect of each strategy immediately after implementation (immediate effect) as well as several weeks after implementation (novelty effect). In addition to the overall effect of each strategy on all vehicles, the study included the effect on specific vehicle types during various lighting conditions. The researchers collected traffic data before, immediately after, and 2 to 3 weeks after the implementation of each strategy (3 consecutive weeks for the changeable message sign). They collected data upstream of the temporary traffic-control zone, in the advance warning area, and adjacent to the active work area. The researchers used various statistical tests to evaluate the significance of speed changes from phase to phase and adjusted vehicle speeds with the upstream speed changes over time. The study indicated that fluorescent orange sheeting and innovative message signs help reduce speeds at highway work zones (with diminished influence over time). Moreover, both strategies influence vehicle speeds more during the day than at night. Drivers of passenger vehicles tended to decrease their speeds more than truck drivers did. Changeable message signs with radar significantly reduced vehicle speeds in the immediate vicinity of the sign and did not demonstrate a novelty effect.

2.2 Traffic Control Devices in Work Zones

As mentioned in the previous chapter, nighttime work zone crashes are generally rare events primarily because of the relatively short duration and length of most work zones combined with drivers' perception of elevated risk while traveling through work zones. The safety benefits that can be attributed to improved visibility/conspicuity of traffic control devices can only truly be evaluated through the direct measurement of devices' impact on crashes. However, because of the transient nature of work zones it is difficult to identify causal relationships between crash occurrence and various work zone characteristics. In order to circumvent this challenge, surrogate measures like driver behavior and performance are often utilized. The common surrogate measures that are pertinent to work zone safety include:

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

The comprehensive search identified a number of studies that dealt with driver behavior/performance and investigated the effectiveness of steady burn warning lights used on various channelization and/or delineation devices in work zones. This research obtained valuable guidance from these studies related to experimental design, field data collection methods, MOEs, and data analysis.

McGee et al (19) conducted a study with an objective to develop a performance requirement or standard for the detection and recognition of retroreflective traffic control devices used in work zones. The scope of the study was limited to an analytical exercise and drew on existing information and data where possible. The discussion focuses primarily on those channelization devices frequently used in work zones (i.e., drums, barricades, panels, and cones). The performance standard developed in this study was established from the principles of driver information needs and, specifically, the requirement for decision sight distance. The performance standard is presented in terms of visibility requirements, that is; the distance at which motorists should be able to detect and recognize the devices at night. The standard selected was a minimum distance of 275 m (900 ft) when illuminated by the low beams of standard automobile headlights at night under normal atmospheric conditions. This appears to be a reasonable, yet arbitrary, standard which should cover most situations.

Garber et al (20) conducted a two-phase longitudinal study to identify the impacts of

Changeable-message signs (CMSs). The first phase, conducted by Garber and Patel, examined the short-term effectiveness of the CMS with radar in reducing vehicle speeds in work zones. In the second phase, some of the results presented, evaluated the influence of the duration of exposure of the CMS with radar on its effectiveness in reducing speeds in work zones. Speed and volume data for the population were collected at the study sites by automatic traffic counters placed at the beginning, middle, and end of each work zone. In addition, the speeds of individual drivers who triggered the CMS by exceeding the threshold speed were also recorded (using a video camera) at two other locations within the work zone for several weeks and then analyzed. The results of the study indicated that the duration of exposure of the CMS does not have a significant impact on speed characteristics and driver behavior. Therefore, the CMS continues to be effective in controlling speeds in work zones for projects of long duration. The results also indicated that the CMS with radar reduces the probability of speeding in work zones and this effect is maintained for up to at least 7 weeks.

Dudek (21) summarized the New Jersey Department of Transportation initiated research study designed in part to further the state-of-knowledge of changeable message sign message designs with specific application to the needs of the state of New Jersey. Laboratory studies of human factors are described here; the studies were conducted in New Jersey to evaluate shorter alternative messages than those currently used to display time of day, days of week, and calendar dates. These types of messages are often displayed on portable changeable message signs used in highway work zones. Among the findings were that a dash can be used instead of the term Thru to indicate roadwork for a range of successive days; the term Weekend is not a good descriptor for work that begins on Friday evening and ends on Monday morning; the term Days did not connote specific day time or off-peak times for roadwork, but it may be satisfactory for certain time periods; likewise, the term Nights did not connote specific night time or off-peak times for roadwork, but it may be satisfactory for certain time periods; Nite is an acceptable substitute for Night; and calendar dates were not easily translated by drivers to specific days of the week.

Bligh et al (22) summarized several research studies sponsored by the Texas Department of Transportation to evaluate the impact performance of various work zone traffic control devices, such as temporary and portable sign supports, plastic drums, sign substrates for use with plastic drums, traffic cones, and vertical panels. Work zone traffic control devices themselves may pose a safety hazard to vehicle occupants or work crews when impacted by errant vehicles. Thus, there was a need to research the safety performance of work zone traffic control devices to ensure that they perform satisfactorily and meet *NCHRP Report 350* guidelines. Specifically addressed are the studies on barricades. Standard wooden barricade construction was found to be unacceptable due to a demonstrated potential for intrusion of fractured members into the occupant compartment. In response to deficiencies identified in the wooden barricade tests, several alternate barricade designs were developed and successfully tested.

Bryden et al (23) presented a quality assurance program that was developed and implemented by the New York State Department of Transportation to manage work zone traffic control on department projects. Using a standardized process, a team of experienced engineers inspect a large sample of projects across the state each year. Standard rating forms are completed to describe the temporary traffic control observed on each project. "Emphasis points," which describe recurring areas of concern, are evaluated on each project, and a quality rating is assigned using a standardized six-point 0 to 5 scale to describe the overall condition and effectiveness of the project. Quality goals have been established both for average ratings for regional program areas and for individual projects. Implementation of this quality assurance program over the past 14 years has led to a substantial improvement in the quality of work zone traffic control on New York State projects.

Bryden (24) examined 461 work zone crashes involving Category 3 and Category 4 work zone safety features, portable traffic signs, and work vehicles and equipment. Category 3 devices include crash attenuators and temporary traffic barriers. Category 4 devices include trailer-mounted arrow panels, changeable message signs, and light towers. Crash data reported here, compiled from recent New York State Department of Transportation construction projects, shows that portable signs and Category 4 devices are involved in a small number of crashes and rarely result in injuries to vehicle occupants or workers. The use of traffic barriers or attenuators to reduce crash frequency and severity involving these devices is not indicated, because severity rates on temporary barriers and work zone attenuators are higher than on the devices they would be used to protect. Both work zone attenuators and temporary barriers were involved in a substantial number of crashes and injuries. These crashes emphasize the importance of deploying the devices according to accepted work zone practices and limiting their use to situations in which they are warranted to protect more serious hazards. Worker injuries reported in a number of these crashes emphasize the importance of safe work practices such as restraint use by vehicle occupants, even at slow speeds in work zones, and effective separation of workers from traffic in work zones.

2.3 Steady Burn Warning Lights

Pain et al (25) conducted research on the design and use of channelization devices so they could be more effectively used for positive guidance in a work zone. All the field experiments for the research were conducted on highways with a speed limit of 55 miles per hour and including stationary, long-term work zones. The effectiveness of several channelizing devices and configurations were examined for spacing, reflectivity and the presence of steady burn warning lights using an instrumented automobile. In particular, the impact of steady burn warning lights on driver behavior was compared with two types of retroreflective sheeting; Type II (engineering-grade sheeting) and Type III (high-intensity sheeting). The steady burn warning lights were found to add considerable detection distance to drums with Type II sheeting and more than triple the distance in which the lane change occurs prior to the taper. The steady burn warning lights on drums were found to be effective on each or alternating devices and the presence of lights in tapers was not statistically different than those that are on each or alternating drums in the tangent sections. Type III retroreflective sheeting was significantly better at night than the Type II sheeting. It was also found that the Type III sheeting and steady burn warning lights were comparable in terms of lane change location and detection distances along straight roadways; however, the effect of vertical and horizontal curves on roadways should be considered when selecting only reflective sheeting due to the angle of the headlights of approaching vehicles. NCHRP Report 236 concluded that steady burn warning lights do provide additional delineation to guide drivers through a work zone during night time driving conditions. The main advantage of the steady burn warning lights was longer detection distance which promoted early lane changing. As the lights are self-illuminating, the lights are not dependant upon the headlights of approaching vehicles as is the case with retroreflective sheeting. The steady burn warning lights would also be suitable for tangent sections, but the spacing could be on alternating channelizing devices or spaced at longer intervals. The steady burn warning lights can also enhance the delineation of the channelizing devices near horizontal and vertical curves, if the lights are properly maintained. The authors recommend the use of steady burn warning lights at night, particularly for taper sections, approach ends, and curved roadways. The steady burn warning lights can be used on all channelizing devices in a taper and on all or alternating devices in tangent sections of work zones.

Shepard (26) performed a study to investigate vehicle guidance through work zones by evaluating the effectiveness of two primary components of traffic control relative to delineation. First, a comparison of the steady burn warning lights now used on top of temporary concrete barriers was made with experimental reflectorized panels. Second, the addition of closely spaced, raised pavement markers as a supplement to the existing pavement markings was evaluated. The study was limited to work zones on Interstates and four-lane highways. The results of this investigation have led to the recommendation that (a) steady burn warning lights on temporary concrete barricades should be replaced with reflectorized panels fabricated with high-intensity sheeting and placed along the tangent sections only and (b) closely spaced, raised pavement markers should be used as a supplement to existing pavement striping in areas where the roadway alignment changes.

FDOT (27) recommended the continued use of steady burn warning lights on channelizing devices. Districts are, therefore, advised to enforce and maintain the use of channelizing devices in accordance with Index 600 requirements, and to cease with any further independent field experiments being conducted on this matter. The Maintenance of Traffic Committee (MOTC) received several requests from the Districts to revisit the Department's policy requiring the use of Type C steady burn warning lights during hours of darkness on channelizing devices. In response, the MOTC reviewed a number of studies completed by different states and educational institutions which provided a range of recommendations and conclusions. Among those studies reviewed, several appear to point to "little or no benefit" when installing steady burn warning lights in work zones. The discussions range from "no effect in tangent areas" to "minimal benefit" in transitional areas dealing with specific driver reactions. On the other hand, none of the studies established provide sufficient evidence to support a decision to eliminate the use of steady burn warning lights at this time. Additionally, none of these studies were conducted in areas that would represent the unique driving characteristics in Florida, which includes large numbers of elderly road users and tourists, both domestic and foreign.

Finley et al (28) performed research to assess the effectiveness of a flashing warning-light system for use at work zone lane closures. The system is composed of a series of interconnected, synchronized flashing warning lights that produce the illusion of motion. Researchers investigated motorist understanding and perceived usefulness of various designs of the warning-light system, and the potential of this system to yield significant operational or safety benefits in actual work zone applications. Results from proving ground and field studies show that the flashing warning-light system used in the work zone lane closure is perceived positively and is not confusing to the motoring public. The field-study results also revealed that the prototype warning-light system may encourage motorists to vacate a closed travel lane farther upstream from the work zone (which is believed to offer a potential safety benefit). When the warning-light system was activated at the urban freeway test site, a relatively new closure, there was a one-fourth reduction in the number of passenger vehicles and a two-thirds reduction in the number of trucks in the closed lane 305 m (1,000 ft) upstream of the lane closure. However, the system did not significantly affect lane choice at the rural road test site where the lane closure had been installed for 6 months. Thus, the greatest potential safety benefit of the warning-light system may be when it is used in conjunction with short-duration or intermediate-term maintenance in construction projects.

