A STUDY OF THE EFFECTIVENESS OF THE USE OF STEADY BURN WARNING LIGHTS ON DRUMS IN CONSTRUCTION WORK ZONES

Final Report

Prepared for:

Construction and Technology Division
Michigan Department of Transportation
8885 Ricks Road
Lansing, MI 48909

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Wayne State University
Transportation Research Group
Detroit, MI

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16. Abstract

The Wayne State University - Transportation Research Group performed a study to evaluate the effectiveness of drums as a delineation treatment in work zone traffic control with and without steady-burn warning lights mounted on them. Currently in Michigan, warning lights are used on drums in work zones. It should be noted that in the United States, only five other states (in addition to Michigan) have similar requirements. The purpose of this study was to evaluate driver performance in terms of delineation and safety in work zones channelized by drums with and without steady-burn warning lights. As a part of this research, two methodologies were used including (1) field observations in actual highway work zone settings and (2) controlled laboratory experiments using a modern driving simulator. The study evaluated various driver performance measures including vehicular lateral placement, speed profile, steering reversals and traffic crash experiences. The statistical analysis performed in the field and driving simulator experiments did not indicate any significant difference in driver performance and safety measures between work zone traffic control with and without steady-burn warning lights on drums. The results of this study may be used in setting future policies in Michigan.

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1.0 INTRODUCTION

As work zone fatalities have consistently risen over the past several decades nationally, work zone safety has become a high priority issue for the road agencies and the road building industry. Between 1997 and 2002, the nation has experienced an increase in work zone fatalities of nearly 55% *(1).* Nationwide in 2002, there were 117,567 work zone crashes with 52,000 injuries and 1,181 fatalities *(1).* In Michigan, the total number of work zone crashes has declined between 1997 and 2003 by nearly 13 percent dropping from 6,638 work zone crashes in 1997 to 5,800 crashes in 2003. The number of injuries has also decreased from 2,510 in 1997 to 1,636 in 2003, nearly a 35 percent decrease *(2).*

The safety gains in Michigan can be attributed to safety conscious decisions made by the road agencies during the past decade. Increasing work zone safety can be achieved through the provision of clear and positive guidance. In a work zone, motorists are expected to travel along the roadway where their path of travel has changed due to lane closures or are constricted due to narrower lanes. In most cases, the available width of pavement may result in a decreased number of lanes or reduced lane widths which create an unanticipated change in the travel way. Also, the shoulders, which often provide a recovery area for the motorists, may not be available in a work zone. Other sources of confusion for motorists include unfamiliar traffic control devices, a lack of visibility due to weather, lighting, deteriorated pavement markings and increased congestion. All of these factors lead to an increased demand on the driver, while reducing the acceptable margin of error for their navigation.

In order to guide motorists through work zones in a safe and efficient manner, various traffic control devices are used including temporary warning signs, pavement markings, and channelizing devices such as drums, cones, tubular markers and barricades. The Manual on Uniform Traffic Control Devices (MUTCD), 2003 Edition, and the Michigan MUTCD state that the primary function of temporary traffic control is to provide the continuity of the movement of the motor vehicle while the normal function of the roadway is temporarily suspended *(3, 4).* Both the National and Michigan MUTCDs also state that no one set of temporary traffic control devices in a project can satisfy all the conditions of safety including the motorist, workers,

emergency personnel and equipment protection. The general safety principles for roadway work zones is to "…route road users through such zones using roadway geometrics, roadside features, and temporary traffic control devices as nearly as possible comparable to those for normal highway situations" *(3).*

There are four elements of a temporary traffic control zone: the advance warning area, transition area, activity area and the termination area *(3).* The advance warning area is where motorists are informed of the upcoming work zone. Drivers are redirected out of their normal path during the transition area. The activity area is where the construction activity occurs and the motorists are returned to their normal path in the termination area. Of the four work zone areas, the transition area is the most critical as it involves the motorist deviating from the normal route which can result in speed adjustment, changes in alignment and merging. Approximately 42 percent of work zone crashes occur in the transition area often due to the increased level of performance that is required of the motorist *(27).*

In most work zones, numerous drums are used as traffic control devices to channelize traffic through the work zone. The drums have alternating orange and white retroreflective stripes which make them highly visible, even during the nighttime. Warning lights are also commonly mounted on the drums to "supplement the guidance function" of channelizing devices and alert the drivers' attention to warning signs *(4).* These lights may be flashing or steady burn warning lights. Flashing lights may be placed on drums and other channelizing devices and may be used alone, or in a cluster, to warn motorists of a condition *(3).* The steady burn warning lights are most appropriate for use on channelizing devices, including drums placed in a series to provide delineation and guide motorists through the work zone *(3).* However, as per the national MUTCD, the warning lights on drums are considered optional *(3).* As per the Michigan MUTCD, Type C steady burn warning lights "are intended to be used to delineate the edge of the traveled way on detour curves, on lane changes, on lane closures and on other similar conditions" *(4).*

Almost half of all traffic fatalities in the United States occur at night, although considerably less travel takes place during the nighttime, as compared to the daylight hours. Due to the reduced

traffic on the roadways during the nighttime hours, the MUTCD states that road/lane closures should be scheduled during off-peak hours and nighttime work should be considered *(3)*. However, there are records of a higher number of injuries resulting from nighttime crashes. It is believed that delineation treatments are likely to represent a highly cost-effective approach *(5)*.

This study will determine the effectiveness of drums, with and without steady burn warning lights, in work zones with regard to driver performance and safety characteristics for a variety of state highway systems.

2.0 PROBLEM STATEMENT AND STUDY OBJECTIVES

Orange colored drums with white reflectorized tape are used for work zone delineation to assist motorists in navigating through road narrowings, lane drops and many other unusual circumstances often encountered in highway construction. Work zones generally pose a higher risk during nighttime conditions in spite of a lower level of travel. The steady burn warning lights are mounted on the drums to improve the visibility of the delineation of the roadway during the nighttime hours.

In recent years, many states have eliminated the use of steady burn warning lights. Some have restricted its use to only specific work zone situations. MDOT has employed the services of the Wayne State University-Transportation Research Group (WSU-TRG) to evaluate the effectiveness of such steady burn warning lights on drums in the context of construction zones in Michigan.

This research was designed to evaluate the effectiveness of steady burn warning lights on drums in comparison to drums without such lights in highway work zones.

The major objectives of this study included:

- Perform a literature review on work zone channelizing devices.
- Conduct a current practices survey of the state departments of transportation (DOTs).

- Investigate crash trends in other states, where available, that have eliminated the steady burn warning lights from the drums in their work zones.
- Conduct controlled laboratory experiments with a driving simulator.
- Conduct a field experiment of driver behavior through work zones with drums, with and without steady burn warning lights on Michigan highways.
- Determine the effectiveness in terms of safety and operational characteristics of the use of drums with and without steady burn warning lights.
- Conduct a Cost/Benefit Analysis if the effectiveness of the warning lights is statistically significant.
- Prepare a final report.

3.0 BACKGROUND

A comprehensive literature review was performed in order to evaluate the effectiveness of drums with and without steady burn warning lights. In order to identify past research results related to this study, extensive literature searches were conducted through Internet queries and traditional library searches for the following areas of study:

- Work zone crashes
- Work zone and traffic control device studies
- Driving simulator studies
- Current practices
- Summary of findings from the state-of-the-art and practices

A summary of the literature review and current practices survey results is presented in the following subsections.

3.1 Work Zone Crashes

Based upon a literature review and research performed by Khattak et al. *(6)* the majority of crashes in work zones do not involve injuries and those involving work zones are less severe than injury crashes that occur in non-work zone areas. The rear-end and sideswipe crashes occur on a more frequent basis in work zones, in comparison to non-work zones. In their research,

Khattak et al. *(6)* studied the differences between work zone crashes with pre-work zone crashes to determine if there are statistically significant differences in the crash experiences. Thirty six observational periods during the pre-work zone and during-work zone were compared in California between 1992 and 1993. The analysis assumed that the traffic remained the same during the roadway work period as compared to the pre-work zone period. The total crash rate observed in the pre-work zone period was 0.65 crashes per million vehicle kilometers (MVKM), while 0.79 crashes per MVKM were observed in the during-work zone period. A paired t-test was performed. The statistical analysis found that the two crash rates were not statistically different at even a 90% level of confidence (alpha = 0.1) *(6)*.

A study by Graham et al. *(7)* in 1978 investigated work zone crashes before and during construction. Crash rates at 79 construction project locations in seven states and covering a wide range of work activities and work zone layouts were studied. A regression analysis was performed to determine the relationship between the independent and dependent variables in the study. It was demonstrated in this study that the overall crash rate increased by 7.5 percent during the construction period, with varying degrees among the states and construction type. Fixed object, rear end, head-on and angle crashes increased while run-off-the-road crashes decreased substantially. Night crashes, as well as crash severity, increased, but remained at the same percentage of total crashes as the pre-construction level. The number of lanes closed and the type of construction had an impact on the crash rate. Bridge construction and roadway reconstruction produced the highest crash rate increases. For urban projects with speed reductions in the work zone, the crash rates increased by six percent, while urban projects without speed reductions increased by 14 percent. In rural areas with speed reductions, crash rates increased by 16.4 percent, while without speed reductions the crash rate increased by only 2.6 percent.

The Garber and Zhao *(8)* study conducted on work zone crashes in Virginia from 1996 to 1999 indicated that the activity area in a work zone had the highest number of crashes and the highest number of fatal crashes. However, for all the crashes studied, property damage only crashes were predominant. Rear-end crashes were also the predominant type of crash, except at the termination area of a work zone where the predominant type of crash was angle crashes. There

were more fixed object crashes and fewer angle and rear end crashes during the nighttime hours, than during the daytime hours. The significant proportion of fixed object crashes during the nighttime hours indicates an issue with lighting at the work zone or the illumination of channelization devices.

Research conducted by Ha and Nemeth *(25)* identified the type and injury level of crashes in work zones using the statewide computerized database of the Ohio Department of Highway Safety between 1982 and 1986. Observations were based upon crashes per unit time. They found that work zone crashes were not more severe than other highway-related crashes, truck crashes were over-represented, fixed object and rear-end crashes were over-represented, and nighttime work zone crashes were under-represented. Sixty projects were then selected for further analysis. This analysis found that injury crashes were generally associated with rear-end and angle crashes, as well as heavy vehicle and multiple vehicle involvement. During daytime driving conditions, rear-end crashes were predominant, while during nighttime driving conditions, fixed object crashes were predominant. Single vehicle crashes occurred predominately at night, while two-car crashes were frequent during daytime driving conditions. Nine sites were chosen to identify the causes of work zone crashes. The study for the nine sites found that contributing factors included inadequate or confusing traffic control measures, edge drop or soft shoulders, traffic slowdowns, lane changes, merging and guardrails.

Another strategy to achieve reduction in work zone crashes is to assure that the traffic control devices that are utilized will not interrupt the traffic flow of other vehicles, or strike the impacting vehicle or others in case they are struck by a motorist. If struck by a passing vehicle, the channelizing device should yield or break away such that fragments do not penetrate the vehicular passenger compartment or become a hazard to workers or pedestrians *(3)*. Bryden *(9)* performed a study to evaluate the impact performance of traffic control devices commonly encountered in work zones in the state of New York. 108 tests were conducted with 62 different combinations of traffic control devices and their installation conditions. Of the 62 tested devices, both drums without warning lights and those with warning lights were tested. Bryden used sedans and tested speeds between 20 and 60 miles per hour for passenger compartment intrusion, loss of vehicle control and the physical threat to workers or other vehicles. The drums without

warning lights performed satisfactorily in 18 of 24 tests. Of the unsatisfactory tests, drum parts flew into the traffic areas thereby creating the potential to cause a severe evasive maneuver or the sandbag holding the drum in place scattering sand along the roadway causing a potential for skidding. During the impact, 11 of the drums were superficially damaged, six sustained intermediate damage and seven of the drums were destroyed. For the drums with lights, only five of the 19 tested performed satisfactorily with the primary problem being the lights separating from the impact of the drum and vehicle, thereby creating a hazard to workers or to other vehicle windshields. In some cases, the lights were thrown free upon impact through the work zone and some flew over the vehicle striking another vehicle's windshield, but never fully penetrating the windshield. Overall, the drums without lights provided an acceptable performance, while the drums with lights caused secondary accidents and intrusions.

3.2 Work Zone and Traffic Control Device Studies

Traffic control devices, specifically channelizing devices, are utilized to warn motorists of potential hazards created at the work zone and to guide the motorists safely past these hazards. Research by King and Luenfeld *(10)* shows the majority of the information needed for an accurate and timely path selection by the driver is acquired visually. Based upon the visual information received from channelizing devices such as drums, motorists can maneuver their vehicle appropriately and maintain a reasonable speed even through unusual and hazardous situations. In research performed for the American Traffic Safety Services Association in 1992, KLD Associates *(11)* studied the effectiveness of steady burn warning lights mounted on drums in delineating the traveled way in terms of positive guidance for the driver. In this study, 53 subjects were exposed to slides of work zones under nighttime driving conditions with steady burn warning lights on all drums, lights on every other drum, or no lights at all on the drums. Thirty additional motorists were also subjected to a 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 drove through 16 simulated work zones during the nighttime hours along a closed section of roadway in Delaware. The study work zone sites included three scenarios including steady burn warning lights on all different traffic control devices, on alternate devices and devices without any steady burn warning lights. The study recommended

the use of steady burn warning lights on alternate channelizing devices for left lane closures and did not recommend the use of steady burn warning lights for right lane closures.

Pant and Park *(12)* studied the effectiveness of steady burn warning lights in 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. Each subject drove an instrumented vehicle along three rural work zones with speed limits of 65 or 55 mph. Data collected included speed, lateral placement, acceleration noise and weaving. 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." Hypotheses were tested by performing t-tests for the means and F-tests for variance at an alpha equal to 0.05. Paired t-tests were also performed for the noted measures of effectiveness. The study found that steady burn warning lights have little effect or no effect on driver performance in tangent sections of rural, unlighted, and divided highways. The high-intensity reflective sheeting outperformed the steady burn warning lights. The presence or absence of the 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 for rural divided highways.