Pant et al (29) embarked upon a research 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 researchers studied the effectiveness of steady burn warning lights on drums with high-intensity retroreflective sheeting along tangent sections of rural, unlighted, four-lane divided highways under dry, rainy and foggy weather conditions. The sample size for the study was 132 motorists between 16 and 75 years of age. The actual number of driver subjects for each type of lane closure scenario, right lane or left lane, was 66. The drums utilized for the work zones were spaced at 100 to 120- foot intervals with some of the drums and pavement markings in the work zones dirty and worn. Each subject drove an instrumented vehicle along one of three rural work zones with speed limits of 65 or 55 miles per hour with a video camera installed on the roof of the automobile to collect the data. The data was collected during three time periods; day time conditions, night time conditions with the steady burn warning lights and night time conditions with the steady burn warning lights covered. The data collected in the research analysis included speed, lateral placement, acceleration noise and weaving data. Lateral placement was defined as the distance between the vehicle and the longitudinal pavement marking. Acceleration noise was defined as the frequency of speed change cycle. Weaving was defined as the "rate of change in lateral displacement of unit time." The data for the right and left lane closures were separately analyzed with hypotheses for speed, lateral placement, acceleration noise and weaving tested. The hypotheses were tested by performing t-tests for the means and F-tests for the variances at a level of confidence of 95% or alpha equal to 0.05. Paired-t tests were also performed for the noted measures of effectiveness. The mean speeds, speed variances, lateral placement, acceleration noise and weaving at each site were tested separately for the day time conditions compared to the night time conditions with the steady burn warning lights, the day time conditions compared to the night time conditions without the steady burn warning lights and the night time conditions with the steady burn warning lights compared to the night time conditions without the steady burn warning lights. The data for all the sites were then combined to perform the remaining tests. The data was also categorized by weather condition, age of subjects, gender and those that noticed the removal of the steady burn warning lights. Hypotheses were tested for each of these categories as well. The authors concluded that the steady burn warning lights have little to no effect on driver performance in tangent sections of rural, unlighted, and divided highways. The authors 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 noise or weaving. The recommendation of this study was to discontinue the use of steady burn warning lights along tangent sections of construction work on rural divided highways.

A second study by Pant et al (30) in 1991 examined the effectiveness of steady burn warning lights on divided and undivided highways with horizontal and vertical curves, with and without ambient lighting, ramps, tapers and crossovers. Again, an instrumented vehicle was used as the measurement tool for 107 human subjects as they drove through a 0.75 mile long work zone during day time conditions and night time conditions with the steady burn warning lights and night time conditions without the steady burn warning lights. The work zones were delineated with drums at 100 to 120-foot intervals in the tangent sections and 50- foot intervals in the taper sections. The steady burn warning lights were maintained in good condition with the pavement markings and drum conditions varying from good to poor and dirty. The drivers did not drive the instrumented automobile in the same sequence to assure unbiased results in the study. Both right and left lane closures were utilized with right and left curves in the work zone. The instrumented automobile was equipped with a video camera on the roof that provided a six-foot view of the roadway including a partial view of the front exterior of the automobile. The automobile was also equipped with underbody lights that illuminated the pavement markings for better photography during night time driving conditions. The authors stated that these lights did not provide extra illumination of the driver's path. The measures of effectiveness were speed, lateral placement, acceleration noise, weaving, traffic conflict, lane change and driver preference. The measures of speed, lateral placement, acceleration noise and weaving were defined similar to the previous Pant and Park study (29). Traffic conflict was defined as an unusual or evasive action taken by the driver while driving through the construction zone. The authors felt that the presence of a traffic conflict in the absence of steady burn warning lights would indicate a dangerous situation for the driver and others on the roadway. The distance from the work zone where the motorists changed lanes in a lane closure situation was the measure of lane change. Driver preference was the observation of any difference between the work zones to measure whether or not the driver noticed the steady burn warning lights or not. Hypotheses were tested by performing two-tailed t-tests for the means and F- tests for variance at a level of confidence of 95% or alpha equal to 0.05 for each site and travel direction separately and again for combined travel directions of each site. A paired-t test was performed at a level of confidence of 95% or alpha equal to 0.05 to test the hypothesis that the mean speeds during any two of the three test periods (day, night with steady burn warning lights and night without lights) were equal. Z-tests were performed to test the significance of lane change with and without steady burn warning lights for each site separately for any two of the three test periods. The authors concluded that steady burn warning lights had no impact on driver behavior regarding speed, lateral placement, acceleration noise, weaving and traffic conflict. The absence of steady burn warning lights also did not have an impact on the lane changing behavior of motorists at night. Only 9 of the 107 subjects noticed the absence of steady burn warning lights during their driving trials. This study recommended that the use of steady burn warning lights along curved, lighted, unlighted and tapered sections of roadways with ramps and crossovers be discontinued.

KLD Associates (31) investigated the effectiveness of steady burn warning lights mounted on drums in terms of delineation and positive guidance for drivers on the approach and through a highway work zone. ATSSA is a national trade association representing over 900 companies involved with traffic control and highway safety. This research consisted of a laboratory experiment as well as a field experiment. In the laboratory experiment, 53 subjects were exposed to 288-35 millimeter slides of work zones under the night time driving condition with steady burn warning lights on all the drums, alternating drums or none on the drums. The subjects were exposed to three work zone configurations; right lane closure, right shoulder closure and left lane closure with the spacing of the drums at 40-foot or 80-foot intervals. The subjects were required to chose the correct driving action that they would take given the configuration of the work zone shown on the 35- millimeter slides at four distance perspectives from the work zone; 250-feet, 500-feet, 700-feet and 900-feet. The study found no significant differences between the three light configurations of steady burn warning lights on all drums, alternating drums or none of the drums. There was a significant difference in response accuracy for those subjects older than 54 years of age and those younger. As expected, the younger subjects yielded a more accurate response. For subjects under the age of 25 at the shortest observation distance of 250 feet, the drums without lights produced better results. However, for those over 65 years of age, lights on alternating drums produced significantly better results at distances of 700 and 900-feet. Based upon the age-distance interaction, a field experiment was conducted to determine the effect various channelizing devices, work zone configuration, warning light use, observation distance and subject age had on the benefits of steady burn warning lights. In addition to drums, vertical panels were tested while the work zone configuration and warning light use remained similar to those tested during the laboratory experiment. The observation distances were modified to 400-feet, 700-feet, 1020-feet, 1350-feet, 1700-feet and 2600-feet. Thirty additional motorists were then subjected to the field study where they were asked to determine the correct action required, as well as which traffic control device was preferred. In this study, the motorists were driven through 16 simulated work zones during the night time hours along a closed section of roadway in Delaware. The subjects changed their seating position every fourth run to assure each subject sat in each vehicular position, other than the driver seat, for four trials. The research study stated that the seating position did not influence the results. The correct response increased for all subjects the closer the observational distances were to the work zone. The percentage of correct responses was higher for the scenario incorporating lights on all the drums for the right lane closures for distances between 2060-feet and 1350-feet from the work zone. However, the scenario without lights on the drums produced better correct responses for the right lane closure between 1350-feet and 400-feet from the work zone than the scenarios with lights or alternating lights. For the left lane closure scenario, the full light scenario produced higher correct responses for distances between 2060-feet and 1350-feet than the no light scenario; however, the no light scenario produced higher correct responses between 1350-feet and 400-feet from the work zone than the full light scenario. Regardless, in the left lane closure scenario, the alternating light scenario produced higher correct responses than the full light and no light scenarios for all distances. For all scenarios, the age group less than 54 years of age responded with higher correct responses than their older counterparts. For the age group greater than 54 years of age, the absence of lights on the channelizing devices produced poor results for the left lane closure, but produced better results in the right lane closure scenario. The authors of the study concluded that steady burn warning lights are effective in influencing driver behavior for distances exceeding 1200-feet. They also concluded that the use of steady burn warning lights on drums are more effective than drums without lights for older drivers. The study recommended the use of steady burn warning lights on alternate channelizing devices for left lane closures. The study did not recommend the use of steady burn warning lights for right lane closures unless high speeds, low visibility, inclement weather or complex maneuvers were required on behalf of the drivers. In these situations, the study recommends steady burn warning lights on all devices for right lane closures.

McAvoy et al (32) performed research to determine the effectiveness of drums with and without the addition of steady burn warning lights in terms of both safety and delineation. A field experiment was conducted throughout the State of Michigan at construction work zone sites on the state's major arterial roadways and freeways, all with various geographical, environmental, and traffic conditions. A total of 15 sites were used for the study (5 interstate, 4 other freeways, and 6 arterials). A work zone site using traffic drums without the addition of the steady burn warning lights was indicated as a "test" site. A work zone site using traffic drums with the addition of steady burn warning lights was indicated as a "control" site. Traffic operational and safety data was collected for each site including traffic crash data, speed data at various locations in the work zone, lateral placement of vehicles, and number of steering reversals. Data was collected in the off-peak hours in the night-time between 9:00pm to 6:00 AM where motorists are free to travel at their desired speed, un-impeded by congestion. Traffic crash data was collected from the Michigan State Police database for each of the study sites. Dates and locations of the crashes were investigated to determine location of crash in the work zone, and whether or not steady burn warning lights on drums were present. At all locations, crash data was collected during the construction period, and one year prior to the said construction period. A comparison using the Poisson Test was made of the crash data for both control/test sites for all the sites combined, the interstates only, freeways only, and arterials only. Results indicate that the number of crashes that occurred during the construction period and for the same period one year prior was similar for 3 of the 6 control sites and 2 of the 9 test sites. Of the control sites, 1 experienced 4 less crashes during construction than during one year prior. The remaining two sites both had two more crashes during the construction period than during one year prior. Four of the test sites experienced an average of two less crashes during construction as compared to prior to construction. The other three experienced an average of two more crashes during the construction period. Thus, the total number of crashes before construction, and during construction for all the test and control sites remained the same. Therefore, it was concluded that there is no difference between the crash rate before and after the installation of traffic control devices in a work zone for both control and test sites. Speed data was collected for vehicles using portable radar detectors at all the sites. Speed data was taken, in general, at the beginning, middle, and end of the work zone during night time conditions. Speed was used as an indication of the motorists' perceived risk of traveling though work zones with and without steady burn warning lights. For test and control sites, group mean speeds and 85th percentile mean speeds were determined. The statistical "t" test was used when comparing the mean speed for a group of test sites with a group of control sites using the 'comparative parallel' evaluation plan. Results indicate no difference in control sites and test sites group mean speeds with a 95% confidence level. Lateral placement data was also taken and quantified in order to assess the ability of drums with and without steady burn warning lights in guiding travelers through a work zone. Driver behavior and vehicle placement was recorded using a digital video camera mounted inside a survey vehicle, following target vehicles. Recording was done for a number of runs through the advanced warning area and the work zone area during night time hours at each site. With the recorded data, lateral placement of the vehicle can be assessed by locating the vehicle in three positions; center of the lane, in the right third of the lane, or in the left third lane. Acceptable lateral placements are the two positions furthest away from the traffic drum. Results show that the percentage in acceptable lane position for control sites and test sites were 92% and 94% respectively. The percentage in acceptable lane position for freeway test sites and freeway control sites were 99% and 91% respectively. Finally, the percentage in acceptable lane positions for arterial control sites and test sites were 95% and 97% respectively. Based on the results, no difference is noticeable between the acceptable lane position percentages for the control sites and the test sites at a 95% confidence level.

Finally, the steering reversal frequency data was also collected similar to that of the lateral placement. For each site, the mean number of steering reversals per vehicle was calculated as the average number of steering reversals observed per vehicle, per site. The average steering reversals per minute for all control sites was 2.54 and 1.84 for test sites. The average steering reversals per minute was 3.08 for interstate control sites and 2.34 for that of test sites. The freeway control sites averaged 2.72 steering reversals per minute while the test sites averaged 1.35. Lastly, the arterial control sites experienced 1.64 average steering reversals per minute in comparison to 1.47 for that of test sites. Overall, there were less steering reversals for the test sites than the control sites. Based on these results, at a 95% confidence interval, again, no significant difference in the number of steering reversals is seen between control and test sites.

Based on the results, McAvoy et al concluded the following:

- There are no significant differences between crashes before and after the installation of the construction zone for both control (with steady burn warning lights on drums) and test (without steady burn warning lights on drums) work zones.
- Statistical analysis of the speed data indicate no difference between the mean and 85th percentile speeds at that of control sites and test sites.
- Statistical analysis of the lateral placement/steering reversals data indicates no significant differences between lateral placement of vehicles while driving through test sites and control sites. However, for most of the grouped comparisons, for lateral placement, the test sites without steady burn warning lights had a higher percentage of vehicles in an acceptable lateral position. Also, in terms of steering reversals, for most of the grouped comparisons, it was seen that the test sites again, without steady burn warning lights on drums, had a lower number of steering reversals per vehicle per minute, and thus, can be considered a safer driver performance.
- Overall, the findings conclude that there is no significant difference in delineation and safety between drums with and without steady burn warning lights. Findings are consistent with that of previous studies (29,30).

2.4 Photometric Properties and Standards for Work Zone Drums

To be effective, work zone traffic control devices must be visible both day and night far enough in advance of a given situation to allow for suitable reaction time. Nighttime visibility of work zone channelizing devices, including 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 adhered to the drum,
- Any auxiliary light sources affixed to the drum,
- Location of the driver with respect to the drum, and
- Visual characteristics of the driver.

2.4.1 Photometric Characteristics Related to Work Zone Drums

It is first necessary to understand basic photometric characteristics used to describe the "brightness" of a work zone drum. 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 (33). 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. For a work zone drum, reflection is provided by two sources: 1) retroreflection of the vehicle's headlamp illumination from the retroreflective sheeting material affixed to the drum and 2) diffuse reflection of ambient light. Emission is provided by an attached light source, such as a steady burn warning light, if present. 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).

Luminance is often confused with other photometric characteristics like illuminance and retroreflectivity. It is important to understand the clear distinction between these terms. Luminance is the amount of light leaving a surface while illuminance is the amount of light striking the surface (33). Retroreflectivity can be defined as the coefficient of retroreflected luminance and is the ratio of retroreflected luminance to the perpendicular headlamp illuminance. Retroreflectivity is essentially a measure of the "efficiency" of a material, such as sheeting or pavement markings, to reflect headlamp illumination back to the driver's eye. 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. Minimum in-service levels for sign retroreflectivity are specified by 2009 MUTCD, but no retroreflectivity minimums are given for pavement markings (4). Table 1 summarizes the basic photometric units typically used in photometric characteristics-related research for traffic control devices.

Table 1: 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 E1709-09 (34) 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 (35) 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°.

As mentioned earlier, retroreflectivity is not an appropriate measurement for light emitting sources, such as a steady burn warning light attached to a work zone drum. It should be used 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. Fontaine et al in Texas used luminance in their work zone-related research for measurement of the brightness of work zone garments (36).

2.4.2 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:

- Detecting the drums,
- Recognizing the message being conveyed by the drums (i.e., taper, lane shift).
- Deciding on the appropriate reaction,
- Initiating response, and
- Completing 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 (37). 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 (38,39). 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

(40) 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 (37,38,39,40), 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 (19) 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 (19). 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.

2.4.3 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 (41). The minimum luminance recommendation of 2.4 cd/m^2 for traffic control devices was referenced by Chrysler (42) 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 E-Modified font legends (43). Schnell et al (44) 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 (45). Similarly, younger drivers have been shown to possess detection distances that are on average 55 percent longer than older drivers (39). 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 (45). 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.

2.5 Summary of Literature Review

A concise summary of all the information reviewed under the literature review section was performed and the following conclusions were derived:

1. Rear-end crashes are the predominant type of work zone crashes during daylight hours while fixed object crashes are predominant at night (8,9). Crashes that involve construction workers account for 30% of the work zone crashes while crashes that involve motorists outside the construction area account for the remaining 70% of work zone crashes (10).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 (11,12). The activity area is the predominant location of work zone crashes regardless of highway type. The use or non-use of steady burn warning lights on drums was found to have no significant impact on work zone crashes (32).

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 investigating the effectiveness of steady burn warning lights on various channelization and/or delineation devices in work zones were found in the literature review (8,9,10,11,12,13). The behavioral/performance-related MOEs utilized in these evaluations included:
    - Lateral placement of vehicles within the travel lane,
    - Erratic maneuvers (i.e., rapid alignement 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 (25). 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 (31). 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 (29,30,32). 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 (30).
6. Luminance is a general measure of “brightness” and represents the quantity of visible light leaving a point on a surface in a given direction (33). 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.
7. 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 (37,38,39,40). 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.
8. 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 (41,42,43,44). Minimum luminance

values within this range are conservative when applied to detection of work zone channelization, as 1) they relate to the more complex task of legibility (i.e., reading) rather than simply detection of a situational characteristic such as that provided by channelizing drums and 2) drums provide a larger target compared to sign text.

CHAPTER 3: Problem Statement and Objectives

3.1 Problem Statement

Until recently, plastic drums with steady burn warning lights had been the primary channelizing device utilized in work zones throughout the State of Michigan for several years. The decision to use steady burn warning lights on drums in Michigan and elsewhere was made prior to the existence of highly visible retroreflective materials. However, the recent use of sheeting materials with improved retroreflectivity, including high intensity and microprismatic (i.e., prismatic) materials, has prompted investigation into the value and effectiveness provided by the steady burn warning lights when used with channelizing drums. Agencies throughout Michigan have begun using drums without warning lights in certain work zones, while several Michigan work zones continue to use drums with steady burn warning lights. This provided an excellent opportunity for an extensive comprehensive field evaluation of the value and effectiveness of steady burn warning lights on work zone channelizing drums in Michigan. Although previous research has explored the effectiveness of steady burn warning lights on drums both in Michigan and elsewhere, these efforts included a relatively limited number of work zone sites and/or focused on controlled human factors experiments and provided inconclusive results with respect to the value that steady burn warning lights provide. Furthermore, microprismatic sheeting materials were recently allowed for use on drums in Michigan work zones to increase visibility of the devices. To address these issues, research was undertaken to explore the impacts associated with the use of steady burn warning lights on channelizing drums considering a variety of work zone scenarios utilized in Michigan.

3.2 Objectives

The purpose of this research was to evaluate the safety impacts associated with the use of steady burn warning lights on drums in roadway work zones in Michigan. The following research objectives were addressed in this study:

1. Determine the state-of-the-art of work zone channelization through a comprehensive literature review.
2. Determine the state-of-the-practice regarding the use of steady burn warning lights by roadway agencies throughout the United States.
3. Assess the crash experiences of states with respect to the work zone steady burn warning light policy or practice.
4. Evaluate the impacts that steady burn warning lights on channelizing drums have on work zone crash occurrence in Michigan.
5. Evaluate the driver behavioral impacts associated with the use of steady burn warning lights on channelizing drums in Michigan work zones.
6. Determine the degree by which steady burn warning lights affect the overall brightness of work zone drums in Michigan.
7. Assess the overall impacts of steady burn warning lights on work zone safety.

3.3 Methodological Summary

A comprehensive research methodology was developed to address these objectives. The initial tasks involved a comprehensive review of the current state-of-the-art and a state DOT survey related to the use of drums or other channelizing devices in roadway work zones, both with and without the presence of steady burn warning lights. 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. To further supplement the crash data, a series of field studies were performed at 36 Michigan work zones to provide a more in-depth evaluation of differences in driver behavior and performance with respect to the use of steady burn warning lights. In addition to these field studies, a series of luminance tests were also conducted to assess the relative brightness levels provided by drums with and without warning lights. The luminance tests were performed both in the field and in a controlled environment to gauge the impacts of steady burn warning lights on drum visibility.

Established sampling procedures were utilized to determine the target sample sizes necessary to assess statistical inference on the MOEs. The data were collected for each study component under a variety of representative field conditions, which included different types of roadways, work zone configuration, levels of ambient lighting, roadway geometry, and other factors. Each of the MOEs were analyzed using appropriate statistical techniques to determine the impacts of steady burn warning lights and the impacts of other factors. A synthesis of the results allowed for conclusions and recommendations to be drawn with respect to the impacts of steady burn warning lights on work zone safety. A full description of the research performed including data collection, analysis, results, conclusions, and recommendations can be found in the chapters that follow.

CHAPTER 4: Current Practice Survey

As a part of this research, an attempt was made to understand the current practices of various departments of transportation (DOTs) throughout the country. A questionnaire survey was developed and distributed to appropriate DOT representatives within each state. Initially, the survey was distributed via email. Telephone follow-ups were performed on an as needed basis to obtain information from the agencies that did not respond to the emails. These telephone follow-ups also helped clarify responses that were not clear or missing. Detailed information related to work zone standards for each DOT, including the usage of drums with or without steady burn warning lights and alternative channelizing devices that were used for both day and night time operations, was collected. Survey was first administered in November 2009 and completed in August 2010. A copy of the blank survey questionnaire is provided in Appendix A.

A total of 41 DOTs responded to the survey. Therefore, including Michigan DOT, information about usage of steady burn warning lights was obtained for a total of 42 DOTs. Eight state DOTs did not respond to the survey. Details pertinent to the usage of steady burn warning lights on drums from these 42 state DOTs are shown in Figure 3. The full survey responses that were obtained from the DOTs are included in Appendix B. A summary of these responses are presented as follows:

- Of the 42 responding DOTs, fifteen DOTs (35.7%), currently or in the recent past, used steady burn warning lights on drums or other devices to some degree.

  Out of these fifteen DOTs:

  - Three DOTs (Florida, Illinois, and Oklahoma) reported frequent usage of steady burning warning lights on drums (≥ 30 %) in work zones.

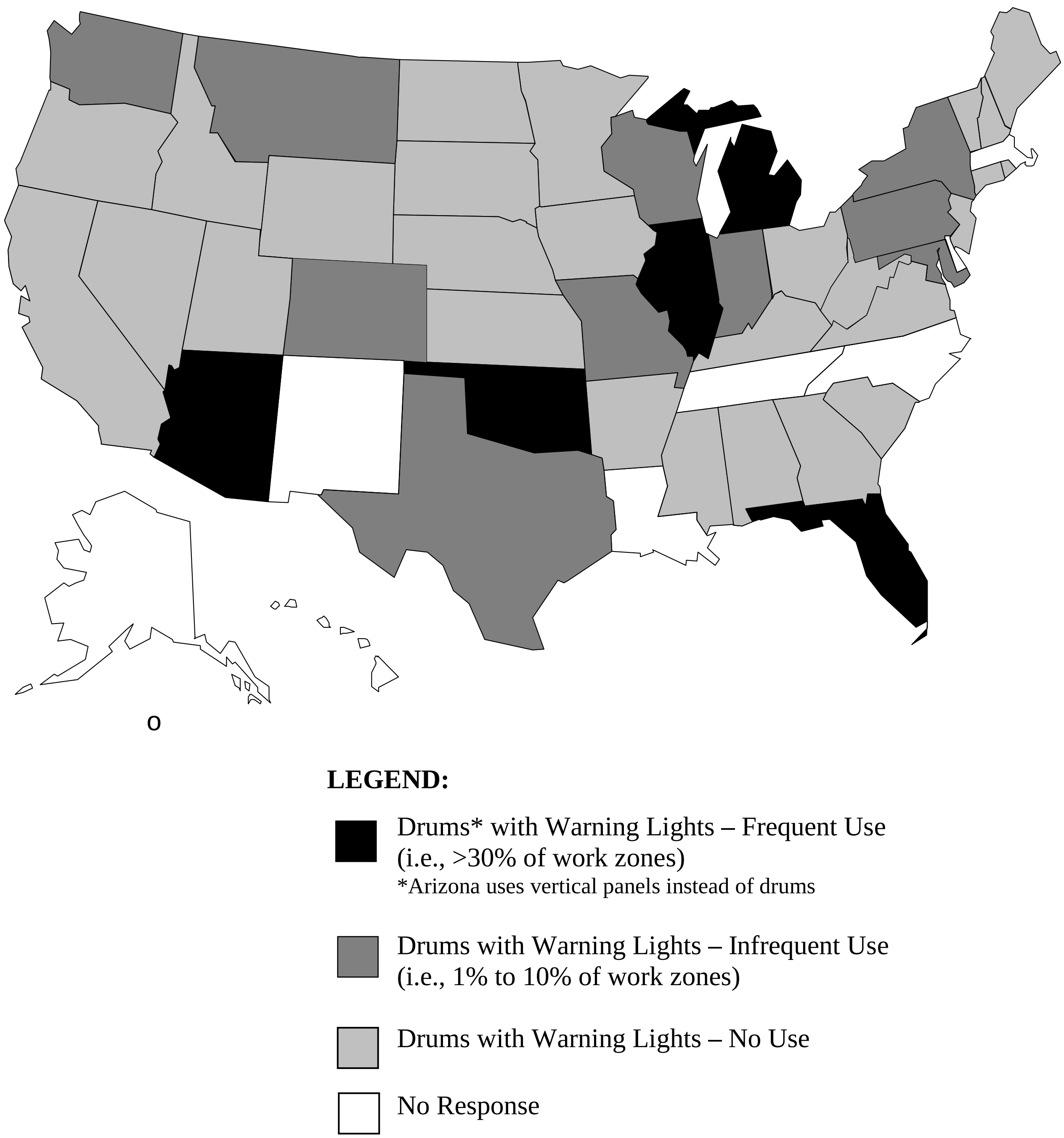


Figure 3: State-of-the-Practice Pertaining to the Use of Warning Lights on Channelizing Drums in Work Zones in the United States

  - Arizona DOT also reported frequent usage of steady burn warning lights, although this usage was mostly for vertical panels rather than drums.
  - Michigan DOT had used steady burn warning lights on all work zone drums that were left in place overnight for all the construction projects that were let until August 6, 2009. Projects let after this date do not use steady burn warning lights on drums, as per the moratorium issued by MDOT.
  - Ten DOTs (Colorado, Indiana, Maryland, Missouri, Montana, New York, Pennsylvania, Texas, Washington, and Wisconsin) reported infrequent usage of steady burn warning lights. This ranged anywhere from 1 % to 10 % of all work zones. It is important to mention that those agencies which infrequently used steady burn warning lights on drums mentioned that lights were or have been used for specific applications like, spot hazards, tapers, lane shifts, and crossovers.
- The remaining 27 DOTs (64.3 % of the respondents) mentioned that they do not use steady burn warning lights on work zone channelizing devices. Work zone channelization is provided by using drums or other types of channelizing devices without steady burn warning lights, like cones, vertical panels or tubular markers.
- With respect to the grade of retroreflective sheeting used on drums and other work zone channelizing devices:
  - No DOT reported using engineer-grade sheeting (ASTM Type I & II) for work zone drums.