A second study by Pant et al. *(13)* examined the effectiveness of steady burn warning lights on divided and undivided highways at horizontal curves and vertical curves, with and without ambient lighting and also at 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. 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 *(12).* Traffic conflict was defined as an unusual or evasive action taken by the driver while driving through the construction zone. The presence of traffic conflict in the absence of steady burn warning lights would indicate a dangerous situation for the driver and others on the roadway. The location 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. This would measure whether or not the driver noticed the steady burn warning lights or not. Hypotheses were tested by performing t-tests for the means and F-tests for variance at alpha equal to 0.05. A paired-t test was performed at 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. The study concluded that steady burn warning lights had no impact on the driver's behavior with respect to speed, lateral placement, acceleration noise, weaving and traffic conflict. Also, the absence of steady burn warning lights did not have any impact on the lane changing behavior of motorists at night. Only nine 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.

Garrett *(26)* of the American Traffic Safety Services Association (ATSSA) published an article in response to the research work performed by Pant *(12, 13).* It stated that the sites that were studied in Ohio included flashing arrow boards and advance warning signs. This article stated that the use of these additional traffic control devices does not allow a study to determine the specific effect of steady burn warning lights, as the combined effect of the traffic control devices constitutes a system. It suggested that to determine the impact of steady burn warning lights, one should study a system with and without lights only. They also disagreed with the measures of effectiveness used in the Ohio studies. They do not believe speed and lateral placement can indicate the effectiveness of steady burn warning lights. The Ohio study collected data with a video camera and light mounted on a test vehicle. The light was utilized to illuminate the edge and centerline of the roadway. ATSSA states that the impact of the light on the video camera could have improved the visibility of the drums for the test drivers. The study by KLD *(11)* concluded that steady burn warning lights were effective in left lane closures; however, the Pant *(12, 13)* study evaluated 17 sites, but only two were left lane closures. The studies by Pant also did not examine the impact of inclement weather, where ATSSA contended that steady burn warning lights are effective. The ATSSA was also concerned with the impact on older motorists as their vision may impede them from detecting the drums without the steady burn warning lights.

A study was performed in Virginia by Shepard *(14)* to evaluate the effectiveness of two traffic control devices for vehicular guidance. The study examined the effectiveness of steady burn warning lights in comparison to reflectorized panels located on the top of temporary concrete barriers along tangent sections in a work zone. The rationale behind studying the use of steady burn warning lights was two-fold. First of all, the steady burn warning lights are dependant on batteries, which require maintenance and inspection. In addition, when the lights burn out in a random fashion, the information offered to the motorists becomes sometimes confusing. Secondly, the New Jersey Department of Transportation found that the use of the six-inch by twelve-inch reflectorized panels caused no decrease in the proportion of vehicles using the lane adjacent to the temporary construction barrier, as well as no difference in the mean speed or speed variance. After using the reflectorized panels for five years, New Jersey has not reported any problems. It is important to note that steady burn warning lights are still utilized in New Jersey in the taper areas.

In Shepard's study *(14)*, the steady burn warning lights and reflectorized panels were compared along tangent sections of two sites. The first site included two-way traffic flow along two adjacent lanes with a temporary concrete barrier between the opposing lanes of flow and the second site included the temporary concrete barrier along the right shoulder. Traffic flow data of vehicular speed and vehicle placement was collected for both sites between 8:00 PM and 5:00 AM. The analysis of the data indicated that the vehicle placement data at the two sites showed no difference at one of the sites. However, the second site showed less straying from the lane with reflectorized panels as compared to the steady burn warning lights. The speed data comparisons showed no difference in speeds at the two sites with the reflectorized panels or the steady burn warning lights. The study concluded that the reflectorized panels were equal or superior to the steady burn warning lights.

Lafferty and Pennington *(15)* conducted a study for the Florida Department of Transportation (FDOT) evaluating the effectiveness of illumination devices on temporary concrete barrier walls in construction work zones. Four one-mile sections of I-75 with various levels of illumination along the temporary concrete barrier were evaluated by a FDOT construction team. Vehicles were videotaped while driving through the work zone and reevaluated in the office. The findings

of this study indicate that without warning lights, motorists were traveling at least 10 miles over the speed limit. The sections without lights were found to provide an increased level of delineation for motorists; however, exactly how much more could not be determined. The sections with lights were found to provide excellent guidance for motorists through the work zone. The recommendations were to maintain the use of steady burn warning lights on temporary concrete barriers in construction work zones; however, the steady burn warning lights should be LED and inspections should be increased.

In the NCHRP Report 236 by Pain et al. *(16)*, the impact of steady burn warning lights on driver behavior was compared between drums with two types of retroreflective sheeting including Type II (super engineering grade) 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 were found to be effective on each or alternating drums and the lights in the taper only are not statistically different than those that are on each or alternating drums. Type III retroreflective sheeting was significantly better at night than the Type II sheeting. It was found that the Type III sheeting and the 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 curve segments in roadways should be considered. NCHRP Report 236 concluded that the main advantage of the steady burn warning lights was the long detection distance and that they are suited for tapers in transition areas. They would also be suitable for tangent sections, but the spacing could be alternate. The Type III (high-intensity sheeting) drums without steady burn warning lights were found to be highly visible and detectable from a long distance during nighttime driving. They promoted early lane changes and resulted in speed reductions along the length of the work zone.

As the average age of motorists begins to increase, special attention should be given to the needs of the older motorists, particularly in construction work zones. Chiu et al. *(17)* studied the performance of 20 older drivers (over the age of 60) in construction work zones, as compared to 12 younger drivers (under the age of 35). Each subject drove through six construction work zone scenarios in a driving simulator showing drums, drums with reflectors and jersey barriers, while

the lateral position and speed of the motorists were recorded in this study. The analysis examined the average velocity, the number of times each driver got out of the driving lane and the amount of time they spent out of the lane. Overall, the younger motorists drove five to eight miles per hour faster than the older motorists. The drum and drum reflectors did not seem helpful to either group; however, the jersey barriers were favored by the older motorists. The reflectors were found to be extremely helpful to the older drivers through the work zone.

The American Traffic Safety Services Association (ATSSA), an industry based organization, issued a policy statement due to the wide variation of practices throughout the United States, stating that the reflectivity of traffic control devices was not adequate in providing a warning or delineation for the motorist *(18).* It also stated that the Type C steady burn warning lights should be used on all devices that are intended for traffic direction in following a different travel path or guiding motorists through work zones at night. The steady burn warning lights should also be mounted on every device in tapers, transitions or detours. However, they also stated that if external lighting was available and equivalent to daytime visibility, the use of the lights may not be needed. The Michigan ATSSA presented objections for eliminating the steady burn warning lights in the June Construction Zone Advisory Committee meeting in 1995 *(19).* Michigan ATSSA stated that if LED lights were used in construction zones, the longevity of the lights (130 to 150 days) would allow the lights to work all the time during the life of a construction project in Michigan which is generally completed in 140 days or less. The steady burn warning lights can be seen from three times the distance than retroreflective devices. Unlike drums without lights, the steady burn warning lights are also visible in all weather conditions.

3.3 Driving Simulator Studies

As data collection of field data related to human factors becomes increasingly difficult due to safety issues related to human subjects, driver simulators emerge as an alternative method which allows experimental control, efficiency, low cost and ease of data collection (driving simulator validation for speed research). However, the question of validity of driver simulators as a useful human factor research tool can be of question. There are two levels of validity of driver

simulators; physical validity and behavioral validity. Physical validity refers to the correspondence between an actual automobile and the simulator vehicle in terms of components, layout and dynamics. Behavioral validity refers to the similarities between the way a driver would behave in a simulator situation and a real-world situation. Considering both validity issues, if behavioral validity can be accomplished, then the question of physical validity should not be an issue. Blaauw *(20)* stated that behavioral validity consisted of absolute validity and relative validity. Absolute validity is the statistical indifference between numerical values, whereas relative validity is the statistical indifference between the difference in the magnitude of the critical driver performance variables as observed in the simulator and real-world. Tornros *(21)* further stated that the absolute validity should not be necessary as researchers usually examine differences between the dependent variables, with experiments involving control and treatments. Therefore, the aim should be on the determination of relative validity.

In the Tornros study *(21)* of driver behavior in a simulated road tunnel, 20 participants drove the simulator through a tunnel six times in each direction in the three different lanes while speed and lateral position data was collected. The speeds of the vehicles were obtained without driver access to the speedometer. The lateral position was measured as a location of the vehicle in regards to the tunnel wall and curvature. Through the use of Analysis of Variance (ANOVA), the motorists' performance variables related to a simulator and real tunnel, were analyzed. The study found that speeds were higher in the simulated tunnel than the real tunnel and that the speed difference was statistically significant. This led the author to show a lack of absolute validity. As there was no interaction between the simulator factor (simulated tunnel and real tunnel) and the lane factor (left, middle or right driving lane), the simulator factor and the speedometer factor (with or without speedometer information) nor the simulator factor and the tunnel wall factor, the author saw this as a sign of good relative validity. However, the interaction between the tunnel wall and the curve was found to be statistically significant indicating that the difference between the simulator and the real-world is significant.

Godley et al. *(22)* completed a behavioral validation of a driving simulator for use in evaluating speeding countermeasures using mean speed including absolute validity, average relative validity

and interactive relative validity. Twenty-four motorists participated in an instrumented car experiment where a vehicle was driven at three sites with rumble strips and three equivalent control sites. Twenty drivers participated in the simulator experiment where the simulator replicated similar scenarios as experienced with the instrumented car experiment participants. The participants of the instrumented car experiment were not utilized for the simulator experiment. The absolute speed values were found to be different in the two experiments through a two one-way ANOVA analysis. However, the experiments did not attempt to establish numerical speeds as in the definition of absolute validity discussed above. Average relative validity was found not to be statistically different through the use of a two-factor ANOVA. The simulator produced larger average speed differences between the treatment and control sites for two of the three trials. In the analysis of the interactive relative validity with a canonical correlation, all sites yielded significant correlations for mean speed. This was deemed the most important measure of validity as it demonstrated that motorists will act similar in a simulator as compared to the instrumented car.

Klee et al. *(23)* performed a study at the University of Central Florida to determine if a driving simulator can provide realistic driving experience. Thirty participants drove an instrumented vehicle along a roadway section on campus while speed, distance and travel time data were collected. Similarly, 21 of those test subjects performed the same task in a driving simulator. The same data was collected for the simulator runs as in the field experiment. Z-tests were performed at the 95 and 99 confidence intervals to test the hypothesis that the difference between the mean speeds of the two experiments were greater than 4.8. At 10 of 16 intervals, the null hypothesis was accepted at the 95 percent confidence interval. At two of the intervals, the null hypothesis would have been accepted at alpha equal to 0.01. Therefore, at four out of 16 intervals, the null hypothesis was rejected. It was found that most of the subjects drove the simulator at slower speeds than the vehicle driven during the field experiment.

Research conducted by Burns et al. *(24)* determined the validity of a head-mounted display unit type driving simulator for studying driver performance at intersections. Driver performance comparisons were made between the simulator and those observed at actual T-intersections. The

subjects included 11 drivers between the ages of 26 and 56. Each subject performed left and right-turns at the actual intersection and the simulated intersection, while a video camera recorded direction, frequency and duration of driver glances. The research found that driver speeds were slower while driving the simulator than an actual automobile. Motorists tended to glance for longer periods of time in the left and right directions while using the simulator. An ANOVA test showed no significant differences in the time to complete turns with an alpha equal to 0.0001. A significant interaction was found for lane positioning by a turn in the simulator and intersection for an alpha equal to 0.01. The research concluded that a head-mounted display type simulator could be used to study driver performance if a wider field of view, better depth perception and improved steering model were provided.

3.4 Current Practices

As a part of this project, an evaluation of current practices of state transportation departments was viewed as one of the most important sources for determining the current state-of-the-practice with regard to the use of drums with and without steady burn warning lights in highway construction work zones.

A survey was conducted of the state departments of transportation to determine current practices in the utilization of drums with and without steady burn warning lights. Questions were asked related to the current practices of channelizing devices used in highway work zones, whether or not drums without warning lights have ever been used, and if so, when and if a study had been conducted comparing the effectiveness of drums with and without warning lights. The survey instrument is included in Appendix I.

Forty-nine (49) states had responded to the survey with the State of Michigan intentionally excluded from this survey. The following outlines the summary of the responses to the survey questions:

Five (5) States require the use of warning lights on drums:

- Alaska
- Arizona
- Florida
- Illinois
- Oklahoma

Two (2) States do not require warning lights on drums, but use them under certain conditions:

- Rhode Island – On curves
- Virginia – At some locations to delineate hazards

Nine (9) States do not require warning lights on drums, but use them under certain conditions:

- Indiana
- Louisiana
- Delaware
- Wisconsin
- Tennessee
- Massachusetts – First three drums
- New Hampshire – First drum
- New York – First two drums in taper
- Pennsylvania – Only use in tapers at selected sites

Thirty (30) States currently do not use warning lights on drums at all:

- Alabama
- Arkansas
- California
- Connecticut
- Georgia
- Hawaii
- Idaho
- Iowa
- Kansas
- Maine
- Maryland
- Minnesota
- Mississippi
- Missouri
- Montana
- Nebraska
- Nevada
- New Jersey
- New Mexico
- North Carolina
- North Dakota
- Ohio
- Oregon
- South Carolina
- South Dakota
- Utah
- Vermont
- Washington
- West Virginia
- Wyoming

Three (3) States use warning lights on drums at the engineer's discretion:

- Texas
- Kentucky
- Colorado

Of the 30 states that indicated that they do not use them at all, 12 states had used warning lights on drums in the past, but had changed their practice and discontinued the use of warning lights on drums in work zone applications:

- Nevada
- Nebraska
- Kansas
- Utah
- New Jersey
- Iowa
- Arkansas
- Virginia
- Ohio
- West Virginia
- Oregon
- Maine

The average number of fatal crashes in construction and work zones and average vehicle-miles traveled for states that exclusively use channelizing devices with steady burn warning lights and exclusively use channelizing devices without steady burn lights are listed in Table 3.1.