  - Eight DOTs (Arizona, Idaho, Illinois, Maryland, New Jersey, New York, Rhode Island, and Utah) reported microprismatic sheeting (ASTM Type VII and above).
  - Eleven DOTs (Alabama, Connecticut, Florida, Georgia, Iowa, Michigan, New Hampshire, North Dakota, Pennsylvania, Washington, and Wyoming) reported high-intensity retroreflective sheeting (ASTM Type III) with microprismatic sheeting (ASTM Type VII and above) given as an option.
  - Thirteen states (Arkansas, Colorado, Mississippi, Missouri, Montana, Nebraska, Nevada, South Carolina, Texas, Vermont, Virginia, West Virginia, and Wisconsin) reported high-intensity retroreflective sheeting (ASTM Type III) only.
- Of all the responding DOTs, seven had performed studies on the effectiveness of steady burn warning lights on drums (Florida, Michigan, New Jersey, Ohio, Texas, Utah, and Wisconsin). Of these seven, four DOTs, including Michigan, have subsequently ceased or have begun phasing-out using steady burn warning lights. 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.

CHAPTER 5: Field Evaluation Methodology

In order to identify if driver behavior and performance related aspects differ between work zones with vs. without steady burn warning lights on drums, extensive field studies were conducted in numerous work zones that used drums as the primary channelization devices. These studies were conducted during periods of darkness so that the data was gathered during conditions when the warning lights were illuminated and presumably most effective. Work zones where these studies were performed were located on both MDOT and locally maintained roadways and were spread throughout the Michigan's Lower Peninsula. This research utilized a comparative parallel study design as the data were concurrently collected at separate work zone locations, including locations with steady burn warning lights and locations without steady burn warning lights. Before-and-after analyses were not performed.

As work zone channelization assists drivers in tasks like maintaining a safe speed and path through the work zone, it follows that the crash risk associated with channelization would be associated with behavioral characteristics related to the ability of drivers to maintain a safe lane position and speed control while negotiating the work zone. Therefore, a careful selection of surrogate MOEs related to driver behavior/performance was performed to provide an indication of the relative crash risk pertaining to the work zone channelization.

5.1 Measures of Effectiveness

Several measures of effectiveness (MOEs) were used to quantitatively assess the effectiveness of steady burn warning lights on drums from the data collected during the field evaluations. The driver behavioral MOEs were similar to those used in previous research by Pant et al (31,32) and McAvoy et al (6). These MOEs were as follows:

- Percent of time each subject vehicle 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. Therefore, a higher percentage of time spent in the center lane position represents a traffic safety benefit. Furthermore, a lower percentage of time spent in the lane position closest to the drums also represents a traffic safety benefit;
- Percent of time each subject vehicle spent in the lane position closest to the drums – As mentioned above, a higher percentage of time spent in the lane position closest to the drums presents a greater potential for a driver to encroach into the work area and thus, represents a negative safety impact;
- Rate of steering reversals for each subject vehicle, per minute - Steering reversals can be explained as a driver's inability to maintain a consistent lane position. Thus, a lower rate of steering reversals represents a traffic safety benefit;
- Percent of drums that were damaged – Damage to a drum is often caused by vehicular collisions. Therefore, lower percentages of damaged drums indicate fewer vehicular intrusions into the work area; and
- Vehicular speed characteristics – Difference in vehicular speed characteristics 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. Reduction in other vehicle speed characteristics, such as the 85^{th} percentile speed or mean speed, provide evidence of additional safety benefits due to reductions in crash severity and stopping distances.

- Mean luminance – Increased luminance was considered a safety benefit as it relates to improved brightness of the device. This MOE was assessed both for data collected in actual work zones and in a controlled environment.

5.2 Sample Size Determination

As mentioned above, data were collected regarding the specific MOEs, they are: 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; 5) the percent of drums that were damaged; and 6) Mean luminance. The characteristics of the data used to compute a particular MOE influences the selection of the appropriate statistical sample size equation. In a situation where data are reported as percentages or proportions, the formula shown below can be used to estimate the number of vehicles that should be observed within each of the two groups (drums with and without steady burn warning lights) in order to identify the specified difference between the MOEs calculated for the two groups:

$$n = \frac{\left[z_{\alpha/2} \sqrt{(p_1 + p_2)(q_1 + q_2)/2} \right]^2}{(p_1 - p_2)^2}, \qquad \text{Equation 1}$$

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

$q_1 = 1 - p_1$

$q_2 = 1 - p_2$

Furthermore, if the data are reported as rates or percentages, 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 calculated for the two groups:

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

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

As a part of this study, using sample data from one particular location and assuming a significance level (α) of 0.05 (per standard statistical practices), the minimum number of subject vehicles required to detect a statistically significant difference in each MOE was determined. Target sample sizes for each of the five MOEs under consideration were determined using the following sample estimates based on sample data collected at a single location:

- 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

It was 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. Table 2 shows 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. Based on the minimum sample size estimates shown in Table 2, the researchers determined, based on the largest sample size for any of the tracking-based MOEs, that a minimum sample of 532 vehicles would be obtained from each group of work zone locations. This would allow for detection of a minimum difference between the two groups (i.e., locations using drums with steady burn waning lights vs. locations using drums without steady burn warning lights) of 0.50 steering reversals per minute and 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 drums observations were necessary to detect a 5-percentage point difference in drums that were damaged.

5.3 Site Selection

A total of 36 work zones in 15 counties across lower Michigan were selected for use in this evaluation. The work zone locations were randomly selected from a list of active work zones in the lower peninsula of Michigan. It was required that each study location include one or more continuous sections of channelizing drums that 1) remained in-place throughout the night and 2) were at least ¼ mile in length, which was assumed as the minimum distance to effectively assess driver behavior. It was not necessary for work to be performed at night.

Table 2: Sample Size Requirements for Study Measures of Effectiveness

MEASURE OF EFFECTIVENESS (MOE)	MINIMUM SAMPLE SIZE 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 SAMPLE SIZE 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

The characteristics for each of the 36 work zones are presented in Table 3. Thirty of the 36 work zone sites were located on MDOT roadways, while the remaining six sites were on local roadways. The work zones selected for use in this study collectively represented a broad range of scenarios, including:

- Drums with steady burn warning lights and drums without steady burn warning lights,
- Drums with high intensity sheeting and drums with microprismatic sheeting,
- Single lane closures, double lane closures, and shoulder closures,
- Roadway lighting and no roadway lighting,
- Undivided arterials and freeways,
- Drums on the left and drums on the right,
- Various drums offsets from the edge of the lane,
- Locations with and without horizontal curvature, and
- Urban and rural environments.

Table 3: Characteristics of Work Zone Safety Sites

Site	County	Length of W.Z. (mi)	Drum Lights	Roadway Light	Roadway Type	Area Type	Horizontal Alignment
M-59	Oakland	6.5	Yes	Mixed	Freeway	Urban	Curved
M-59	Oakland	2.1	No	Yes	Freeway	Urban	Curved
I-96	Wayne	12.0	Yes	Yes	Freeway	Urban	Curved
M-39	Wayne	1.7	No	Yes	Arterial	Urban	Straight
US-24	Oakland	1.0	No	Yes	Arterial	Urban	Straight
I-275	Wayne	9.7	No	No	Freeway	Urban	Curved
I-75	Monroe	2.0	No	No	Freeway	Rural	Straight
I-75	Monroe	8.0	No	No	Freeway	Rural	Straight
I-675	Saginaw	7.9	Yes	Mixed	Freeway	Urban	Curved
I-696	Macomb	4.0	Yes	Yes	Freeway	Urban	Straight
M-43	Ingham	2.0	Yes	Yes	Arterial	Urban	Straight
M-1	Wayne	1.5	No	Yes	Arterial	Urban	Straight
I-75	Monroe	2.5	No	No	Freeway	Rural	Straight
I-94	Kalamazoo	0.5	Yes	No	Freeway	Urban	Curved
US-131	Kalamazoo	6.6	No	No	Freeway	Rural	Curved
US-12	Wayne	1.3	No	Yes	Arterial	Urban	Straight
I-94	Washtenaw	13.0	Yes	No	Freeway	Rural	Straight
I-94	Jackson	2.7	No	No	Freeway	Rural	Curved
I-75	Bay/Saginaw	3.7	No	No	Freeway	Rural	Straight
Rochester Rd	Oakland	1.0	No	Yes	Arterial	Urban	Straight
John R Rd	Oakland	1.0	No	Yes	Arterial	Urban	Straight
Geddes Rd	Washtenaw	0.5	No	No	Arterial	Urban	Straight
I-196	Allegan	6.7	Yes	No	Freeway	Rural	Straight
US-24 Business	Oakland	1.1	No	Yes	Arterial	Urban	Curved
I-75	Wayne	1.5	No	Yes	Freeway	Urban	Straight
M-17	Washtenaw	1.0	Yes	Yes	Arterial	Urban	Straight
Utica Rd	Oakland	1.0	No	Yes	Arterial	Urban	Straight
I-96	Ottawa	15.3	Yes	No	Freeway	Rural	Curved
I-196	Kent	2.5	No	No	Freeway	Urban	Curved
I-94 Business	Berrien	1.5	Yes	Yes	Arterial	Urban	Straight
I-94	Berrien	19.0	Yes	No	Freeway	Rural	Curved
I-94	Macomb	3.0	No	Yes	Freeway	Urban	Curved
M-40	Van Buren	1.6	No	Yes	Arterial	Urban	Curved
I-696	Macomb	4.0	No	Yes	Freeway	Urban	Curved
Metro Pkwy	Macomb	1.0	No	Mixed	Arterial	Urban	Straight
19-Mile Rd	Macomb	2.0	No	No	Arterial	Urban	Straight

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.

5.4 Field Data Collection Procedures

Field data collection was performed at the study sites during periods of darkness between January and May of 2010. These studies were conducted from early evening (after dark) hours until the required number of samples were collected.

5.4.1 Driver Behavior

A two member crew along with a survey vehicle was utilized for the video data collection. The survey vehicle was used to covertly record the nighttime driver behavior data of randomly selected subject vehicles while they were followed through the work zone. This process of following a subject vehicle (each pass) typically started several hundred feet upstream of the work zone. The driver would position the vehicle a safe distance (i.e., 4 to 8 seconds) behind the selected subject vehicle as the survey vehicle approached the section of drums. In a situation where multiple lanes were available, vehicles that were traveling in the lane closest to the channelizing drums were observed. During this process of following a subject vehicle, the survey vehicle driver made reasonable attempts to maintain a 4 to 8 second spacing between vehicles.

A high definition video camera mounted on a tripod was utilized to covertly capture the behavior of the subject vehicle. Care was taken that 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. In order to assess the subject vehicle's lateral position within the travel lane, the camera's view was positioned to include a substantial distance beyond the left and right lane markings, including the channelizing drums. In order to make sure that the desired camera view was maintained, the passenger in the survey vehicle held the tripod in a uniform position throughout each pass. Camera position adjustments were only made if absolutely required to ensure a uniform field-of-view. After each pass, the driver would turn around at the nearest crossroad, turnaround, exit, or a driveway and the survey process was repeated in the opposite direction, assuming the work zone had two-directional traffic. If work zone was only in a single direction, then the survey vehicle went back to the starting position and repeated the process. A minimum of 20 passes per direction were typically obtained at each work zone.

Not all passes went smoothly or without interruption. Occasionally, a subject vehicle exited from the lane prior to the end of the work zone. In these cases, the driver of the survey vehicle would take reasonable measures to reposition the data collection vehicle behind the next closest subject vehicle, assuming a sufficient length of drums still remained. If an another vehicle merged between the vehicles, the survey vehicle driver would make necessary adjustments and continue following the new subject vehicle, again if sufficient length of drums was still left to cover.

Nighttime road work was active during data collection at six of the 36 study locations. Of these six locations, extensive work activity was being performed at three locations, while at the other three locations had localized bridge repair work. Fearing that the presence of workers and/or equipment would potentially bias the driver behavior characteristics, driver behavioral data were not collected in the proximity of the work area.

5.4.2 Luminance Measurement

Research was undertaken to explore the relative differences in the nighttime brightness characteristics between drums with and without steady burn warning lights used in a variety of work zone scenarios. Two evaluations were performed: 1) measurement of in-service-drum luminance in actual work zones and 2) measurement of drum luminance in a controlled environment. The objectives of this research were as follows:

- Controlled environment - Examine nighttime luminance characteristics of commonly used work zone drums with and without steady burn warning lights in a controlled environment.
- Field 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.

Selection of 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 was important. A review of the literature found that the most appropriate unit of measurement for comparing the relative brightness of drums with and without steady burn warning lights was luminance. This is because luminance describes the physical measure of brightness regardless of whether the light is reflected from the sheeting or emitted from the steady burn warning light. It is important to note that retroreflectivity is not an appropriate unit of measurement for this research as it is only applicable to reflective surfaces and not to light emitting sources, such as a steady burn warning light.

The instrument used for all luminance measurements was a Konica/Minolta LS-100. This utilizes a flareless fixed aperture single-lens-reflex optical system with a 1 degree acceptance angle. All drums and drum components observed in this study followed Michigan Department of Transportation (MDOT) standards (4). The sheeting materials affixed to the drums were ASTM D 4956 Type III sheeting (i.e., high intensity) or higher (i.e., microprismatic sheeting). All steady burn warning lights followed the current MDOT standard for Type C (i.e., steady burn) warning lights and included an LED enclosed inside a 360-degree yellow lens. MDOT's standard requires all steady burn warning lights to conform to the current Institute of Transportation Engineers *Purchase Specification for Flashing and Steady Burn Warning Lights* (46).

5.4.2.1 Controlled Environment

This research involved nighttime luminance measurement of several drum scenarios at the top of a large parking structure on the campus of Wayne State University. The objective was to evaluate the luminance impacts associated with the presence/absence of a steady burn warning light in a controlled environment from a stationary vehicle. This evaluation utilized three sample drums with each of them having a different sheeting type and/or condition. The sheeting on these drums met or exceeded MDOT's in-service standards. All drums used were MDOT standard size, measuring 36 inches tall with a top diameter of 18 inches. Each drum had a 360 degree amber steady burn warning light that 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 shown below:

- Sheeting Type – Three types of sheeting were used, they are:

  - New high intensity sheeting
  - Used high intensity sheeting
  - Used microprismatic sheeting

- Drum lighting condition – Both with and without conditions were evaluated:
  - Steady burn warning light on drum
  - No warning 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 – Two different vehicles with different driver eye height levels and headlamp characteristics were used, including:
  - 2002 Oldsmobile Alero
  - 2008 Ford E-Series Cargo Van

Luminance data for each combination of the above mentioned conditions were obtained. Therefore, a total of 3*2*2*2 = 24 drum scenarios were measured during the controlled evaluation.

The vehicle used for the study was first carefully positioned at the predefined location with its center aiming straight ahead to make sure a consistent headlamp alignment. The vehicle was not moved from this spot until all the measurements were completed; rather the drums were moved or modified accordingly to form the predefined drum scenarios. For all the measurements, the vehicle's low beam headlamps were utilized.

As was measured in the field, all drum scenarios' luminance was measured through the windshield from the passenger seat of the vehicle from a distance of 200 ft. This 200 ft.

measurement distance corresponds to the distance where in the drum and warning light fits into the 1-degree aperture measurement circle on the luminance meter. Care was taken to ensure that the measurement circle was positioned identically for all drums, regardless of whether or not it had a steady burn warning light. As each drum possessed a warning light, the “without warning light” condition was created simply by covering the light with dark heavy towel. Figure 4 shown below displays the photographs of drums with and without steady burn warning lights viewed at a distance of 200 ft.

In order to keep a consistent level of background luminance, the drum technician wore dark clothing and stood behind the drums. However, it was not possible to block the parking structure lighting during the study and therefore some amount of ambient lighting was present as can be seen in Figure 4. It is important to note that care was taken to minimize the impact of ambient lighting by keeping the drums as far away from the sources as possible and were approximately 50 feet from the nearest lamp post’s base. Furthermore, since the drums were placed in identical locations during each test, all scenarios had consistent ambient light.

5.4.2.2 Field Evaluation of Drum Luminance

A total of 15 work zones in 10 counties within Michigan were randomly selected for this field luminance evaluation. These work zones were all under MDOT jurisdiction and were on limited-access freeways. These identified work zones represented different scenarios collectively. They include:

- 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

(a) Used prismatic drum

(b) Used high intensity drum

Figure 4: Example Drum Scenarios Used in the Controlled Evaluation

(Taken from the 2002 Olds Alero at 200-ft with a 6-ft lateral offset from the vehicles center)

- Urban and rural environments.

The collection of field luminance was performed between the hours of 10:30 PM and 4:00 AM on dry nights in late-May and early-June of 2010. Luminance data was collected by a two person crew driving through the work zone at low speeds. 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.

Similar to video data collection, 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 such 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 of the meter 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. Figure 5 provides examples of the luminance measurement area (within the circle) at a distance of approximately 200 feet for drums with and without steady burn warning lights.

All luminance data were measured from the travel lane that was adjacent to the drums. Luminance data were only collected for continuous sections of channelizing drums that were parallel to the travel lane on flat, straight sections of roadway. Drums were positioned no more than 4-ft from the edge of the travel lane. In order to remove any potential biasing factors, measurement of the luminance was not performed 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 a another vehicle were traveling closely behind the data collection vehicle, stray light from the

trailing vehicle's headlamps may tend to inflate the subsequent luminance measurements;

(a) Drums without steady burn warning lights, unlit freeway, prismatic sheeting

(b) Drums with steady burn warning lights, unlit freeway, high intensity sheeting

Figure 5: Field Luminance Measurement Examples

- 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.

Table 4 presents the list of all the locations where luminance data was collected and also the basic characteristics of these work zones.

5.4.3 Drum Physical Condition and Spacing

Information related to the physical condition of the drums along with the spacing from the edge of the road was assessed as a part of field data collection. This information was collected at 29 work zones, out of which 12 work zones used drums with steady burn warning lights while the other 17 used drums without steady burn warning lights. The drum condition information was extracted from the videos collected as part of the driver behavior evaluation described in the previous section.

Table 4: 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

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, 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.

5.4.4 Vehicular Speeds

Collecting spot speed data within a work zone required positioning of data collector within the work zone limits. However, most of the times it is challenging to get a safe spot for the data collector to park the car for gathering spot speeds. Because of these difficulties, spot speed studies were conducted at at total of 13 work zone locations, seven of which were locations without steady burn warning lights and six were 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 were 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 were also collected in both directions. To reduce the possibility of external bias, care was taken to collect data only 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. No workers were present at the work zone locations during any of the speed data collection efforts. The summary of the sites where speed data were collected are shown in Table 5.

Table 5: Characteristics of Freeway Work Zone Locations for Speed Measurement

SITE	COUNTY	WARNING LIGHTS ON DRUMS	WORK ZONE POSTED SPEED LIMIT (MPH)*	ROADWAY LIGHT	AREA TYPE
US-131 (Center to Flowerfield)	Kalamazoo	No	60/45	No	Rural
I-94 (Sergeant to Race)	Jackson	No	60/45	No	Rural
I-196 (Fuller to M-37)	Kent	No	60/45	No	Urban
I-94 (10 Mile to 12 Mile)	Macomb	No	60/45	Yes	Urban
I-696 (I-94 to Hayes)	Macomb	No	60/45	Yes	Urban
I-275 (Sibley to Huron River)	Wayne	No	60/45	No	Urban
I-75 (MM5 to MM11)	Monroe	No	60/45	No	Rural
I-94 (US 131 to Westnedge)	Kalamazoo	Yes	60/45	No	Urban
I-94 (Baker to Jackson Co.)	Washtenaw	Yes	60/45	No	Rural
I-96 (48^{th} to 68^{th})	Ottawa	Yes	60/45	No	Rural
I-94 (US-12 to I-94 BR)	Berrien	Yes	60/45	No	Rural
M-59 (Mound to Van Dyke)	Oakland	Yes	60/45	Mixed	Urban
M-59 (Adams to Dequindre)	Oakland	Yes	60/45	Yes	Urban

* Workers not-present/workers present

5.5 Extraction of Diver Behavior Data from Videos

Video data was gathered from more than 1,200 total passes of the survey vehicle through the study work zones. This video data was 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.

From the video data, each pass through the work zone was reviewed and specific characteristics of the behavior for each subject vehicle were 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 where channelizing drums were present. The following information was obtained for each subject vehicle during the review:

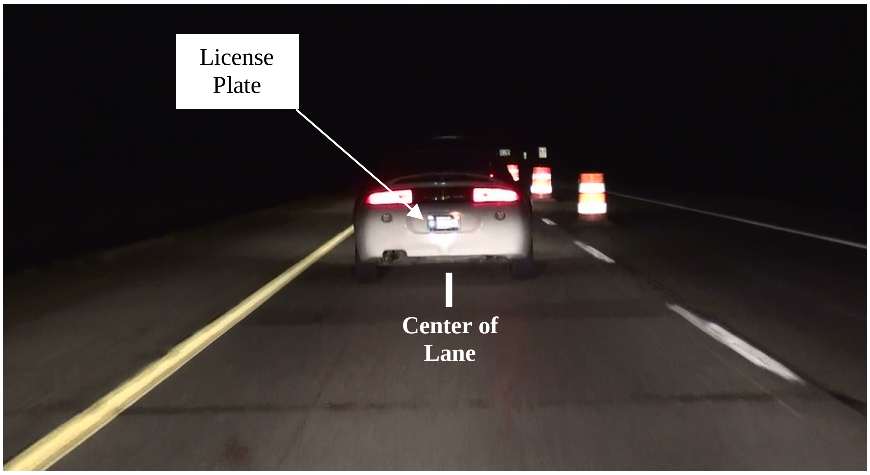
- Time spent in left-of-center lane position,
- Time spent in center lane position,
- Time spent in right-of-center lane position,
- Total tracking time, and
- Frequency of lane position changes (i.e., steering reversals).

Prior to reviewing the videos, each observer was trained according to the following procedures. An initial training session was provided for each of the observers in which the instructor demonstrated the techniques for extracting the necessary data from a sample video. The observers were then provided with a set of training videos that included 12 vehicles tracked through a work zone. Each observer was instructed to determine both for each vehicle and overall 1) the percent time spent in each of the lateral positions and 2) the number of steering reversals. Upon completion of the training videos, the extracted vehicular data for each observer was then compared to the instructor's data, which were considered to represent the "true" values. The lateral positioning data were considered "correct" if they were within 2% of the instructor's values, while the raw steering reversal data were considered correct if they were within one reversal. If any of the data did not comply with the specified tolerances, the observer was provided with targeted feedback and required to reassess all training videos. This was repeated until the observer met the specified tolerances for all MOEs. The average observer required three reviews of the training videos to fall within the specified tolerances.