Table 3.1. Construction Work Zone Fatal Crash Data for 1994-1998

STEADY BURN WARNING LIGHT USE	AVERAGE FATAL CRASHES PER YEAR	AVERAGE VMT** PER YEAR	CONSTRUCTION ZONE CRASH RATE (CRASHES PER VMT**)
For 19 States Who Use Steady Burn Warning Lights* (Control Group)	104.8	441,724,000	0.65
For 30 States Who Do Not Use Steady Burn Warning Lights* (Test Group)	319.4	1,234,760,000	0.70

* As listed on page 16.
** VMT (Vehicle Miles Traveled)

3.4.1 Analysis of Work Zone Traffic Crashes of States in the USA Categorized by Group

The comparative parallel ‘control and test’ study (Figure 3.1) was used to evaluate the crash experience among states that use drums with warning lights in work zones, with the states that do not. This plan uses a control group (states who use warning lights on drums) and a test group (states that do not use warning lights) in order to compare the various measures of effectiveness. Measures of effectiveness for the test group are compared with the control group, and the difference between the two groups is used to determine the effectiveness in terms of the statistical significance.

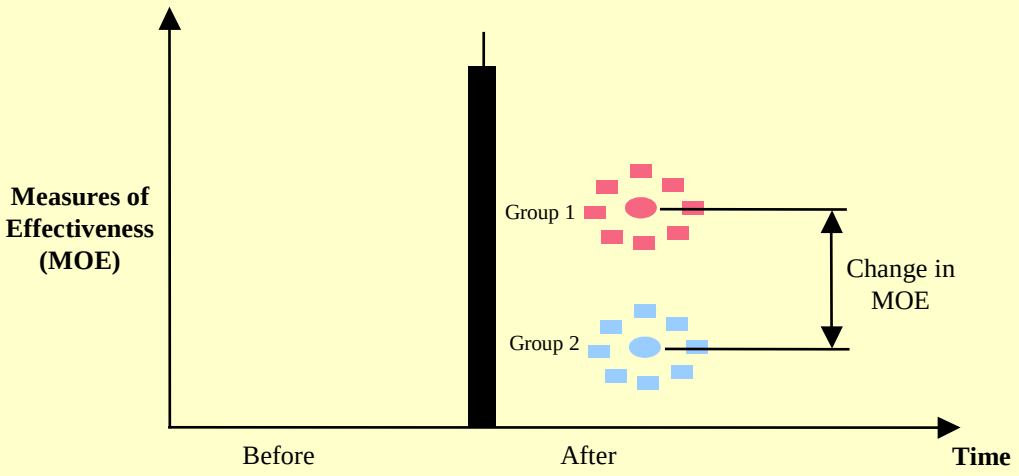


Figure 3.1. Comparative Parallel Evaluation Plan Used in Analysis of States' Work Zone Crash Data

The Poisson test was used to test the significance of the differences between the two groups. This test uses the Poisson curves to determine whether a change in crash experience is statistically significant. This curve plots expected crash frequency without treatment (which corresponds to drums with steady burn warning lights) versus the percent change for various levels of confidence, as shown in Figure 3.2. For a specific level of confidence (in this case 95 percent) the actual data point being tested must fall above the curve in order to be significant. If the result is significant, then the null hypothesis is rejected and there is a significant difference between the before and after total crashes, typically a reduction.

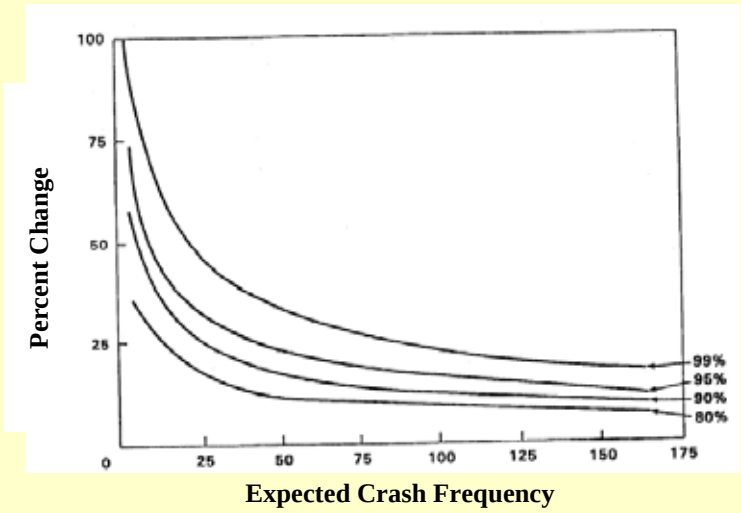


Figure 3.2. Poisson Frequency Curves

The null and alternative hypotheses for the "Comparative Parallel Study" are as follows:

H_o (null hypothesis): There is no difference in the crash rates between the 'control' group of states (using drums with warning lights) and the 'test' group of states (using drums without warning lights).

H_a (alternative hypothesis): There is a difference in the crash rates between the 'control' group of states (using drums with warning lights) and the 'test' group of states (using drums without warning lights).

The Poisson Test was used to compare the state data from 1994 to 1998 where fatal crash data and vehicle miles traveled (VMT) was available for each state using drums with the steady burn warning lights (control group), and each state using drums without steady burn warning lights (test group). The procedure involves the calculation of the 'expected' frequency of fatal crashes of the 'test' group (E_T) which equals the frequency of fatal crashes of the 'control' group (A_C), adjusted for volume differences between the test and control groups. The equation is:

$$E_T = A_C \times \text{(VMT of the Test Group)} / \text{(VMT of the Control Group)}$$

The percent change is calculated as follows:

$$\text{Percent Change} = [(E_T - A_T)/E_T] \times 100$$

Where: E_T = Expected crash frequency for the test group of states if warning lights on drums were used

A_T = Actual crash frequency for the test group of states

The value for the expected crash frequency is used directly in the statistical testing procedure.

A sample calculation for the expected crash frequency for the test group of states and the percent change is as follows:

$$E_T = 319.4 \times (1{,}234{,}760) / (441{,}724) = 292.95 \text{ fatal crashes}$$

$$\text{Percent Change} = [(292.95 - 319.4)/292.95] \times 100 = 9\%$$

Based up the calculations shown in Table 3.2 and above, the crash rates between the test group and control group were not significantly different at a 95 percent confidence interval (alpha = 0.05).

Table 3.2. Results of the Poisson Test for Fatal Crashes 'Test' versus 'Control' Group of States in the USA

VARIABLE	CALCULATIONS
Estimated Expected Average Fatal Crashes, Test Group	292.9
Actual Fatal Crashes, Test Group	319.4
Percent Change	9.0%
Significant Difference?	No, Not Significant

3.4.2 Before and after Analysis of Crash Data in Iowa

Prior to 1995, the State of Iowa utilized drums with Type C steady burn (incandescent) warning lights on work zone channelizing devices with engineering grade reflectorized sheeting. Since 1995, Iowa has only used high intensity grade sheeting (Type III) on drums without any type of steady burn warning lights. Table 3.3 summarizes the crash statistics for Iowa between 1989 and 1994 during the time the steady burn warning lights were used, and between 1995 and 2000 during the time the steady burn warning lights were eliminated. The data summarized in Table 3.3 was obtained from the Iowa Department of Transportation. Iowa has fatal, injury and property damage only crashes subdivided into categories of interstate, state highway, county roads and city streets. For the purpose of this study, the total number of crashes per year by various levels of severity has been utilized.

Table 3.3. State of Iowa Work Zone Crash Statistics

YEAR	FATAL CRASHES	INJURY CRASHES	PROPERTY DAMAGE ONLY CRASHES	TOTAL CRASHES	VEHICLE MILES TRAVELED (VMT)
1989	4	112	364	480	22,571,000
1990	4	129	244	377	22,993,000
1991	8	123	267	398	23,020,000
1992	8	126	204	338	23,926,000
1993	4	135	209	348	25,118,000
1994	12	139	198	349	25,737,000
1995	3	169	203	375	25,987,000
1996	3	150	216	369	26,880,000
1997	10	151	195	356	28,004,000
1998	9	121	154	284	28,911,000
1999	17	173	226	416	29,138,000
2000	6	151	170	327	29,433,000

In order to conduct the statistical analyses, the average crash frequencies for the years when Iowa used drums with steady burn warning lights (1989 to 1994) and when Iowa used drums without steady burn warning lights (1995 to 2000) were calculated and are shown in Table 3.4.

Table 3.4. State of Iowa Work Zone Crash Frequencies

YEAR	AVERAGE FATAL CRASH FREQUENCY (CRASHES PER YEAR)	AVERAGE INJURY CRASH FREQUENCY (CRASHES PER YEAR)	AVERAGE PROPERTY DAMAGE ONLY CRASH FREQUENCY (CRASHES PER YEAR)	AVERAGE TOTAL CRASH FREQUENCY (CRASHES PER YEAR)	AVERAGE VEHICLE MILES TRAVELED (VMT)
1989-1994	6.67	127.33	247.67	381.67	23,894,200
1995-2000	8	152.5	194	354.5	28,058,800

Since the State of Iowa had discontinued the use of steady burn warning lights in 1995, statistical tests examining the differences in construction zone crashes for fatal crashes, injury crashes, property damage only and total crashes were performed using the Poisson Test.

The 'before and after' study was used to evaluate the traffic crashes for Iowa's statewide crash data where 'before' data was available. 'Before' data is classified as the utilization of drums with steady burn warning lights for channelization in construction zones, whereas 'after' data is classified as the utilization of drums without steady burn warning lights for channelization in construction zones. In the 'before and after' study plan (Figure 3.3) Iowa's statewide crash data was compared 'before' and 'after' the elimination of the use of steady burn warning lights on drums.

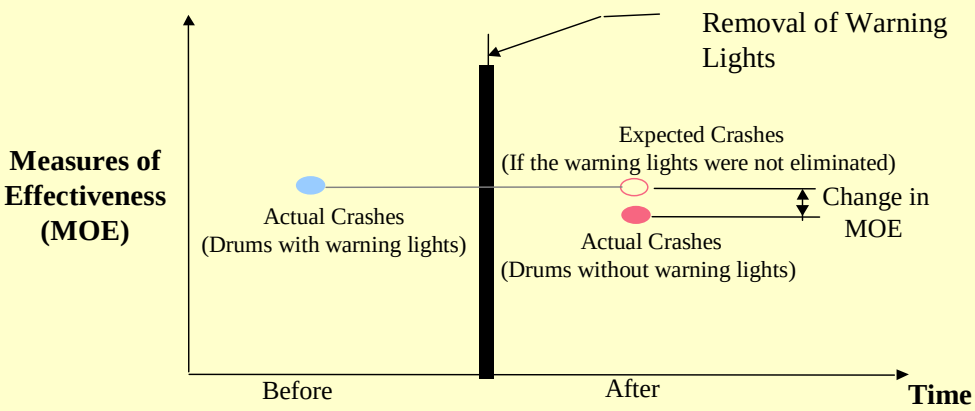


Figure 3.3. Before and After Evaluation Plan Used in the Analysis of Iowa's Crash Data

The null and alternative hypotheses for the 'Before and After Study' are as follows:

H_o (null hypothesis): No difference between the crash rate 'before' and 'after' the removal of the steady burn warning lights and the modification to high intensity sheeting on the drums from engineering grade sheeting in Iowa.

H_a (alternative hypothesis): A difference between the crash rate 'before' and 'after' the removal of the steady burn warning lights and the modification to high intensity sheeting on the drums from engineering grade sheeting does exist in Iowa.

A comparison was made between the average crash data when drums with the steady burn warning lights were used with the crash data when drums were used without the steady burn warning lights. The procedure involves the calculation of the 'expected' crash frequencies for the 'after' period (without treatment, i.e. had the warning lights not been eliminated) based on volume adjustments between the 'before' and 'after' period at the test sites. The percent change is then calculated and used in testing for statistical significance. The following are the equations:

$E_T = B_T \times$ (After VMT/Before VMT)

Percent Change = $[(E_T - A_T)/E_T] \times 100$

Where:

E_T = Expected crash frequency at the test sites, if the warning lights were continued.

B_T = Actual 'before' (drums with warning lights) crash frequency at the test sites.

A_T = Actual 'after' (drums without the warning lights) crash frequency at the test sites.

Based upon the calculations summarized in Table 3.5, the null hypothesis was not rejected for the fatal and injury crash comparisons. In other words, for the State of Iowa, the fatal and injury crashes were not significantly different at a 95 percent confidence interval or alpha equal to 0.05. However, the null hypothesis was rejected for the property damage only and total crash comparisons. For both instances, the actual number of crashes observed for the test sites was lower than expected, as determined using the before and after evaluation plan, by 33 percent for the property damage crashes and nearly 21 percent for total crashes. Therefore, a significant difference was found between the 'before' and 'after' elimination of the use of steady burn warning lights on drums in terms of property damage and total crashes. However, the crashes before the elimination of steady burn warning lights on drums had a significantly greater number of crashes than after the elimination of their use. A conclusion can be drawn from the State of Iowa's data that the elimination of warning lights from the drums and use of high intensity sheeting on drums resulted in the reduction of PDO (property damage only) and total crashes. How much of this reduction is attributable to the elimination of warning lights only can not be determined, since the use of high intensity sheeting was coincidental with the elimination of warning lights on drums.

Table 3.5. Results of the Poisson Test for Iowa Crashes

CALCULATIONS	CRASH TYPES			
	FATAL CRASHES	INJURY CRASHES	PDO CRASHES	TOTAL CRASHES
Estimated Expected Average Crashes, Test Sites*	7.8	148.98	289.77	446.55
Actual Crashes, Test Sites**	8	152.5	194	354.5
Percent Change	2.56%	2.36%	-33.05%	-20.61%
Significant Difference?	No, Not Significant	No, Not Significant	Yes, Significant Difference	Yes, Significant Difference

* (If drums were equipped with warning lights.)

** (Drums where warning lights were eliminated.)

3.5 Summary of Findings from the State-of-the-Art and Practices

Past studies by various researchers yielded the following:

- Work zone crashes are generally less severe than normal highway crashes.
- Rear-end and side-swipe type crashes are most predominant in work zones.
- Crash frequencies generally increase in highway work zones.
- Some highway work zone crash studies found that rear-end and fixed object crashes in highway work zones are over-represented.
- Separation of warning light fixtures from the drums could cause a hazard for other non-involved vehicles.
- Test of effectiveness of steady burn warning lights as a delineation device ranged from marginally effective under certain situations to not at all.
- A study comparing delineation effectiveness between steady burn warning lights and reflectorized panels concluded that reflectorized panels performed equal to or better than steady burn warning lights.
- One study concluded that the use of steady burn warning lights is appropriate for tapers in transition areas.

- The industry group recommends the use of warning lights on drums. They also recommend the use of LED lights for longer life and a failure proof operation of the entire construction season.
- Driving simulators have been used by many researchers to study driver performance under a controlled driving environment.
- Several studies have established reliability of driving simulator-based studies.
- Most studies have proven relative validity of simulator use.

A survey of all studies, except Michigan, resulted in the following information:

- Thirty (30) states out of 49 (Michigan excluded) states do not use warning lights on drums.
- Five (5) state use warning lights on drums everywhere.
- Fatal crash rates at highway work zones do not vary significantly between the states who use warning lights and the states who do not.
- The State of Iowa's work zone crash data indicates a significant reduction in total and PDO crashes after the discontinuance of warning lights on drums, yet no difference in injury or fatal crashes.

4.0 STUDY METHODOLOGY FOR THE MICHIGAN STUDY

4.1 Statistical Analysis of Effects of Drums With and Without Warning Lights

In order to compare the effectiveness of drums with and without steady burn warning lights in Michigan, various evaluation methodologies were used including:

- Before and after with control study
- Comparative parallel study

In the 'before and after with control' study plan, (Figure 4.1) data for the test and control sites is compared 'before' and 'after' the installation of the construction zone. In this study plan, the percent change in the crashes is compared at the test sites with the percent change in the crashes at the control sites for the same before and after periods. The use of control sites allows the influences of variables on the study results to be controlled.

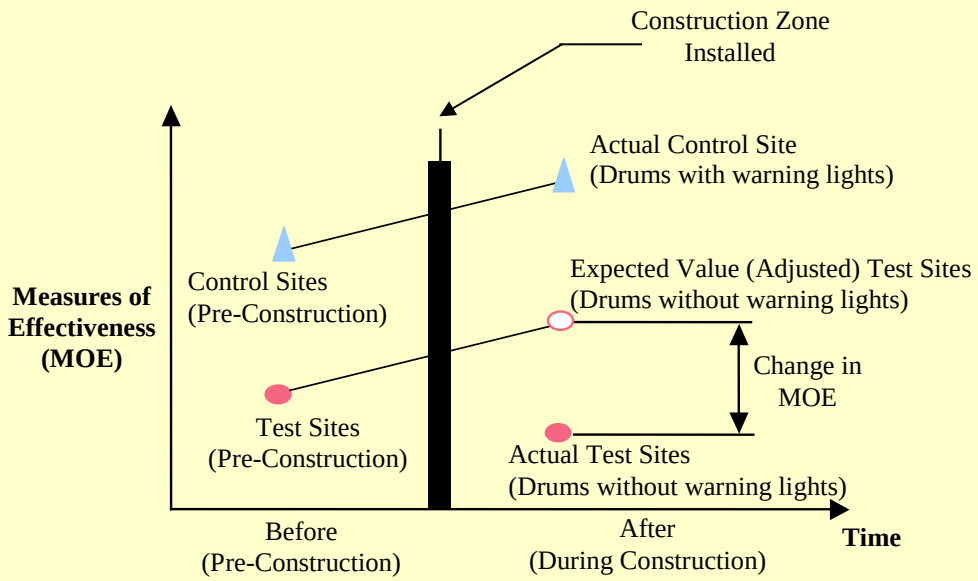


Figure 4.1. Before and After With Control Evaluation Plan Used in the Michigan Study

Test sites are the locations where steady burn warning lights were not used during the construction phase of the project. The control sites are those locations where warning lights were used during the construction phase.

The comparative parallel 'control and test' study (Figure 4.2) was used where 'before' data was not available at the test site. This plan uses control sites with the steady burn warning lights in order to compare the various measures of effectiveness with the group of test sites where steady burn warning lights were not used. This test uses the measures of effectiveness for the 'after' period for the test sites compared with the 'after' period at the control sites (similar sites) and uses the changes in the measures to determine the effectiveness.

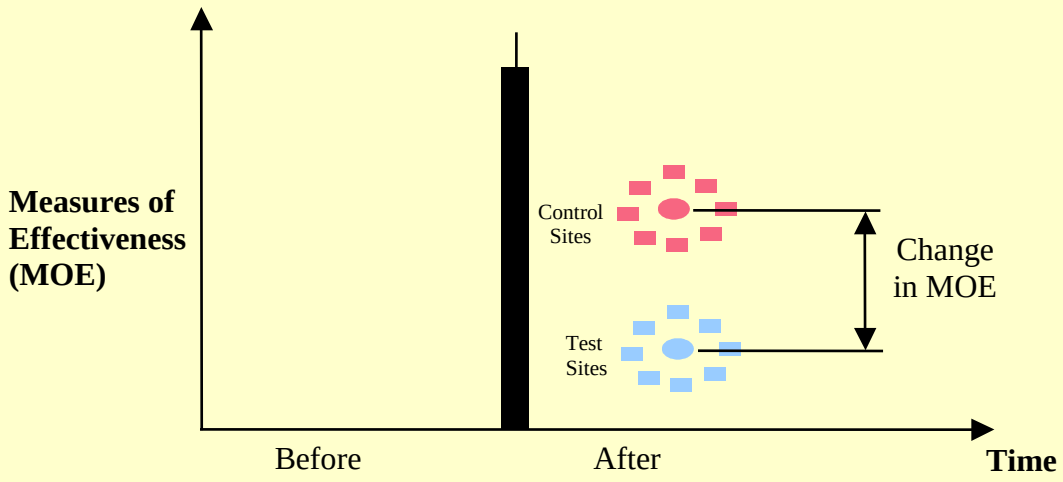


Figure 4.2. Comparative Parallel Evaluation Plan Used in the Michigan Study

The statistical significance of the effectiveness of the drums with and without steady burn warning lights must be tested in order to better understand whether the changes observed in the measures of effectiveness of crash data, lateral placement, steering reversals, etc. are attributable to the steady burn warning lights on the drums. Statistical analyses that were performed to test the effectiveness of drums with and without steady burn warning lights are as follows:

- Poisson test – for traffic crash frequencies 'before and after' and at 'control and test' sites
- Chi-square test – for focus group sample to determine if the sample is representative of the population
- T-Test– for traffic crash rates, speed, and lateral placement, and steering reversal data (student's t-test for 'comparative parallel studies')

Poisson Test

The Poisson test was used to test the effects on traffic crash data for construction zone crashes in other states. This analysis compared the 'before' and 'after' traffic crash data, where the 'before' data represents the use of drums with steady burn warning lights and the 'after' data represents the use of drums without steady burn warning lights. This test uses the Poisson curves to

determine whether a change in crash experience is statistically significant. This curve plots expected crash frequency without treatment, which is channelizing drums with steady burn warning lights versus the percent change in the measure of effectiveness (MOE) for various levels of confidence, as shown previously in Figure 3.2. For a specific level of confidence (in this case 95 percent) the actual data point being tested must fall above the curve in order to be significant. If the result is significant, then the null hypothesis is rejected and there is a significant difference between the before and after total crashes, typically a reduction if the treatment is safer.

Chi-Square Test

When comparing an observed frequency distribution or percentage with the corresponding values of an expected distribution, the intent is to test whether the discrepancies between the observed and expected frequencies or percentages can be attributed to chance. The statistical equation to determine if the gender and age distribution in the sample population used in the focus group study was significantly different than the population in the State of Michigan, is the statistic for test of goodness of fit, or the chi-square test. The following equation was used to test the chi-square or goodness of fit:

$$c^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)}{e_i}$$

Where:

o_i = value of the observed frequency, the focus group sample

e_I = value of the expected frequency, the population of the State of Michigan

k = number of frequencies, categories

The result of this calculation gives the calculated chi-square value (c^2_{calc}). The critical chi-square value may be obtained from statistical tables (c^2_{cr}). If $c^2_{calc} > c^2_{cr}$ then the differences are significant and the null hypothesis is rejected.

Student's t-test

In order to test the effectiveness of the drums with and without steady burn warning lights for the traffic crash rates, speed data, lateral placement, and steering reversals, the t-test were used to determine if the differences are significant. The data used in the statistical analysis is based on the individual observations measured from the video data taken in the field as well as data collected from a driver simulator laboratory.

The student's t-test was used when comparing the mean for a group of test sites with a group of control sites using the 'comparative parallel' evaluation plan. The following are the equations used to calculate the t-statistic and degrees of freedom (k') since unequal sample sizes were used.

$$t_{calculated} = \frac{\overline{X}_B - \overline{X}_A}{\sqrt{\frac{S^2_B}{N_B} + \frac{S^2_A}{N_A}}}$$

$$k' = \frac{\left[S^2_B / N_B + S^2_A / N_A \right]^2}{\frac{\left(S^2_B / N_B \right)^2}{N_B} + \frac{\left(S^2_A / N_A \right)^2}{N_A}}$$

Where:

$\overline{X}_B$ = sample mean of test sites

$\overline{X}_A$ = sample mean of control sites

N_B = number of test sites

N_A = number of control sites

S_B = standard deviation of test sites

S_A = standard deviation of control sites

If the calculated t-value is greater than the critical t-value, the difference in means is statistically significant.

For the student's t-test, a two-tailed test was used which utilizes a null hypothesis that states there is no difference between two means or treatment. The alternative hypothesis would state that one of the means is higher or lower than the other, or that one treatment is better or worse than the other treatment. A one-tailed test requires the direction of the difference to be specified prior to the analysis. The two-tailed test was used for this research, as the difference between the effectiveness of the steady burn warning lights was not known. Specifically, it could not be stated prior to this analysis that the use of steady burn warning lights on drums were better or worse than the drums without steady burn warning lights.

There are two potential errors involved in a statistical analysis, a Type I error or a Type II error. A Type I error would indicate that a particular treatment has an impact on dependent variables, when in fact there is no impact on the dependant variables. A Type II error would indicate that the treatment does not have an impact on the dependant variables, when in fact there is an impact. The Type I error can be reduced by selecting a small alpha level. However, this increases the possibility of a Type II error. Therefore, the selection of an alpha is critical. Statisticians in traffic engineering have consistently used an alpha equal to 0.05 or a level of confidence of 95 percent for evaluations of various treatments. Alpha is simply equal to 95 percent subtracted from 100 percent.

The results of the statistical analysis are described in the Section 5 (Results) of this report.

4.2 Field Experiment

In order to select sites to perform the field experiment, researchers from the WSU-TRG worked collaboratively with MDOT's Construction and Technology Division. The criteria for selection of work zone sites for inclusion in this study are as follows:

- Work zones are located on MDOT roads and highways
- Work zones were operational during the nighttime
- Work zones were delineated through the use of drums

The sites selected represented a variety of geographic, environmental, and traffic conditions in the State of Michigan. The selected sites encompassed urban and rural areas, locations with and without ambient street lighting, high and low traffic volume conditions and for different types of construction projects. A **test site** was considered a **work zone where drums were being used without the steady burn warning lights**. A **control site** was considered a location where **drums with steady burn warning lights** were being used.

MDOT initially provided a list of possible test sites available for inclusion in the study. Upon receipt of the list, each of the Transportation Service Centers were contacted to request additional information regarding potential schedule changes, further information on the traffic control details, and obtaining traffic crash data during the construction period. After discussions and/or field observations of the prospective study locations, several of the test sites were eliminated for various reasons. Table 4.1 outlines the list of the test sites that are work zones without steady burn warning lights, provided by MDOT and their status in the study. Sites that were eliminated from the study generally included those which used traffic regulators (flaggers), those that used temporary traffic signals for traffic control purposes, those that used grabber cones instead of drums, if the project was completed prior to the start of this research, or if the number of drums along a tangent was insufficient to collect any valid data.

As the study continued with a lesser number of sites, MDOT was able to provide additional study site information for Grand River Avenue and Telegraph Road. The final list of selected sites is shown in Table 4.2 with the respective MDOT region, setting, functional class, traffic volume and lighting available. The urban and rural setting was determined based upon the jurisdictions for Federal-Aid funding for urban areas with populations greater than 50,000 people. The functional class was based upon the National Functional Class information provided by MDOT. The roadway volumes reflect 2003 average daily traffic volumes as provided by MDOT.

Table 4.1. Test Site Descriptions and Status

LOCATION OF PROJECT	BRIEF DESCRIPTION	TRANSPORTATION SERVICE CENTER	STATUS	REASON FOR ELIMINATION/INCLUSION
US-23, Alpena County	Reconstruct 4 miles	Alpena	Eliminated	Traffic Regulators/ Temporary Traffic Signal
US-131, Osceola County	Resurface 9 miles	Cadillac	Test Site	Included in the Study
US-12, Three Oaks	Milling and Resurfacing	Coloma	Eliminated	Project Completed prior to study
I-94, Bridgman	Bridge Reconstruction	Coloma	Eliminated	Limited number of Drums in one tangent
US-2, Gogebic County	Resurface 4.5 miles	Crystal Falls	Eliminated	Traffic Regulators/ Detours
US-41, Delta County	Resurface 8.6 miles	Escanaba	Eliminated	Traffic Regulators/ Temporary Traffic Signals
US-41	N/A	Ishpeming	Eliminated	Intermittent/Traffic Regulators
US-131, Kalamazoo	Pavement Repair 10 miles	Kalamazoo	Test Site	Included in the Study
I-69, Calhoun County	Reconstruct 5 miles	Marshall	Test Site	Included in the Study
M-66, Calhoun County	N/A	Marshall	Eliminated	Traffic Regulators
US-127 BR, Mt. Pleasant	N/A	Mt. Pleasant	Eliminated	Project Completed prior to study
US-127, Isabella County	N/A	Mt. Pleasant	Eliminated	Project duration less than 14 days
M-115, Clare	N/A	Mt. Pleasant	Test Site	Included in the Study
US-127 BR Ithaca	Streetscape 2.9 miles	Mt. Pleasant	Eliminated	Short time, Project Completed prior to study
US-10, Clare County	Resurface 8.6 miles	Mt. Pleasant	Test Site	Included in the Study
M-29, Marine City	Reconstruct 1.6 miles	Port Huron	Eliminated	Grabber Cones used instead of drums
I-94, Taylor	Reconstruct 3 miles	Taylor	Test Site	Included in the Study
M-115, Manistee and Benzie Counties	Deck Replacement	Traverse City	Eliminated	Temporary Signals
US-10/I-75	Rehabilitate Bridge	Bay City	Test Site	Included in the Study

Table 4.2. Selected Test and Control Sites

Location	Site Type*	MDOT Region	Urban / Rural Setting	Roadway Functional Class	Roadway Volume (ADT)	Lighting Availability
Grand River Avenue; Evergreen to Greenfield	Test	Metro	Urban	Arterial	19,900	Ambient
Telegraph Road at I-94	Test	Metro	Urban	Arterial	68,900	Ambient
Bus. US-10 (Main St.); US-127 and M-115 Clare	Test	Bay	Rural	Arterial	8600	Ambient
US-12 (Michigan Avenue); Canton Center to Denton	Control	Metro	Urban	Arterial	27,900	None
M-39 (Southfield Road); Fort to Dix	Control	Metro	Urban	Arterial	48,750	Ambient
I-69; Mile 30 to 35	Test	University	Rural	Interstate	20,950	None
I-75 at US-10	Test	Bay	Urban	Interstate	54,300	None
I-75 at M-57	Control	Bay	Urban	Interstate	56,350	None
I-94; Pelham to Beach Daly	Test	Metro	Urban	Interstate	136,000	Mix
I-96, M-39 to US-24	Control	Metro	Urban	Interstate	176,000	Ambient
US-10; Ludington to US-127	Test	Bay	Rural	Arterial	9500	None
US-23 at M-59	Control	University	Urban	Other Freeway	49,300	None
US-131; M-43 to M-89	Test	Southwest	Rural	Other Freeway	39,500	None
US-131; US-10 to Luther	Test	North	Rural	Other Freeway	12,100	None
M-10; Davison Fwy. to I-94	Control	Metro	Urban	Other Freeway	137,000	Ambient

*A **test site** was considered a **work zone where drums were being used without the steady burn warning lights**.
A **control site** was considered a location where **drums with steady burn warning lights** were being used.