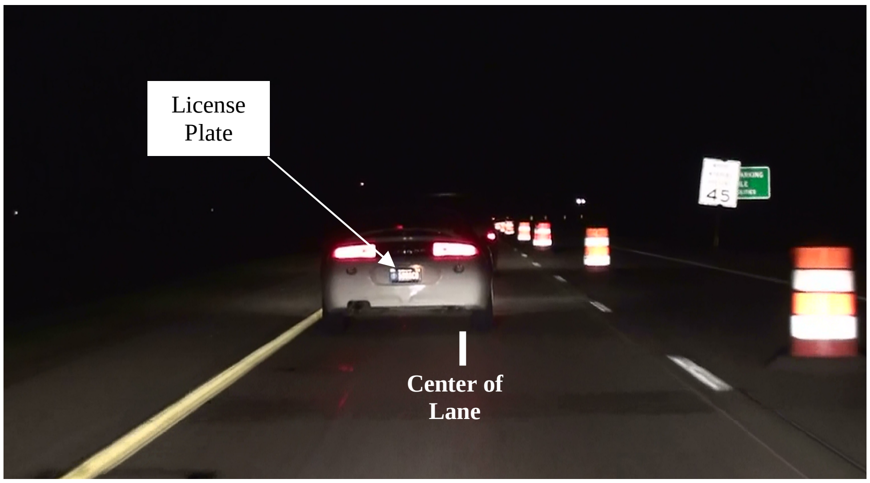
To provide consistent boundary definitions for each of the three lateral positions, the video reviewers were instructed to fixate their view on the position of the vehicle's license plate with respect to the center of the lane, provided that the license plate was centered on the vehicle. A vehicle was 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 6. 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 software. All times were recorded 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 were 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 were tabulated and coded into a single data set for analysis.

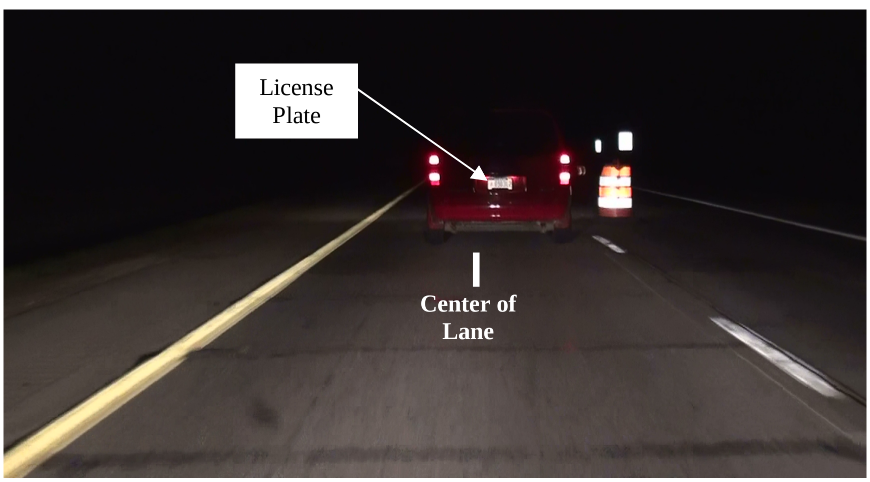
Each MOE was computed such that equal weighting was given to all subject vehicles, regardless of the amount of time that each vehicle was tracked. The following example provides an explanation of the procedure by which each MOE was computed for a subject vehicle.



a. Center Lane Position



b. Left-of-Center Lane Position



c. Right-of-Center Lane Position

Figure 6: Example of Vehicular Lateral Lane Position Assessment

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 for this vehicle was computed as (3/56)*60 = 3.21 steering reversals per minute. The percent time this vehicle 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 vehicles included in the data set.

5.6 Site Categorization

As mentioned in the previous sections, work zones selected for use in this study collectively represented a broad range of 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,
- Undivided arterials and freeways,
- Drums on the left and drums on the right,
- Various drums offsets from the edge of the lane,
- Locations with and without horizontal curvature, and
- Urban and rural environments.

Using the above mentioned criteria the sites were categorized into different groups for analytical purposes. Note that not all grouping factors were used for all MOEs because in many cases only a subset of the study sites was utilized for a specific evaluation.

5.7 Statistical Analysis Methods

The statistical significance of the impact of using the drums with and without steady burn warning lights was tested in order to better understand whether the changes observed in the MOEs are attributable to the steady burn warning lights on the drums.

Appropriate statistical analyses techniques were determined, to compare data between locations with and without steady burn warning lights, after sample data for each MOE were examined.

Two-sample Z-test of proportions was used to compare data expressed in terms of percentages, this can be calculated by the following general formula:

$$Z = \frac{P_{with} - P_{without}}{\sqrt{P_{total}\left(1 - P_{total}\right)\left(\frac{1}{n_{with}} + \frac{1}{n_{without}}\right)}} \qquad \text{Equation 3}$$

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).

Test of equality of means was used to compare those MOEs that are expressed in terms of a continuous random variable. Such tests include Student's t-Test, Welch's t-Test, or non-parametric equivalents such as the Mann-Whitney U Test. The appropriate test among these is determined based upon whether the underlying data are 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 are normally distributed with equal variances, Student's t-Test is appropriate; if the data are normally distributed with unequal variances, Welch's t-Test is appropriate; and if the data are 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 also expanded to a multi-factor analysis of variance (as an alternative to the t-Test) or using the Kruskal-Wallis Test (as an alternative to the Mann-Whitney U Test). For example, the lane positioning data were 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).

CHAPTER 6: Results of Field Evaluation

The results of the statistical analyses of all the field data collected are discussed in this chapter. The analyses were performed using the General Linear Model procedure in PASW (formerly SPSS) version 18.0 (47).

6.1 Driver Behavioral Factors

As mentioned earlier, a total of 36 sites were utilized for the driver behavior characteristics. From these sites data a total of 1,400 subject vehicles were obtained from the videos, representing an average of 38.9 vehicles per study site. Of the total sample of 1,400 subject vehicles, 793 were observed in work zones without steady burn warning lights on drums, while the remaining 607 were observed in work zones with steady burn warning lights on drums. One-hundred twenty-seven of the work zone pass videos included two or more subject vehicles, representing 10.2 percent of the 1,251 total passes. No significant differences were detected between the behavioral data obtained from passes containing multiple subject vehicles compared to passes containing a single vehicle.

The behavioral MOEs were analyzed using a multi-factor analysis of variance (ANOVA). All statistical inferences were determined at a 95 percent confidence level. Each of the three MOEs were analyzed individually. Main factor effects and interactions of the main factor effects were included in the ANOVA. The independent factors examined included:

- Steady burn warning light on drums (presence or absence),
- Roadway type (arterial or freeway),
- 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).

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 each vehicle spent in the center lane position was 39.99 and 39.52 for locations without and with steady burn warning lights on drums, respectively, representing a statistically insignificant difference of 1.2 percent. These results are shown in Table 6 along with the results for the other MOEs.

Table 6: Results of Driver Behavior Impacts Associated with Steady Burn Warning Lights on Drums

MEASURE OF EFFECTIVENESS	STEADY BURN WARNING LIGHT PRESENCE/ABSENCE	MEAN	Arithmetic Difference	Percent Difference	Are the Means Significantly Different?
Percent of Time Each Vehicle Spent in the Center Lane Position	Drums Without Light	39.99	-0.47	-1.2	No
	Drums With Light	39.52			
Percent of Time Each Vehicle Spent in the Lane Position Closest to Drums	Drums Without Light	7.14	+4.28	+59.9	Yes
	Drums With Light	11.42			
Steering Reversals per Minute for Each Vehicle	Drums Without Light	3.94	+0.8	+20.3	No
	Drums With Light	4.74			

Notes: These data represent 793 vehicles observed in work zones without steady burn warning lights on drums and 607 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 did impact drivers' tendency to travel in close proximity to the drums. The average percent time each vehicle spent in the position nearest the drums was 7.14 and 11.42 for locations without and with steady burn warning lights on drums, respectively, representing a statistically significant difference of 59.9 percent. This finding may indicate that drivers are more confident while driving through work zones with steady burn warning lights on drums or a natural tendency of drivers to drift toward the lights.

The presence of a steady burn warning light on the drums had a marginal impact on the rate of steering reversals. The average rate of steering reversals per minute for each vehicle was

3.94 and 4.74 for locations without and with steady burn warning lights on drums, respectively, representing a difference of 20.3 percent. However, the ANOVA results indicated that this difference was not statistically significant.

6.2 Other Roadway or Work Zone Related Factors

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. While none of these four factors were found to have a statistically significant impact on all MOEs, several statistically significant differences were observed. The ANOVA results for these additional factors are reported in Table 7. Note that these factors were tested simultaneously along with the presence or absence of steady burn warning light factor in the ANOVA model. As such, the ANOVA model controls for the effects of each of the other factors.

Table 7: ANOVA Results for Additional Factors Related to the Roadway or Work Zone

Factor	Level	No. of Vehicles	Pct. Time Each Veh. Spent in Center Lane Position		Pct. Time Each Veh. Spent in Lane Pos. Closest to Drums		Steering Reversals per Minute for Each Vehicle	
			Mean	Significant Difference?*	Mean	Significant Difference?*	Mean	Significant Difference?*
Roadway Type	Arterial	500	46.07	Yes	8.16	No	3.87	Yes
	Freeway	900	36.29		9.46		4.52	
Horizontal Alignment	Straight	705	41.44	No	7.96	No	3.85	No
	Curved	695	38.10		10.05		4.74	
Drum Side	Left	797	45.75	Yes	12.65	Yes	4.75	No
	Right	603	31.90		4.17		3.68	
Drum Dist. from Edge of Lane	<1-ft	540	41.84	Yes	8.31	No	3.90	No
	≥1-ft	860	38.50		9.43		4.53	

* Based on a 95-percent confidence level

Roadway type was found to significantly impact the center lane positioning and steering reversal MOEs. Vehicles traveling through work zones on arterial roadways had significantly higher rate of center lane positioning and a significantly lower rate of steering reversals compared to freeways. This may have been due to the fact that two-way traffic was often maintained through the arterial work zones, prompting drivers to maintain a centralized position between oncoming traffic and the channelizing drums.

Drum side (e.g., left or right) was found to have a statistically significant impact on both 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 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.

Drums positioned within 1-ft of the edge of the travel lane were found to significantly increase center lane positioning, although no impact was observed for the other MOEs. The horizontal alignment of the roadway did not have a significant impact on any of the three MOEs, although slight differences were observed.

Additional statistical testing was also performed for each of the MOEs by considering each of the independent factors (i.e., steady burn warning light, horizontal alignment, drum side, and drum distance from edge of lane) individually rather than together, as was the case for the ANOVA testing. The additional testing included both the independent sample t-test and the Mann-Whitney U-test, which is similar to the t-test, but does not require the data to be normally distributed. The results for each test for each MOE and factor are shown in Table 8, which show very little differences between the two tests for any of the variables.

Table 8: Comparison of t-Test and Mann-Whitney U-Test Results for Various MOEs

Factor	Pct. Time in Center Lane Position		Pct. Time in Lane Pos. Closest to Drums		Steering Reversals per Minute	
	Type of Test	**Statistical Significance of the Factor***	**Type of Test**	**Statistical Significance of the Factor***	**Type of Test**	**Statistical Significance of the Factor***
Steady Burn Warning Light	T-test	Not Significant	T-test	Significant	T-test	Significant
	U-test	Not Significant	U-test	Significant	U-test	Significant
Horizontal Alignment	T-test	Not Significant	T-test	Not Significant	T-test	Significant
	U-test	Not Significant	U-test	Not Significant	U-test	Not Significant
Drum Side	T-test	Significant	T-test	Significant	T-test	Significant
	U-test	Significant	U-test	Significant	U-test	Significant
Drum Dist. from Edge of Lane	T-test	Not Significant	T-test	Not Significant	T-test	Significant
	U-test	Not Significant	U-test	Not Significant	U-test	Significant

*At 95 percent level of confidence

6.3 Speeds

Spot speed studies were conducted at a total of 13 locations and all of these locations were on freeways because these locations had consistent work zone speed limits (i.e., 60 mph when no workers were present). Arterial locations were not utilized as the work zone speed limits varied widely. Of the 13 study locations, seven were within work zones without steady burn warning lights and six were within work zones with steady burn warning lights. All spot speed studies were conducted during nighttime conditions using a radar gun from a covert location on an overpass. Data were only collected under dry pavement conditions and only in work zones where no work was being performed at the time of the study. Only freely flowing vehicles were sampled. The summary of the speed data are shown in Table 9.

Comparing the resultant speed data between these groups of locations showed that the median, mean, and 85th percentile speeds tended to be 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 57.8 mph, 59.5 mph and 63.8 mph, respectively.

Table 9: 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)	85^{TH} % 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 (48^{th} to 68^{th})	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

Work zones on freeways with steady burn warning lights on the drums exhibited median, mean, and 85^{th} percentile speed of 60.9 mph, 63.4 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.

6.4 Drum Condition Assessment

The nighttime drum condition assessment was performed at 29 work zone locations. Of these, 17 locations did not have steady burn warning lights on the drums and 12 locations did have steady burn warning lights on the drums. When compared with each other, relatively minor differences between the two groups were observed. 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 are shown in Table 10.

6.5 Luminance

As mentioned earlier luminance data was collected both under controlled environment and also in actual work zones. The following sections describe the statistical analyses results obtained from the data collected under both conditions.

6.5.1 Controlled Environment

Each of the 24 drum scenarios was 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 11. 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 11 have been combined for the two vehicles used in the study.

Table 10: 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**				

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 R^2 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. 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/m^2 (59.3 percent) greater than the new high intensity drum and 8.45 cd/m^2 (177.1 percent) greater than the used high intensity drum.

Steady burn warning light presence had relatively little impact on luminance, although the impact was statistically significant. The addition of a steady burn warning light to the drum increased the average luminance by 0.11 cd/m^2 (1.3 percent) and 0.22 cd/m^2 (4.7 percent) for the new and used high intensity drums, respectively and 0.50 cd/m^2 (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 the F-statistics for 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.

Table 11: 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

The lateral offset of the drum also significantly impacted luminance, as the average luminance decreased by 1.56 cd/m^2 (21.3 percent) for the two high intensity drums and 2.41 cd/m^2 (16.7 percent) for the prismatic drums when moved from a 6-ft lateral offset to a 10-ft lateral offset.

6.5.2 Field Evaluation

Field luminance data was collected from 15 locations which yielded a total of 372 nighttime drum luminance measurements with 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 descriptive statistics for field measured luminance data are shown in Table 12.

Table 12: Descriptive Statistics for Field Luminance Evaluation

SHEETING TYPE	ROADWAY LIGHTING	STEADY BURN WARNING LIGHT	MEAN (cd/m^2)	STANDARD DEVIATION (cd/m^2)	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 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, 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. This finding was consistent with the controlled evaluation.

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.

6.5.3 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 7.

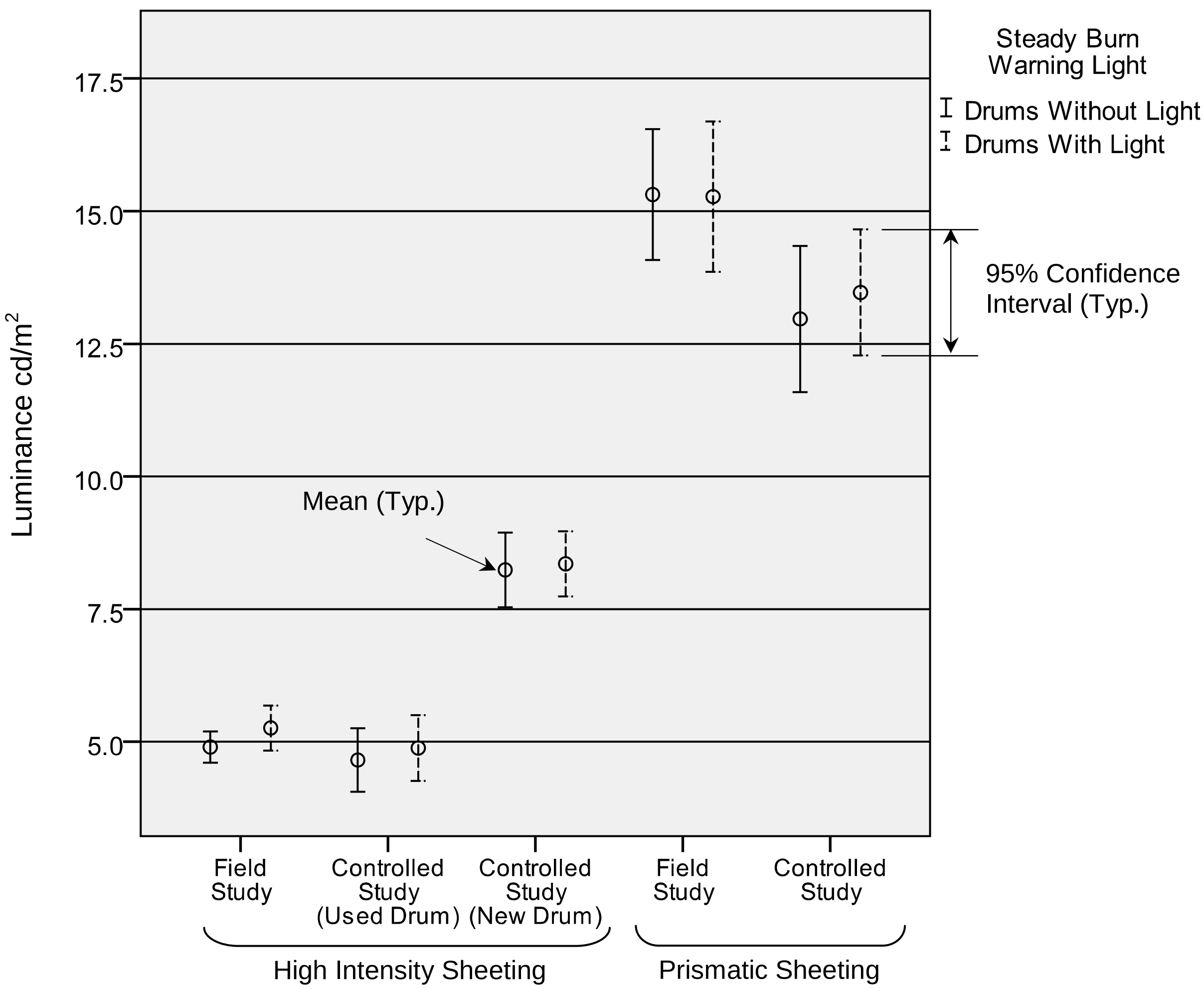


Figure 7: Mean and 95 Percent Confidence Interval for Drum Luminance by Evaluation Type, Sheeting Type, and Steady Burn Warning Light Presence

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.

An independent samples 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 13.

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.

Table 13: t-Test Results for Luminance Measured During the Field Evaluation Versus the Controlled Evaluation

SHEETING MATERIAL	EVALUA-TION	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

CHAPTER 7: Impacts of Steady Burn Warning Lights on Work Zone Crashes

Work zone crash data were examined for the state of Michigan and also other states where such data were available, as a part of this research. Crash trends were examined to see whether the use of steady burn warning light had any impact on such trends. Also, an in-depth study of crash data for specific work zones within the state of Michigan was performed. The results of these statewide and location-specific comparisons are presented in this chapter.

7.1 Work Zone Crashes in Other States

While performing the state-of-the-practice survey, additional data were 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. Also, additional data searches were conducted to identify other relevant sources of information that were available for each state. Data were requested for the period from 2006 through 2008. Complete information from 26 states was obtained for all of the requested data categories.

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

- 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).

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 14.

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 14: 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.

7.2 Work Zone Crashes on MDOT Roadways

Evaluation of statewide work zone crash trends did not show significant differences, however, a more detailed analysis of Michigan work zone crashes was conducted in order to gain further insight into the potential impacts 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.

Thirty-one 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 15 and 16, 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.

Tables 15 and 16 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 15: 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 15 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.

Table 16: 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	67
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 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 UD-10 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.

7.3 Statistical Evaluation of Steady Burn Warning Lights' Impacts on Work Zone Crashes

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 were 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. 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 17 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 17 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 17 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.

Table 17: Work Zone Crashes versus Steady Burn Warning Light Presence

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

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.

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 18 presents these comparisons for the locations with steady burn warning lights while Table 19 presents similar data for the work zones without steady burn warning lights.

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 one of the crashes in the work zones without steady burn warning lights involved such drivers. This difference was also not statistically significant.

Table 18: 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	DARK	TOTAL	DARK	TOTAL	DARK
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	-50.0%	-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	-28.0%	-2.0%
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%**

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 20 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.

Table 19: 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	DARK	TOTAL	DARK	TOTAL	DARK
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%**

Similarly, while older drivers are slightly over represented 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 20: 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%

CHAPTER 8: Conclusions and Recommendations

The primary purpose of this research was to evaluate the safety impacts associated with the use of steady burn warning lights on drums in roadway work zones in Michigan. Initial research tasks included a comprehensive review of the current state-of-the-art and a state DOT survey related to the use of drums or other channelizing devices in roadway work zones. From there, a series of field studies were performed at 36 Michigan work zones to provide an assessment of driver behavior and performance with respect to the use of steady burn warning lights. A series of luminance tests were also conducted to assess the relative brightness levels provided by drums with and without warning lights, both in the field and in a controlled environment in order to determine the impacts of steady burn warning lights on visibility of drums. A comparison of work zone crash trends was also performed, 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. Several conclusions were formulated based on the research results, which are described in the section that follows.

8.1 Conclusions

The presence of steady burn warning lights on work zone channelizing drums increased the occurrence of risky driver behavior, as evidenced by a higher proportion of drivers traveling too close to the drums, more frequent steering reversals, and higher vehicular speeds. This may be due to drivers possessing a greater level of confidence when driving past sections of drums with steady burn warning lights. These findings were further substantiated by the observance of a greater proportion of damaged drums at work zone locations with steady burn warning lights.

The presence of a steady burn warning light provided very little improvement to drum luminance under any condition. It was determined that the use of microprismatic sheeting materials provide considerably greater luminance increases for the drums compared to the addition of a steady burn warning light to the drum. The luminance increase observed after changing the drum sheeting from high intensity to prismatic was approximately 77 times greater than luminance increase attained by adding a steady burn warning light to the drum.

The state DOT survey revealed that only approximately one-third of the 42 responding state agencies utilize steady burn warning lights on channelizing devices in work zones and only one-tenth of the responding agencies utilize them on a frequent basis. The majority of agencies that use steady burn warning lights do so on an infrequent basis, typically for specific types of applications, such as at spot hazards, tapers, lane shifts, and crossovers.

The investigation of nationwide work zone crash statistics revealed only slight differences between the rates of work zone crashes for the various steady burn warning light usage practices. The states that frequently use lights on drums exhibited a slightly higher aggregate work zone crash rate, while the states that infrequently use lights on drums had the lowest aggregate crash rate. No discernable differences were observed between any of the three groups of states when examining work zone crashes as a proportion of total crashes. **This finding suggests that steady burn warning lights on channelizing devices do not impact work zone crash occurrence at night.**

The detailed review of Michigan work zone crash statistics revealed that a higher proportion of work zone crashes tended to occur during nighttime conditions at locations with steady burn warning lights compared to locations without steady burn warning lights. Deeper investigation showed that among the nighttime 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. **This finding suggests that steady burn warning lights on channelizing drums do not impact work zone crash occurrence at night.**

It should be noted that the use of steady burn warning lights introduces significant increases in both the initial drum costs and subsequent maintenance costs. The average MDOT unit contract cost in 2010 was approximately 130 percent greater for drums with steady burn warning lights ($46.00 vs. $20.00). 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 Michigan indicated that the typical in-service battery life for steady burn warning light is 6 to 8 weeks with a replacement cost of $2.00. Thus, for a standard MDOT work zone setup, on a per-mile basis, the materials and battery maintenance costs (equivalent uniform annual cost) were found to be between $5,744 (high speed work zones) and $7,157 (low speed work zones) greater for drums with steady burn warning lights. In addition to these tangible costs, it is also important to consider other factors, including the costs and environmental impacts associated with battery disposal and the increased risks created by the traffic exposure for workers during light or battery replacement. Collectively, these factors do not support the use of steady burn warning lights on drums in work zones.

Based on a synthesis of all results, steady burn warning lights demonstrate no substantive value to nighttime brightness, driver behavior, or crash prevention when used on channelizing drums in work zones. Thus, it was concluded that steady burn warning lights demonstrate no additional safety benefit when used on channelizing drums in work zones. Furthermore, steady burn warning lights may actually contribute to a <u>greater</u> crash risk due to the increase in risky driver behavior that was observed when steady burn

warning lights were present. These conclusions are consistent with those found in previous research on this topic, particularly research performed by Shepard, Pant et al, and McAvoy et al.