Traffic operational and safety data was collected for each site including lateral placement of vehicles, speed through the work zone, traffic crash data and a physical inspection of the work zone including drums and lights. Driver behavior and vehicle placement within the lanes was recorded using video cameras. The video camera was mounted inside a survey vehicle and data was recorded for a number of runs through the advanced warning area and the work zone during

the nighttime hours, while following target vehicles. With this approach, the motorists were not aware that they were being monitored and thus their driving behavior was unbiased. The following pictures depict the view from the survey vehicle for both a sample test and control site.

Photograph 4.1 Test Site

Photograph 4.2 Control Site

The video data was then analyzed in the laboratory in order to obtain quantifiable lateral placement data. When analyzing the video data, the lateral placement of vehicles was determined by locating the vehicle in the center of the lane, in the right third of the lane or in the left third of the lane. An acceptable lateral placement included the two furthest positions in the lane. Speed data was collected for vehicles traveling through the work zones using portable radar detectors. The speed data was collected at three locations in the work zone where a safe location for speed measurements was available. In general, the speed data was collected: 1) at the beginning of the work zone just before or immediately following the taper, 2) in the middle of the work zone, and 3) at the end of work zone (prior to the beginning of the departure taper). All speed data was collected during nighttime hours only.

Traffic crash data (UD-10 forms) was collected from the Michigan State Police database for each of the study sites (both test and control sites). The dates and locations of the traffic crashes were analyzed in order to determine where the crash occurred within the work zone, and whether or not the steady burn warning lights were present on the drums. A survey of the current work zone set up and condition of the drums and the surrounding traffic control devices was also performed as a part of this study. The drums were surveyed in terms of their approximate location and condition assessment in order to establish the baseline reference. For the control site, details

regarding the type of warning light used, as well as the operational and physical characteristics of the steady burn warning lights (burn out, and orientation being turned and not properly visible, etc.) were collected. In addition, a digital video was taken of the drums and traffic control devices in the surrounding area for documentation and verification purposes. Further details of the field data collection and video data extraction are outlined in the following sections: Traffic Crash Data, Speed Data, Physical Investigation of the Drums, and Lateral Placement Data.

Statistical tests have been performed to determine if there are significant differences between the use of drums with and without steady burn warning lights. For these statistical tests, several categories were examined. The sites were subdivided into those with drums with and without steady burn warning lights with statistical tests being performed between these two groups. The sites were further subdivided by roadway functional classification and setting as shown in Table 4.3. The sites were then further subdivided by the availability of ambient lighting in the work zone. Statistical tests were also performed for these subcategories where appropriate. Detailed information on the statistical analysis can be found in Section 5 (Results) of this report.

Table 4.3. Test and Control Site Categorization

Category	Location	Site Type	Urban / Rural Setting	Lighting Available
Interstate	· I-75 at M-57	Control	Urban	None
	· I-94	Test	Urban	Mix
	· I-96	Control	Urban	Ambient
	· I-75 at US-10	Test	Urban	None
	· I-69	Test	Rural	None
Freeway	· US-23	Control	Urban	None
	· M-10	Control	Urban	Ambient
	· US-131; M-43 to M-89	Test	Rural	None
	· US-131; US-10 to Luther	Test	Rural	None
Principal Arterial / Major Collector	· US-10	Test	Rural	None
	· Grand River Avenue	Test	Urban	Ambient
	· Telegraph Road	Test	Urban	Ambient
	· Bus. US-10 (Main St.)	Test	Rural	Ambient
	· US-12 (Michigan Avenue)	Control	Urban	None
	· M-39 (Southfield Road)	Control	Urban	Ambient

4.2.1 Traffic Crash Data

In order to assess safety characteristics at sites utilizing drums with and without steady burn warning lights, traffic crash data (UD-10 forms) was collected from the Michigan State Police database for each of the field study sites. The dates and locations of the traffic crashes were investigated to determine where the crash occurred within the work zone, and whether or not the steady burn warning lights were present on the drums. Details of the crash occurrences are generally provided by the police officers in written and pictorial form on the 'Crash Diagram and Remarks' section of the UD-10 form and are used to identify the probable cause or contributing factors of the crash. The crash analyses performed in this study concentrated on those crashes related to delineation within the work zone.

It is important to note that the number of traffic crashes that occur in a given work zone are fairly low. This is due, in general, to the fact that traffic crashes are rare events, compounded by the temporary nature of work zones, and the short duration they are in place. In order to perform the proper statistical tests, the crash frequencies for all the test sites were aggregated. Likewise, the crash data for some of the control sites which exhibited the most similarity with a particular test site, were also aggregated.

In addition, crash rates were used which account for traffic volume differences between test and control sites. The traffic crashes were analyzed to determine the probable cause of the crash and also the time of day/night, in order to separate the daytime crashes from the nighttime ones. Significant changes between the various types of crashes, at the test and control groups were tested for significance using the chi-square test and/or the t-test at a 95 percent level of confidence.

The analysis of the traffic crash data serves as a direct measure of safety. In addition, the occurrence of other surrogate measures was also compared as a part this study in order to assess the differences between the traffic operational and safety characteristics of the test and control sites. The statistical tests can be found in Section 5 (Results) of this report.

Construction sites are subdivided into two categories; control sites and test sites. Control sites in this study represent construction sites with steady burn warning lights and test sites indicate construction sites without steady burn warning lights. Construction period beginning and ending dates were identified from the MDOT website, for test and control sites. At all locations, crash data was extracted during the construction period and one year prior to the construction period. For example, if the construction period started in April 2004 and ended in November 2004, the during construction time period data will include all crashes from April to November of 2004. However, prior to construction period data will include crashes beginning from April to November of 2003. Time spans are kept the same for both 'during construction' and 'before construction' periods. Crashes occurring during the construction period may or may not encompass crashes that are directly related to construction activity. For example, a crash due to skidding because of snow/ice on the road surface is not directly related to the construction activity; however, crashes in a narrow lane as a result of construction drum placement are directly construction activity related. Crashes directly involved with construction zone treatment and crashes not directly involved with construction zone treatment, but occurred during the construction period, were also identified.

Construction zone related work usually begins in late Spring and continues until late Fall and sometimes the beginning of Winter, but in most cases from April to November. The daytime period is longer during the summer months. For this study, the time period between 9:00 PM to 6:00 AM is considered as the nighttime period. All crashes occurring during this time were defined as nighttime crashes and were the focus of this study.

During construction period crashes were identified based on the following criteria:

1. From the UD-10 Form, the section of "*construction zone*" is examined to identify whether the crash is related to any type of construction activity or construction related lane closure or detours.

2. The crash should be on the road where the construction zone treatments were present at the time of crash. If the crash is on an intersecting road, the crash is not considered as a construction zone related crash.

3. In case the study site is on a freeway, crashes on service drives were not identified as construction zone related crashes. However, construction zone related crashes on service drives were counted as a construction zone crash if construction zone treatments were present on the service drive.

4. Each UD-10 form has a section called "*crash diagram and remarks*". The investigating officer writes his/her comments with relevant crash information and a sketch of the crash location. Crashes in construction activity areas are sketched with construction drums and the investigating officer's remarks, in most cases. If the crash is not in a construction zone and no construction related activity is identified from the *crash diagram and remarks* section, that particular crash is not considered as a construction related crash in this study.

Driving within the construction zone becomes even more critical during nighttime. Therefore, all crashes during the construction period were subdivided into daytime and nighttime crashes for both test and control sites.

4.2.2 Speed Data

Speed data was collected for vehicles traveling through the work zones using portable radar detectors. The speed data was collected at three locations in the work zone where a safe vantage location for speed measurements was available. In general, the speed data was collected at the beginning of the work zone just before or immediately following the taper, in the middle of the work zone, and at the end of the work zone prior to the taper. Figure 4.3 depicts these locations for the speed data collection points. The speed data was collected during nighttime driving conditions for each selected site and each location of the work zone.

The analysis of speed data was used as an indication of a motorist's perceived risk of traveling through the work zones using drums with and without steady burn warning lights. The speed data was collected and analyzed during the nighttime off-peak period when motorists are able to travel at their desired speed, unaffected by congestion experienced during the peak periods.

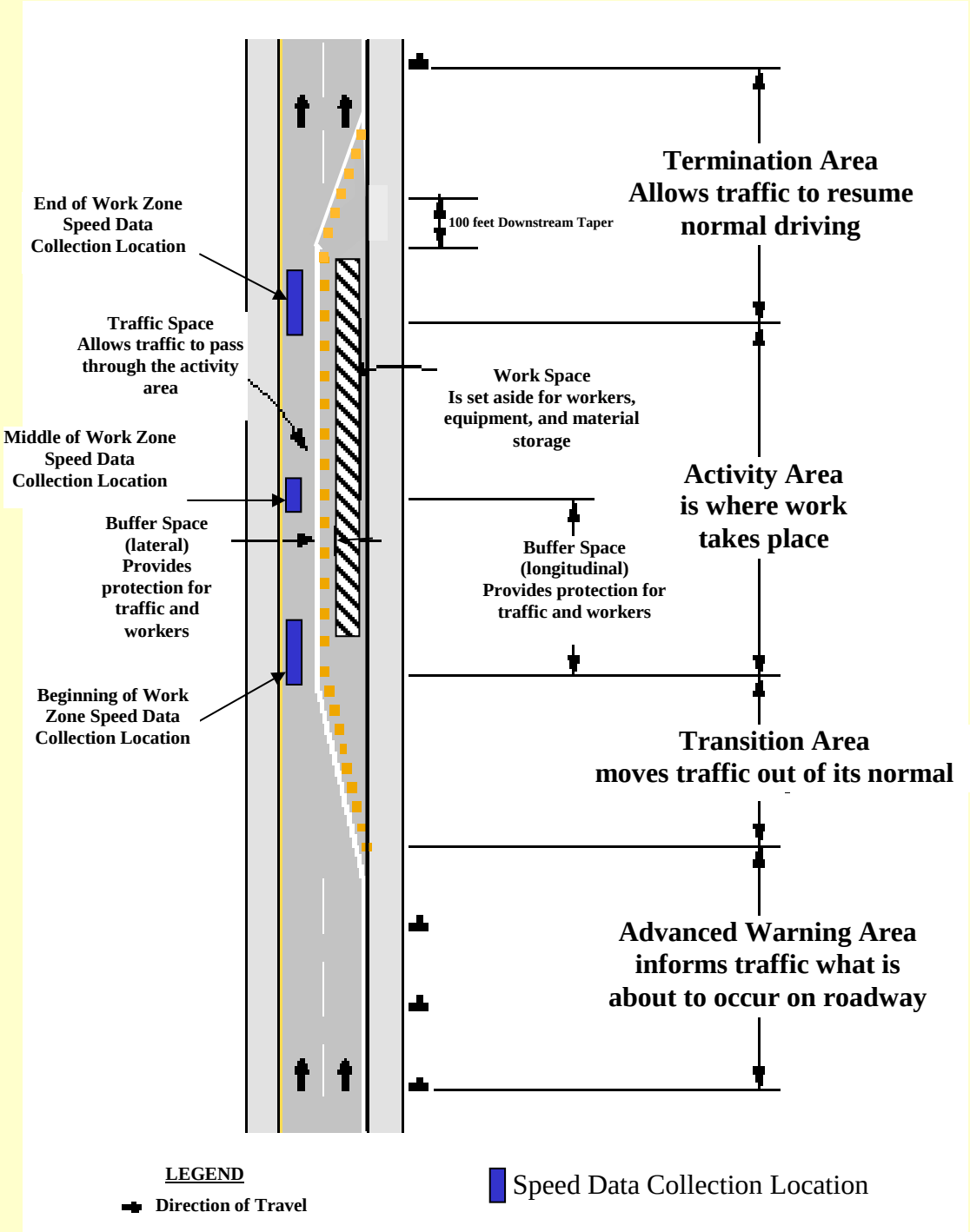


Figure 4.3. Speed Data Collection Locations

4.2.3 Physical Investigation of Drums

Another surrogate measure used in this study was the inspection of the work zones at the test and control sites in order to identify vehicle contact with the channelizing devices. Specifically, drums being knocked-down, scratched, dented or moved as a result of vehicular contact were investigated.

Initially, a survey of the current work zone set up and condition of the drums surrounding traffic control devices was performed. The drums were surveyed in terms of their approximate location and their physical condition was assessed in order to establish the baseline reference. For the control site, details regarding the type of warning light used and power source was identified, as well as the operational and physical characteristics of the steady burn warning lights (burn out, and orientation being turned and not properly visible, etc.). In addition, a digital video was taken of the drums and the surrounding traffic control devices for documentation and verification purposes.

Photographs and video data were obtained to document the condition of the drums during the observation period. The weather condition, lighting condition and time of survey were also recorded.