8.2 Recommendations

Drums with high intensity sheeting that is in good condition will provide adequate nighttime brightness for work zone channelization regardless of whether a steady burn warning light is attached or not. Therefore, it is recommended that the use of steady burn warning lights on work zone drums be discontinued. If additional nighttime brightness of the channelizing devices is desired, the use of microprismatic sheeting on the drums provides far greater increases in brightness than the addition of a steady burn warning light**.**

CHAPTER 9: Future Work

This research was successful in identifying the impacts of steady burn warning lights on the work zone safety. However, several related questions remain unanswered. As such, future work is recommended in the following four areas:

1. Quantifying the night time luminance requirements for the various traffic control devices used in work zones. Currently there are no minimum required luminance standards set for the work zones. Having this standard will help the road agencies to develop policies related to the visibility of work zone traffic control devices.
2. Quantifying the minimum retroreflectivity requirements for the sheeting materials used on the drums, assuming that no steady burn warning lights are utilized. Currently the sheeting materials used on the drums have a wide range of retroreflectivity values. Higher retroreflectivity values tend to increase the visibility/detectability of traffic control devices. However, higher retroreflectivity material tends to cost more therefore reasonable minimum values should be established.
3. Quantifying the minimum preview time necessary for proper lane positioning guidance with respect to work zone channelizing devices. Having a minimum preview time will help the road agencies in better designing the work zones, from optimizing the usage of channelizing devices stand point.
4. Determining what if any value is provided by steady burn warning lights in highly specialized environmental conditions, such as: fog or heavy rain; and under extreme changes in horizontal and/or vertical curvature, where headlamp transmission may not provide adequate retroreflectivity from the sheeting material. These conditions were outside the scope of this research, therefore can be considered for future studies.

APPENDIX A

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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Professor of Civil and Environmental Engineering
Wayne State University-Transportation Research Group
5050 Anthony Wayne Drive, Room #0504
Detroit, MI 48202
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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	
Alabama Department of Transportation	Jeff Benefield, benefieldj@dot.state.al.us (334)242-6213	Yes	No	Yes	Yes	Tubular Markers	6" Type III or IV (High Intensity Reflective Sheeting, or Prismatic Sheeting)	Yes	Not Sure	Not Available	Not Sure	N/A	No	No	N/A	No
Alaska Department of Transportation	Kurt Smith, kurt.smith@alaska.gov, (907)465-6963	DID NOT RESPOND														
Arizona Department of Transportation	Curtis Litin, clitin@azdot.gov, (602)712-8687	Yes	Rarely uses drums	No	Yes	Vertical Panels with Lights	6" Type IV (High Intensity Prismatic Sheeting) With a Class 5 Backing	No	N/A	Yes- Two Way	Over 20-25 Years	Usually only has lights on other devices and rarely ever uses drums in work zones.	Yes	No	N/A	No
Arkansas Highway and Transportation Department	Tony Sullivan, tony.sullivan@arkansashighways.com, (501)569-2231	Yes	No	Yes	Yes	None	4" Type III (High Intensity Reflective Sheeting)	Yes	Forever	No	N/A	N/A	No	No	N/A	No
California Department of Transportation	Gordon Wang, gordon_wang@dot.ca.gov, (916)653-7312	Not Available	No	Not Avail.	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
Colorado Department of Transportation	San Lee, San.Lee@dot.state.co.us, (303)9345	Yes	Very low use - 2%	Yes	Yes	Drums with Flashing Lights (2%)	(2) 4" to 6" Orange and White Stripes Type III (High Intensity Reflective Sheeting)	Yes	For Day Work	Yes- Two Way	Nighttime Work	Nighttime Work, Used to Delineate the edge of traveled way.	No	No	N/A	Yes, Separate Contact Info Given
Connecticut Department of Transportation	Terri Thompson, Terri.Thompson@ct.gov, (860)594-2667	Yes	No	No	Yes	None	(2) 4" Orange Stripes and (2) 6" White Stripes Type III or IV (High Intensity Reflective Sheeting, or Prismatic Sheeting)	Yes	Not Available	No	N/A	N/A	No	No	N/A	Yes, Separate Contact Info Given
Delaware Department of Transportation	Stephen Treut, steve.treut@state.de.us, (302)659-4088	DID NOT RESPOND														
Florida Department of Transportation	Stefanie Maxwell, stefanie.maxwell@dot.state.fl.us, (850)414-4314	Yes	Yes - 30% used	No	Yes	Tubular Markers, Vertical Panels	Type III or Better (High Intensity Reflective Sheeting, or Prismatic Sheeting, or Better)	No	N/A	Yes- Two Way	Over 20 Years	During Nighttime Hours & for Channelizing Devices	Yes	Yes	Available	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	
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

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ABSTRACT

EVALUATING THE USE OF STEADY BURN WARNING LIGHTS ON DRUMS FOR WORK ZONE SAFETY

by

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Roadway maintenance and repair has become increasingly commonplace in the United States over the past several decades as our roadway infrastructure has continued to age and deteriorate. Maintenance and repair work on an existing roadway often presents the challenge of maintaining traffic on the existing roadway while work is being performed, thereby necessitating the use of what is commonly referred to as a roadway “work zone”. One of the most important components of traffic control in a work zone is delineation of the edge of the traveled way, which assists drivers with tasks such as: lane selection; lateral positioning within a lane; and speed control. Delineation of the edge of the traveled way is commonly provided by a series of portable devices, such as drums, cones, vertical panels, or barricades. The type and duration of the work being performed often requires that these channelizing devices remain in place at all times.

Maintaining traffic through nighttime work zones poses increased risks for drivers and roadway workers due to the lack of ambient light. To help overcome nighttime visibility issues, the 2009 Manual on Uniform Traffic Control Devices (MUTCD) requires work zone traffic

control devices to be retroreflective or internally illuminated. To help supplement retroreflectivity, Section 6F.81 of the 2009 MUTCD allows for the use of auxiliary steady burn warning lights (SBWL) on work zone channelizing devices.

Until recently, plastic drums with steady burn warning lights had been the primary channelizing device utilized in work zones throughout the State of Michigan for several years. However, the use of sheeting materials with improved retroreflectivity, including high intensity and microprismatic (i.e., prismatic) materials, has prompted investigation into the value and effectiveness provided by the steady burn warning lights. Furthermore, although previous research has explored the effectiveness of steady burn warning lights on drums both in Michigan and elsewhere, these efforts included a relatively limited number of work zone sites and/or focused on controlled human factors experiments. As a result, research was undertaken to explore the impacts associated with the use of steady burn warning lights on channelizing drums considering a variety of work zone scenarios utilized in Michigan.

The primary goal of this research was to evaluate the safety impacts associated with the use of steady burn warning lights on drums in roadway work zones in Michigan. The following research objectives were addressed in this study:

1. Determine the state-of-the-art of work zone channelization through a comprehensive literature review.
2. Determine the state-of-the-practice regarding the use of steady burn warning lights by roadway agencies throughout the United States.
3. Assess the crash experiences of states with respect to the work zone steady burn warning light policy or practice.

4. Evaluate the impacts that steady burn warning lights on channelizing drums have on work zone crash occurrence in Michigan.
5. Evaluate the driver behavioral impacts associated with the use of steady burn warning lights on channelizing drums in Michigan work zones.
6. Determine the degree by which steady burn warning lights affect the overall brightness of work zone drums in Michigan.
7. Assess the overall impacts of steady burn warning lights on work zone safety.

A comprehensive research methodology was developed to address these objectives. The initial tasks involved a comprehensive review of the current state-of-the-art and a state DOT survey related to the use of drums or other channelizing devices in roadway work zones, both with and without the presence of steady burn warning lights. 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. To further supplement the crash data, a series of field studies were performed at 36 Michigan work zones to provide a more in-depth evaluation of differences in driver behavior and performance with respect to the use of steady burn warning lights. In addition to these field studies, a series of luminance tests were also conducted to assess the relative brightness levels provided by drums with and without warning lights. The luminance tests were performed both in the field and in a controlled environment to gauge the impacts of steady burn warning lights on drum visibility.

Established sampling procedures were utilized to determine the target sample sizes necessary to assess statistical inference on the measures of effectiveness (MOEs). The data were collected for each study component under a variety of representative field conditions, which included different types of roadways, work zone configuration, levels of ambient lighting, roadway geometry, and other factors. Each of the MOEs were analyzed using appropriate statistical techniques to determine the impacts of steady burn warning lights and the impacts of other factors.

The results showed that the presence of steady burn warning lights on work zone channelizing drums increased the occurrence of risky driver behavior, as evidenced by a higher proportion of drivers traveling too close to the drums, more frequent steering reversals, and higher vehicular speeds. These findings were further substantiated by the observance of a greater proportion of damaged drums at work zone locations with steady burn warning lights.

Steady burn warning lights were not found to provide substantial increases to the luminance of the drums either in the field or in a controlled environment. It was determined that the use of microprismatic sheeting materials provide considerably greater luminance increases for the drums compared to the addition of a steady burn warning light to the drum.

The state DOT survey revealed that only approximately one-third of the 42 responding state agencies utilize steady burn warning lights on channelizing devices in work zones and only one-tenth of the responding agencies utilize them on a frequent basis. The majority of agencies that use steady burn warning lights do so on an infrequent basis, typically for specific types of applications, such as at spot hazards, tapers, lane shifts, and crossovers.

The investigation of nationwide work zone crash statistics revealed only slight differences between the rates of work zone crashes for the various steady burn warning light usage practices. The states that frequently use lights on drums exhibited a slightly higher aggregate work zone crash rate, while the states that infrequently use lights on drums had the lowest aggregate crash rate. No discernable differences were observed between any of the three groups of states when examining work zone crashes as a proportion of total crashes.

A detailed review of Michigan work zone crash statistics revealed that a higher proportion of work zone crashes tended to occur during nighttime conditions at locations with steady burn warning lights compared to locations without steady burn warning lights. Deeper investigation 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.

Based on a synthesis of all results, steady burn warning lights demonstrate no substantive value to nighttime brightness, driver behavior, or crash prevention when used on channelizing drums in work zones. Thus, it was concluded that steady burn warning lights demonstrate no additional safety benefit when used on channelizing drums in work zones. Furthermore, steady burn warning lights may actually contribute to a greater crash risk due to the increase in risky driver behavior that was observed when steady burn warning lights were present.

Drums with high intensity sheeting that is in good condition will provide adequate nighttime brightness for work zone channelization regardless of whether a steady burn warning light is attached or not. Therefore, it is recommended that the use of steady burn warning lights on work zone drums be discontinued. If additional nighttime brightness of the channelizing devices is desired, the use of microprismatic sheeting on the drums provides far greater increases in brightness than the addition of a steady burn warning light.

AUTOBIOGRAPHICAL STATEMENT

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PUBLICATIONS/PRESENTATIONS:

1. "Pedestrian Safety on Livernois Avenue Corridor" presentation at ITE 2008 Technical Conference in Miami.
2. "Road Diet – Livernois Avenue" presentation at ITE Michigan Chapter, December 7, 2006.
3. "Trip-Generation Models for Multiuse Highway Commercial Developments", ITE Journal, Feb. 1998.
4. "Public-Private Partnership: A Model for Mitigating Traffic Crash Problems", Traffic Safety on Two Continents, Lisbon, Portugal, Sep. 1997.
5. "Mitigation of Rear End Accident Problems at Signalized Intersections" 24^{th} PTRC European Transport Forum, Brunel University, London, Sep. 1996.
6. "Pro-Active Safety Program A Key To Safety Management System", National Workshop on Safety Management Systems-Methodology, Tucson, Arizona, July 1994.
7. "Development of Icon Based Accident Analysis Package", R.E.C Warangal, May 1992.
8. Seminar on "Roller Compacted Concrete Pavements", R.E.C. Warangal, February 1991.

PROFESSIONAL PARTICIPATION:

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SCHOLARSHIPS AND AWARDS:

1. Graduate Teaching Assistant from 1996 to 1997
2. Graduate Research Assistant from 1992 to 1995
3. Included in National Dean's list for academic years 1992-93 and 1993-94.
4. Recipient of **Best Student of the Year Award** from **ITE Michigan Chapter, 1994**.
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