4.2.4 Lateral Placement and Steering Reversal Data

The lateral placement and steering reversal of vehicles within a travel lane through the work zone was quantified in order to assess the ability of drums with and without lights in guiding motorists through the work zone. Driver behavior and vehicle placement within the lanes was recorded using video cameras. A digital video camera was mounted inside a survey vehicle and data was recorded for a number of runs through the advanced warning area and the work zone during the nighttime hours while following a vehicle. With this approach, the motorists were not aware that they were being monitored and thus, their driving behavior was unbiased.

The video data was then analyzed in the laboratory in order to obtain quantifiable lateral placement and steering reversal frequency data. When analyzing the video data, the lateral

placement of vehicles was determined by locating the vehicle in the center of the lane, in the right third of the lane or in the left third of the lane. An acceptable lateral placement included the two furthest positions from the location of the drums. For example, if the drums were located on the left of the vehicle, an acceptable lateral placement of the vehicle would be in the center of the lane or in the right third of the lane. This acceptable lane positions provide for the protection of the workers as well as the motorists by maintaining the position of the vehicle from traveling near the drums where drums could be hit or the worker may be hit by a passing vehicle. It was assumed that a vehicle traveling in an 'unacceptable' lane position would have a higher probability of hitting the drums due to the close proximity of the vehicle to the drums. In turn, these vehicles would also have a higher probability of penetrating the work zone, thus making their choice of travel path undesirable.

The average steering reversal was determined similar to the definition of weaving in the studies by Pant (10, 11), where the absolute value of the difference in lateral placements was divided by the number of intervals of lateral placement data.

4.3 Simulator Experiment

The WSU-TRG utilized the driving simulator owned by Wayne State University's Department of Occupational Therapy for the controlled laboratory experiment portion of this project. The simulator was used to conduct a controlled laboratory experiment of driver performance through work zones that used drums with and without warning lights. A sample focus group of drivers (89 individuals) participated in the driving simulator experiment.

The simulator used in this project was the "Advanced Mobile Operations Simulator (AMOS™) manufactured by Doron Precision Systems, Inc. of Binghamton, New York. This driving simulator was developed to enhance the training of emergency vehicle and law enforcement personnel, but has been used by WSU researchers for a wide variety of driving instructional purposes, including occupational therapy. The simulator is operated from a control station (desktop computer) that is used to run a variety of driving scenarios as projected on a five-screen display that produces a realistic 225-degree panoramic field of view for the driver. The simulated vehicle is operated within a computer-synthesized interactive universe, displayed from the driver's point of view. As shown in Photographs 4.3, 4.4 and 4.5, the driving simulator

consists of five viewing screens, steering wheel, gas and brake pedals, starting ignition, rear view mirror with simulated views, headlights, high beam lights, and turn signals as well as other features replicating the interior of a typical automobile. The simulator is equipped with packaged software programs to simulate typical driving scenarios and can be modified to simulate specific driving conditions.

The driving simulator that was used in the simulator experiment is shown in Photographs 4.3, 4.4 and 4.5. The multi-screen display of the simulator replicates the driver's view of the environment and thus generates driver performances similar to real-life situations.

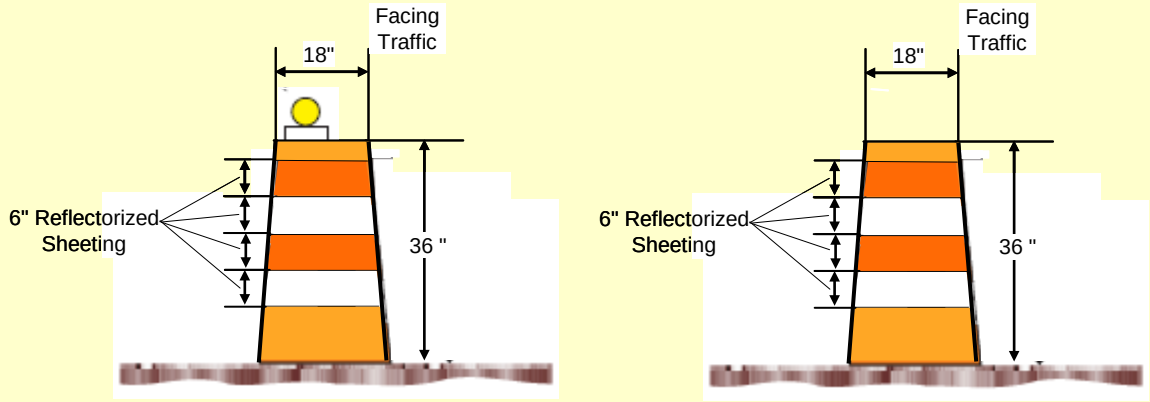
**Photograph 4.3. Driving Simulator-
Close Up View of the Virtual Driving Environment**

Photograph 4.4. View of the Driving Simulator Configuration

Photograph 4.5. Sample Driver Using the Driving Simulator

The WSU-TRG worked with computer programmers and technicians to customize a program to simulate driving through work zones that have drums with and without steady burn warning lights. The programmers provided the necessary specifications of the drums, including lumens of light emitted from the steady burn warning lights, and traditional work zone traffic control plans and layouts to assist in creating an accurate virtual driving environment. In a typical driving scenario, the driving simulator is able to replicate a normal nighttime driving environment and is also able to simulate retroreflectivity of headlights hitting traffic signs at night. This logic was used in the programming of the simulated scenes to replicate the retroreflective nature of the drums as well as the light emitted from the steady burn warning lights.

The driving environments simulated included a construction work zone along a tangent section of a two-lane divided highway with construction drums with and without Type 'C' warning lights, as shown in Figure 4.4.



With Type 'C' Warning Lights **Without Type 'C' Warning Lights**

Figure 4.4. Construction Drums used in Highway Work Zones

Drums with lights contain Type ‘C’ warning lights that emit a steady burn yellow light and are used to delineate the edge of the traveled way on lane changes, lane closures, and other similar conditions. The Type ‘C’ warning light must be visible on a clear night from a distance of 3,000 feet. The drums consist of lightweight and flexible materials. If struck, they are intended not to inflict undue damage to the vehicle that strikes them and behave in a manner consistent with the type of crash. The drums are 36-inches in height and 18-inches in diameter on top. The markings on the drums are horizontal, circumferential, with alternating orange and white retroreflective stripes which are six inches wide. Typically the drums have two orange and two white reflectorized stripes.

The driving scenarios allowed a driver to travel on the freeway under typical (non-construction) conditions for approximately two miles before entering the work zone. The speed limit was posted at 70 mph for typical (non-construction) freeway conditions. The motorists then entered a highway work zone setting. For the work zone setting in the simulator, the drums for the construction zone were placed on both sides of the travel lanes to assure that each driver chose a position in the travel lane instead of driving on the shoulder. With the simulator, it was found on the trial runs that drivers would utilize more than one lane if provided. Therefore, the drivers were not provided that option when drums were placed on both sides of the highway.

Diagrams of four work zone settings have been prepared for each of the desired scenarios, as shown in Figures 4.5 and 4.6 and are as follows:

- Scenario 1: Construction Zone on a Freeway Using Drums with Warning Lights (Figure 4.5)

- Scenario 2: Construction Zone on a Freeway Using Drums without Warning Lights (Figure 4.6)

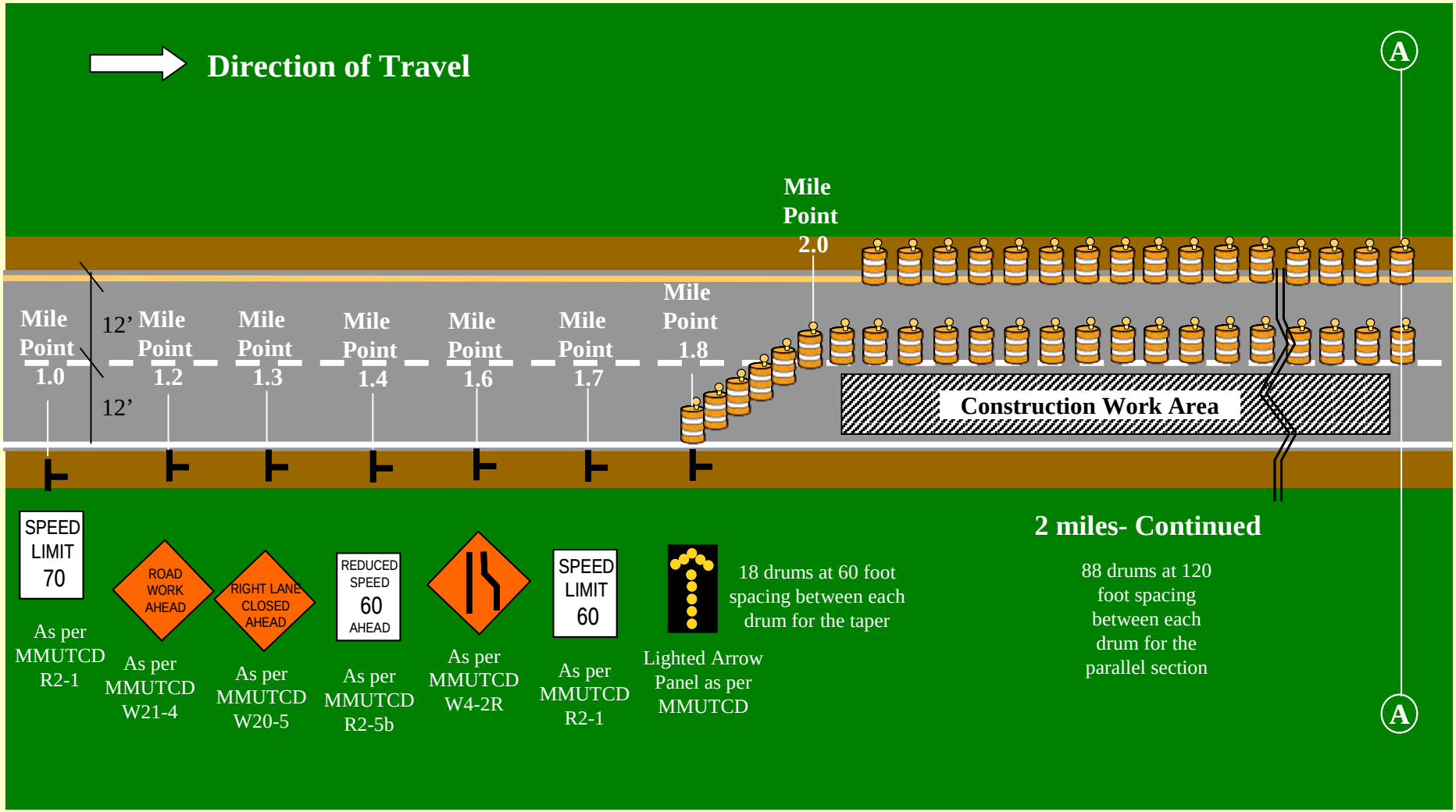


Figure 4.5. Driving Scenario 1: Highway Work Zone Using Drums with Warning Lights

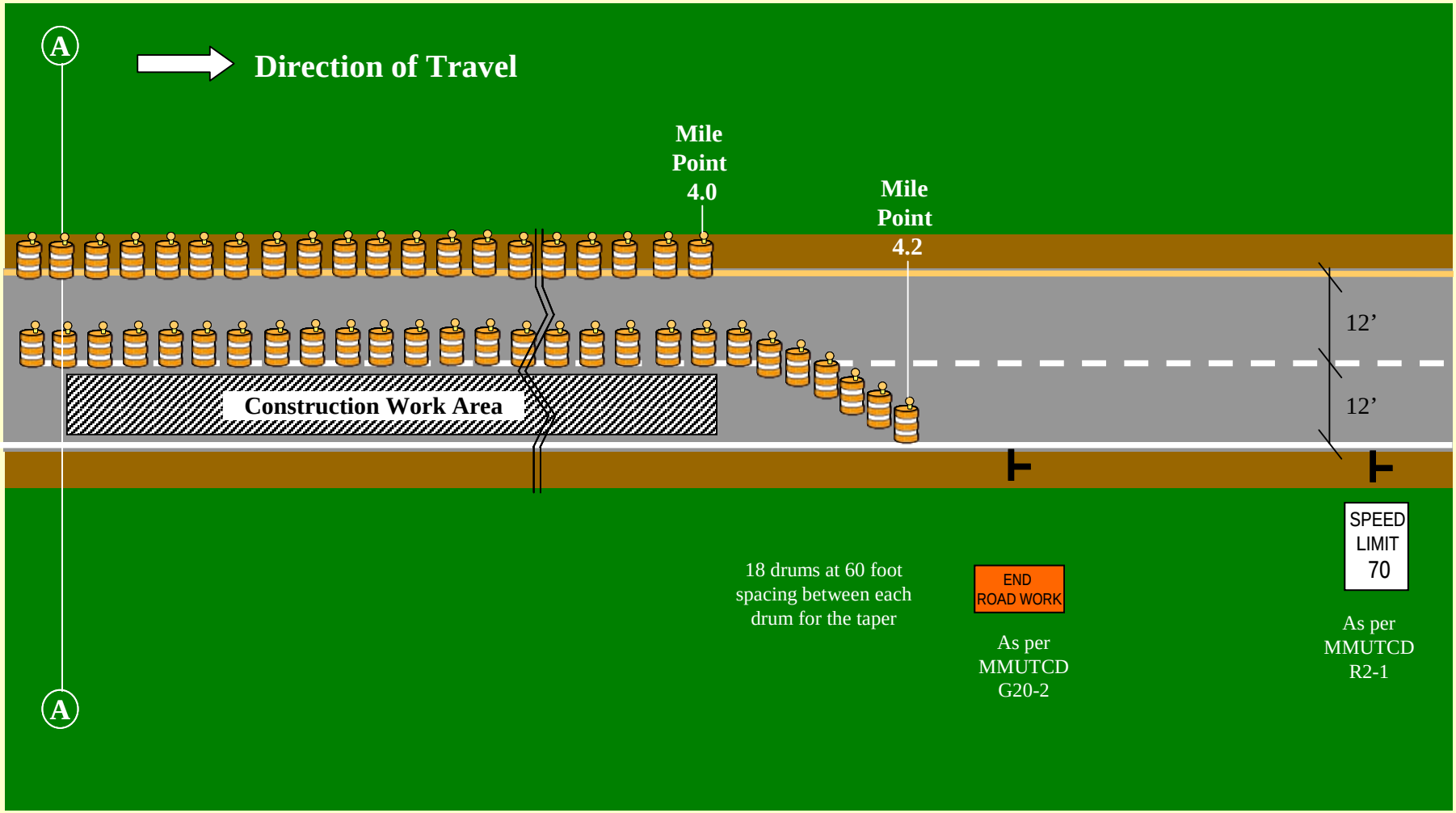
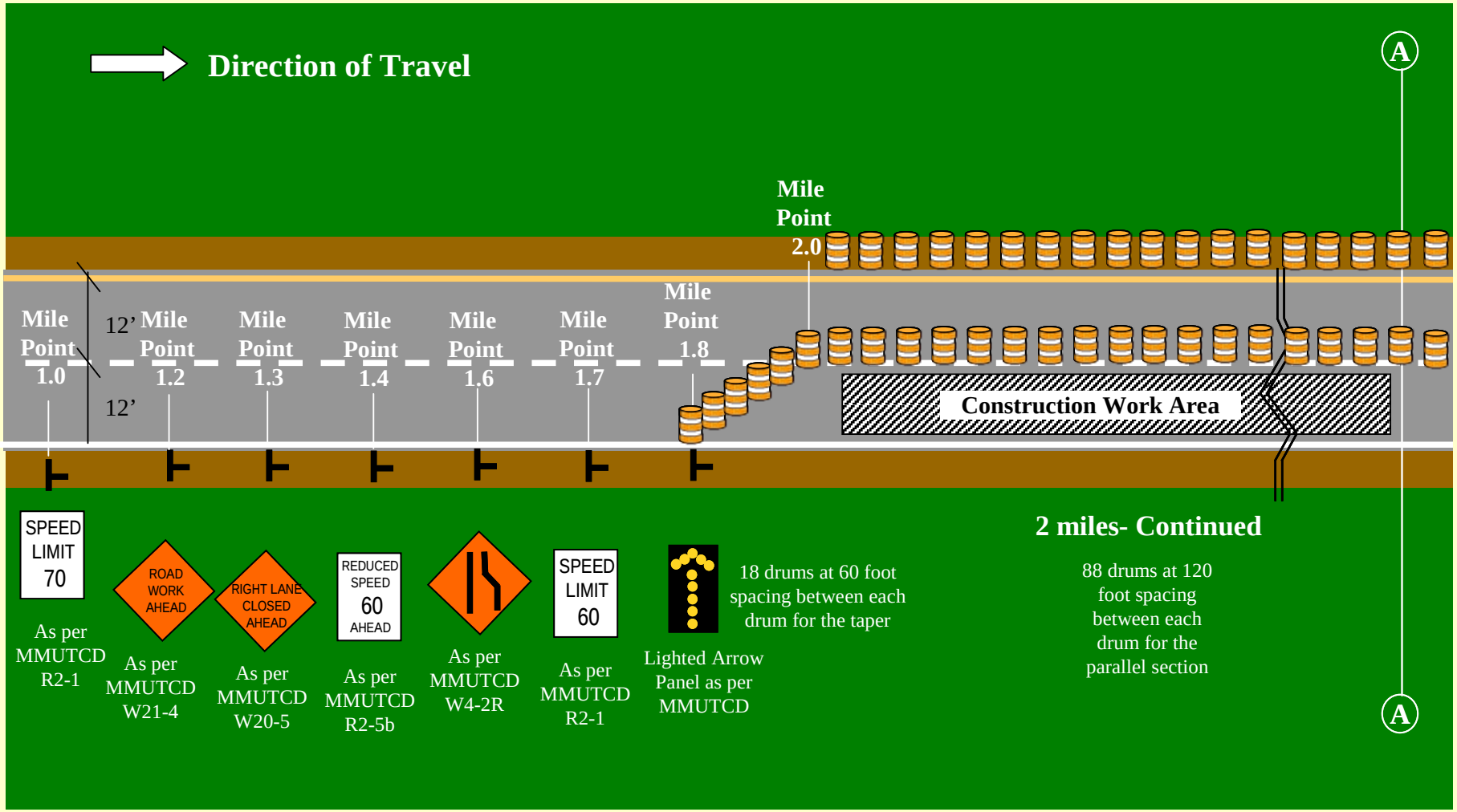
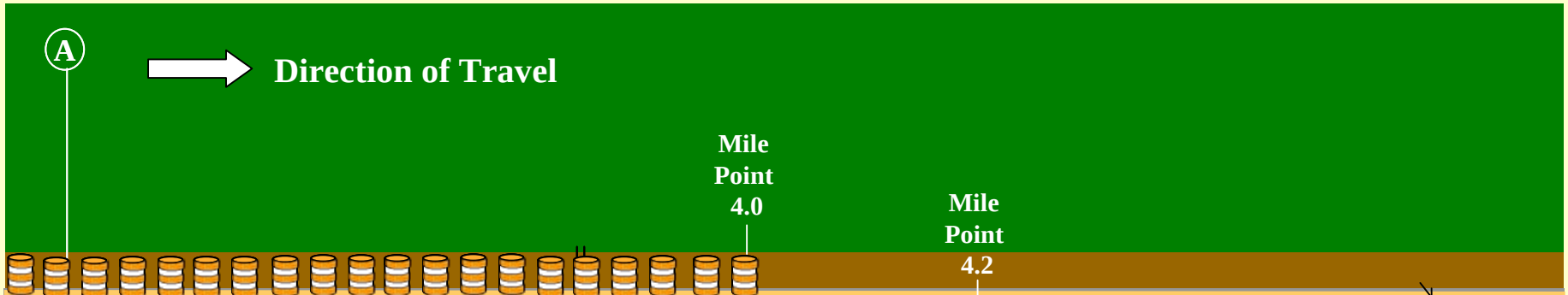


Figure 4.5. Driving Scenario 1: Highway Work Zone Using Drums with Warning Lights (Continued)


Direction of Travel
A
Mile Point 2.0
Mile Point 1.0
12'
12'
Mile Point 1.2
Mile Point 1.3
Mile Point 1.4
Mile Point 1.6
Mile Point 1.7
Mile Point 1.8
Construction Work Area
SPEED LIMIT 70
As per MMUTCD R2-1
ROAD WORK AHEAD
As per MMUTCD W21-4
RIGHT LANE CLOSED AHEAD
As per MMUTCD W20-5
REDUCED SPEED 60 AHEAD
As per MMUTCD R2-5b
As per MMUTCD W4-2R
SPEED LIMIT 60
As per MMUTCD R2-1
Lighted Arrow Panel as per MMUTCD
18 drums at 60 foot spacing between each drum for the taper
2 miles- Continued
88 drums at 120 foot spacing between each drum for the parallel section
A


A
Direction of Travel
Mile Point 4.0
Mile Point 4.2

The first mile of each simulated driving scenario is a two-lane (each way) freeway scene, with a regulatory speed limit sign of 70 mph at mile-point 1.0. The standard MUTCD 'Road Work Ahead' warning sign appears at mile-point 1.2, the 'Right Lane Closed Ahead' warning sign appears at mile-point 1.3, the 'Reduced Speed 60 mph Ahead' appears at mile-point 1.4 with the right lane closed ahead symbol warning sign appearing at mile-point 1.6. The speed is reduced with a speed limit regulatory sign of 60 mph at mile point 1.7. The construction zone taper begins at mile-point 1.8 and ends with the full lane closure at mile-point 2.0. After the end of the taper closing the right lane, the work zone continues for another two miles with drums on both sides of the traffic lane. At mile point 4.0, the work zone ends, the closed lane opens, and the speed limit is resumed to 70 mph. This is where the simulation ends.

The driving environments were simulated for daytime and nighttime driving conditions and could also have included inclement weather conditions, such as rain and/or fog. For the nighttime condition, the driving environment simulated the retroreflectivity of headlights hitting all traffic signs and the drums (regardless of the presence or absence of the warning lights). In the driving scenarios, when warning lights were included on the drums, they emitted a steady burn yellow light.

The focus group was comprised of a sample of the general driver population, selected from residents of the metropolitan Detroit area, with experience in driving on the region's freeway system to commute to work or school. The gender breakdown of the subjects was 42.5 percent male and 57.5 percent female, with varied ages and educational levels. In a pre-test survey form, the subjects were asked about their driving experience in terms of commuting through work zones, involvement in work zone crashes, and speeding violations over the past five years. The pre-test survey was performed in order to obtain demographic information regarding the test subjects in order for correlations to be made with their performance in the driving simulator and to determine if the focus group consisted of a representative sample of motorists in the State of Michigan. Table 4.4 presents a summary of test subject profiles.

Table 4.4. Test Subject Profiles

DEMOGRAPHICS	NUMBER	PERCENTAGE
Gender		
Male	37	42.5%
Female	50	57.5%
Age in years, Mean Age = 27.31 years		
16-20	7	8%
21-25	51	58.6%
26-35	21	24.1%
36-45	1	1.1%
46-60	5	5.7%
61-70	2	2.3%
Daily commute in hours, Mean Travel Time, 1.18 hours		
0.0 – 0.5	13	14.9%
0.5 – 1.0	23	26.4%
1.0 – 1.5	23	26.4%
1.5 – 2.0	21	24.1%
2.0 – 2.5	5	5.7%
Over 2.5	2	2.3%
Frequency of work zone encounters over past 5 years		
None	1	1.1%
Rarely (less than 5 occurrences)	11	12.6%
Occasionally (average of once or fewer per week)	39	44.8%
Frequently (almost every day of commute)	36	41.4%
Work zone crash experience over past 5 years		
None	85	97.7%
One	2	2.3%
Two	0	0%
Three or more	0	0%
Speeding violations over past 5 years		
None	42	48.3%
One	29	33.3%
Two	8	9.2%
Three or more	8	9.2%

In order to generalize the data and results of the driver simulator experiment, comparisons must be made between the sample population used in the laboratory experiment and the population at large in the State of Michigan. Table 4.5 presents a summary of the 2003 population estimates from the U.S. Census Bureau.

Table 4.5. State of Michigan 2003 Data Profile *(28)*

Demographics	Percentage
Gender	
Male	48.7%
Female	51.3%
Age in years, Mean Age = 36.6 years	
15-19	6.94%
20-24	6.70%
25-34	12.88%
35-44	15.42%
45-54	14.93%
55-59	5.56%
60-64	4.32%
65-74	6.24%
Daily commute in hours, Mean Travel Time = 0.38 hours	

It should be noted that the age categories used in Table 4.5 (Profiles of Focus Group) slightly differ from that shown in Table 4.4 (US Census Bureau data). The age categories used in the survey instrument to obtain the driver profiles of the focus group participants for the simulator study were based on age classifications used by the Michigan State Police in their annual 'Traffic Crash Fact Books' when assessing the relative crash risk of drivers by age throughout the State of Michigan.

When comparing an observed frequency distribution or percentage with the corresponding values of an expected distribution, the intent is to test whether the discrepancies between the observed and expected frequencies or percentages can be attributed to chance. If the discrepancies are attributed to chance, then the differences between the two percentages can be deemed insignificant. The statistical equation to test for this is the statistic for test of goodness of fit, or the chi-square test.

The chi-square equation was used to test the null hypothesis that the focus group sample was similar to the population in the State of Michigan in terms of gender and age distribution. Although the age groups in the sample population and the State of Michigan population differed, it was assumed that the age difference of one year per grouping would not provide substantially

different results in the chi-square test. It was found that there was no significant difference in the gender distribution between the focus group sample and the population in the State of Michigan. However, a significant difference was found between the age groups in the focus group sample and the State of Michigan population. Table 4.6 shows the results of the statistical test for these hypotheses.

Table 4.6. Results of the Chi-Square test for Goodness of Fit

CALCULATIONS	X^2 GENDER GROUPS	X^2 AGE GROUPS
X^2 calculated	1.539	442.402
Degrees of Freedom k-m	1	5
X^2 Critical at a = 0.005 and k-m	7.879	16.750
Significant Difference?	No, Not Significant	Yes, Significant

The age group of 16-24 was over-represented in the sample population for the driver simulator laboratory experiment in comparison to the State of Michigan 2003 Census Estimates. Although there are differences in these percentages, the sample population can be considered to include higher percentages of high risk drivers than the driving population in Michigan, since the per capita crashes are higher for the age group of 16 through 24 than the under-sampled age groups of 25 through 64 and 65 and over. Table 4.7 indicates the number of crashes per age group and the per capita rate for the year 2003.

Table 4.7. Crash Rates for Michigan Motorists by Various Age Groups

AGE GROUP	POPULATION	TOTAL CRASHES	FATAL CRASHES	INJURY CRASHES	PER CAPITA RATE OF TOTAL CRASHES
16-24	1,340,388	156,496	427	36,423	0.12
25-64	5,219,289	380,983	1133	83,020	0.07
65 and over	1,177,082	43,964	229	10,103	0.04

For the driver simulator experiment, a detailed test procedure/sequence was developed with standard instructions as summarized below:

Step 1 – Give orientation before driver enters the simulator.

Step 2 – Have the subject locate the controls in the simulator.

Step 3 – Have the subject drive the base condition scenario until they feel comfortable using the simulator.

Step 4 or 5 – Have the subject drive the drums with lights scenario.

Step 4 or 5 – Have the subject drive the drums without lights scenario.

Prior to their simulation tests, each subject was given a brief introduction and description of the general purpose of the experiment and what their role would be. The purpose stated was "to test the effect of various traffic control devices on driver behavior as they drive through a freeway construction work zone". They were told they would be driving three scenarios. However, they were not given any information regarding the test and control scenarios. The first scenario was intended to acclimate the subject to the vehicle controls and computer-generated images. The subjects were asked to tell the instructor when they felt comfortable with the simulator's controls so that they could move on to the next two scenarios. They were all told that the two test scenarios represent various freeway construction work zone layouts over a four-mile long course during nighttime driving conditions. They were then instructed to drive as if they were returning from/going to work or school, driving at a speed they felt comfortable with, given the conditions presented on the computer screens. They were asked to try and maintain a constant speed as much as possible, and adjust their speed as necessary when the conditions demanded.

Experience with the driving simulator indicated that some operational "seat time" is necessary for the test subjects to become acclimated to the driving simulator and to be able to perform as he/she would in a real highway driving situation, in particular the simulator's response to actions by the driver relative to braking, accelerating, and steering. This is consistent with the simulator user's guide provided with the manufacturer's instructional materials. Initial "dry runs" by members of the WSU-TRG resulted in some individuals experiencing varying levels of nausea

and dizziness (akin to sea-sickness) due to driving simulations that encompassed numerous turning, braking, and accelerating. In most instances, these effects were alleviated by wearing a sea-sickness wristband on each wrist that applied a small amount of pressure on the driver's wrist nerves. However, a few (2 out of 91) test subjects did not continue with the test runs due to such motion sickness. To further alleviate this situation, the base condition scenario for the driver simulator experiment was utilized due to the use of a long tangent section of roadway and lack of turning movements required by the subject. For these reasons, it was important to provide each test subject with an initial training scenario with no special highway conditions or speeding countermeasures. Only after the subjects were accustomed to and comfortable with the simulator, were they asked to drive the virtual work zone scenarios.

The purpose of using the driving simulator is to observe and quantify the focus group test subjects' reactions and performance in work zone driving with the presence or absence of the steady burn warning lights on the drums without informing them of the differences. The performance of the test subjects was recorded on the control station as well as with a video for more comprehensive data tabulation and further analysis, including a closer examination of driver performance, after the conclusion of the test drive and without the subject in the simulator testing laboratory. The performance measures included speed characteristics, near misses/traffic crashes, lateral placement in the driving lane, number of steering reversals and location of lane change. Each test subject encountered a work zone setting that used drums with and without warning lights. They were not informed of the specific reason for the experiment to keep their driving performance unbiased. Comparisons were made of the driving performances of the focus group test subjects for both the work zone settings.

4.3.1 Simulator Traffic Crash Data

Traffic crash data was extracted from the driving simulator video data. For each driving scenario, drums with lights and drums without lights and the number of traffic crashes occurring was totaled for all test subjects. In addition, the location of the crash was noted and summarized. A traffic crash occurred when the driver of the simulator veered from the travel lane and hit a

drum. Upon hitting a drum, the simulation experiment for that driver ended. In reality, upon hitting a drum, a driver could continue along the roadway or would respond with evasive maneuvers to correct the vehicle's lane position.

The analysis of the simulated traffic crash data also serves as a measure of safety. In addition, the occurrence of other surrogate measures was also compared in order to assess the impact of traffic operations and safety at the test and control sites.

4.3.2 Simulator Speed Data

The average group speed (including all test subjects) at each point along each scenario was calculated. Then, a speed profile plot was developed for the two scenarios (drums with lights and drums without lights) using the tenth-mile measurements for plotted points on the profiles.

Comparisons of the travel speed were also made at specific data points along the work zone configuration: at the beginning of the work zone lane closure taper, half the distance into the work activity area and at the end of the lane closure. These points are representative of the data point locations for the field experiment work zone speed measurement done as a part of this study. However, it is expected that average speeds observed in the simulator will be lower than those measured at similar points in actual work zones. This is due to the effects that are associated with the test subjects' unfamiliarity with the driving simulator as compared to their own vehicles. Furthermore, most motorists who drive through a work zone have done so, for that same work zone, many times over the course of the project's construction, and have become relatively comfortable with the conditions and features that might influence their speeding behavior. This is not the case with test subjects who spend only a few minutes driving through simulated scenarios, only one time per scenario. What is important to focus on when conducting driver simulation studies is the relative difference in driving behavior among various simulations, not differences in driving behavior between simulations and the field experiment conditions. This point has been made by others conducting such research, including van der Horst and Hoekstra *(14)*.

4.3.3 Simulator Lateral Placement and Steering Reversal Data

The lateral placement of vehicles through the work zone was quantified in order to assess the ability of drums with and without lights in guiding motorists through the work zone. Driver behavior and vehicle placement within the lanes was recorded using video cameras. The digital video camera was located just behind the simulator and data was recorded during the experiment with the driver and again with the driver absent. Data was recorded while the driver was present to record any comments the test drivers made during the simulation. In general, the test subjects, while driving the simulator, rarely spoke during the experiment. The data was then re-recorded while the test subject was absent in order to superimpose a grid system on the monitor to extract the lateral placement data.

The video data was then analyzed in the laboratory in order to obtain quantifiable lateral placement data. When analyzing the video data, the lateral placement of vehicles was to be determined by superimposing a calibrated grid system on the television monitor during the viewing process. Similar to the field experiment, lateral placement was determined by locating the vehicle in the center of the lane, in the right third of the lane or in the left third of the lane. For the simulator experiment, the drums were placed along both lane lines; thus, an acceptable lateral placement would involve a vehicle traveling in the center of the lane. Therefore, any deviation from the center of the lane to either the right third of the lane or the left third of the lane was considered unacceptable, since vehicles in these positions would have a higher probability of hitting the drums and/or penetrating the work zone.

The lateral placement data collected for the two scenarios was analyzed using a series of statistical analyses to determine if the distribution of lateral placement of the vehicles is different at the test and control sites, using an appropriate statistical test.

The video data was then analyzed in the laboratory in order to obtain quantifiable steering reversal data. When analyzing the video data, the steering reversal data was determined by observing the number of times the driver shifted from one lane position to a second lane position due to movement of the steering wheel.

The steering reversal data collected for the two scenarios was analyzed using a series of statistical analyses to determine if the distribution of steering reversals of the vehicles is different at the test and control sites, using a t-test.

Comparisons between the field and simulator experiments were not made. It is assumed the simulator experiment may not be representative of the field experiment's steering reversal data, but that the relative differences between the field experiment will follow the simulator experiment.

5.0 Results

5.1.1 Field Experiment Traffic Crash Data and Analysis

Work zone sites along roadways and highways were selected for inclusion in this study were under MDOT jurisdiction, available for observation, and identified by MDOT's Construction and Technology Division as candidate sites. The sites selected represented a variety of geographic, environmental, and traffic conditions in the State of Michigan. A **test site** was considered a **work zone where drums were being used without steady burn warning lights**. A **control site** was considered a location where **drums with steady burn warning lights** were being used.

In order to assess safety characteristics at sites utilizing drums with and without steady burn warning lights, traffic crash data was statistically analyzed to determine if there were any significant differences. The number of traffic crashes that occur in a given work zone are fairly low. This is due in general to the fact that traffic crashes are rare events, compounded by the temporary nature of work zones, and the short duration that they are in place. In order to perform the proper statistical tests, the crash frequencies for all the test sites were aggregated. Likewise, the crash data for some of the control sites which exhibit the most similarity with a particular test site were also aggregated.

In addition, crash rates were used which account for traffic volume differences between test and control sites. The traffic crashes were analyzed to determine the probable cause of the crash and also the time of day/night, in order to separate the daytime from the nighttime crashes. Significant changes between the various types of crashes at the test and control groups, were tested for significance using the Poisson Test at a 95 percent confidence level or alpha equal to 0.05.

Tables 5.1 and 5.2 summarize the number of nighttime (9:00 PM to 6:00 AM) crashes that occurred during the construction period as shown for each site location in 2004 and for the same monthly period one-year prior (2003) without the presence of construction. The total number of crashes remained the same during the construction and the same period in the year prior for both the control and test sites.

Table 5.1. Control Site (Drums with Steady Burn Warning Lights) Work Zone Crash Data Summary

STUDY LOCATION	NIGHTTIME CRASHES WITH CONSTRUCTION ZONE IN PLACE (2004)	NIGHTTIME CRASHES BEFORE CONSTRUCTION ZONE (2003)
I-75 at M-57 (April-November)	7	7
I-96 (April-December)	5	9
US-23 (April-November)	2	2
M-10 (April-November)	8	8
US-12 (Michigan Avenue) (April-November)	5	3
M-39 (Southfield Road) (April-November)	11	9
Total	**38**	**38**

Table 5.2. Test Site (Drums Without Steady Burn Warning Lights) Work Zone Crash Data Summary

STUDY LOCATION	NIGHTTIME CRASHES WITH CONSTRUCTION ZONE IN PLACE (2004)	NIGHTTIME CRASHES BEFORE CONSTRUCTION ZONE (2003)
I-94 (April-November)	3	4
I-75 at US-10 (May-September)	1	2
I-69 (April-November)	2	2
US-131; M-43 to M-89 (June-October)	0	0
US-131; US-10 to Luther (May-August)	0	2
US-10 (April-August)	1	0
Grand River Avenue (April-November)	14	9
Telegraph Road (April-November)	7	10
Bus. US-10 (Main St.) (April-November)	1	0
Total	**29**	**29**

In the ‘before and after with control’ study plan, data for the test and control sites are compared ‘before’ and ‘after’ the installation of the construction zone. In this study plan, the percent change in the crashes is compared at the test sites with the percent change in the crashes at the control sites for the same before and after periods. The use of control sites allow the influences of variables on the study results to be controlled.

The null and alternative hypotheses for the ‘Before and After With Control Study’ of the drums are as follows:

H_o (null hypothesis):	There is no difference between the crash frequency ‘before’ and ‘after’ the installation of the construction site at the ‘control’ and ‘test’ sites.
H_a (alternative hypothesis):	There is a difference between the crash frequency ‘before’ and ‘after’ the installation of the construction site at the ‘control’ and ‘test’ sites.

A comparison was made of the crash data for the control and test sites for all the sites combined, the interstate sites only, the other freeway sites and the arterial study sites using the Poisson Test. The procedure involves the calculation of the estimated after crashes of the ‘test’ sites by multiplying the before crashes for the ‘test’ sites by the quantity of the after crashes of the control sites divided by the before crashes of the control sites. This calculation yields the estimated after crashes per year for the ‘test’ sites. The percent change was then calculated by subtracting the actual crashes per year from the estimated crashes per year for the ‘test’ sites and then dividing by the estimated crashes per year.

Based upon the calculations summarized in Table 5.3, the null hypothesis was not rejected for the total site, interstate, freeway and arterial comparisons. In other words, crashes at all the sites, at the interstates, freeways and arterial test sites were not significantly different from the control sites at a 95 percent confidence interval or alpha equal to 0.05.

Table 5.3. Results of the Poisson Test for Crashes

CALCULATIONS	LOCATIONS			
	TOTAL SITES	INTERSTATES	FREEWAYS	ARTERIALS
Estimated Expected 'After' Crashes at Test Sites	29	8	0	17.25
Actual 'After' Crashes at Test Sites	29	8	2	19
Percent Change	0%	0%	Undefined*	10.01%
Significant Difference?	No, Not Significant	No, Not Significant	No, Not Significant	No, Not Significant

* Denominator is zero, thereby resulting in an undefined solution.

5.1.2 Simulator Experiment Traffic Crash Data and Analysis

The simulator was used to conduct a controlled laboratory experiment of driver performance through work zones that used drums with and without warning lights. A sample focus group of 89 motorists participated in the driving simulator experiment.

The driving environments simulated included a construction work zone along a tangent section of a two-lane divided highway with construction drums with and without Type 'C' warning lights. The driving environments were simulated for a nighttime driving condition. For the nighttime condition, the driving environment simulated the retroreflectivity of headlights hitting all traffic signs and the drums (regardless of the presence or absence of the warning lights). In the driving scenarios, when warning lights were included on the drums, they emitted a steady burn yellow light.

The purpose of using the driving simulator is to observe and quantify the focus group test subjects' reactions and performance in work zone driving with the presence or absence of the steady burn warning lights on the drums without informing them of the differences. The performance of the motorists was recorded on the control station as well as video for more comprehensive data tabulation and further analysis, including closer examination of driver

performance, after the conclusion of the test drive and without the subject in the simulator testing laboratory. The performance measures included speed characteristics, near misses/traffic crashes, lateral lane placement, number of steering reversals and location of lane change. Each subject encountered a work zone setting that used drums with and without lights. They were not informed of the specific reason the experiment was being conducted so their driving performance would be unbiased. Comparisons were made of the driving performance of the test subjects for both work zone settings.

Traffic crash data was extracted from the driving simulator video data. For each scenario, drums with lights and drums without lights, and the number of traffic crashes occurring was totaled for all test subjects. Additionally, the location of the crash was noted and summarized. A traffic crash occurred when the driver of the simulator veered from the travel lane and hit a drum. Upon hitting a barrel, the simulation experiment for that driver ended. In reality, upon hitting a drum, a driver could continue along the roadway or could respond with evasive maneuvers to correct the vehicle's lane position.

Significant differences between the various types of crashes, at the test and control groups, were investigated for significance using the Poisson Test at a 95 percent confidence level or alpha equal to 0.05.

Table 5.4 summarizes the number of crashes that occurred during the simulator experiment for the control and test sites. The total number of crashes was higher for the control site scenario than for the test site scenario.

The null and alternative hypotheses for the crashes for the control and test site scenarios is as follows:

H_o (null hypothesis):	There is no difference in the crash rate between the control and test site scenarios.
H_a (alternative hypothesis):	There is a difference in the crash rate between the control and test site scenarios.

Table 5.4. Simulator Crash Data

SITE TYPE	TOTAL NUMBER OF CRASHES	NUMBER OF CRASHES PER SUBJECT	MEAN LOCATION OF CRASHES	HIGHEST FREQUENCY OF CRASHES
Control Site (Work zones with steady burn warning lights)	7	0.117	3.00	3.9 and 2.2
Test Site (Work zones without steady burn warning lights)	2	0.027	2.9	3.7 and 2.1

Based upon the calculations, the null hypothesis was rejected for the control and test site scenario comparisons. It was found that the actual number of crashes observed for the test sites was lower than expected by slightly more than 71 percent than the control site scenario. Therefore, a significant difference was found between the control and test site scenario in terms of crashes. The control site scenario had significantly greater crashes than the test site scenario.

5.1.3 Field and Simulator Speed Data and Analysis

The analysis of the speed data was used as an indication of the motorist's perceived risk of traveling through the work zones using drums with and without steady burn warning lights. The speed data was collected and analyzed during the nighttime off-peak period when motorists are able to travel at their desired speed, unaffected by congestion experienced during the peak periods.

The speed data for each site was studied and has been tabulated at each location for the 85th percentile speed. The deviation of the 85th percentile speed from the posted speed limit has also been calculated for the arterial sites. The deviation of the 85th percentile speed is the difference between the posted speed limit and the calculated 85th percentile speed of the field data.

The calculated 85th percentile speed results for the field experiment are shown in Table 5.5.

Table 5.5. Summary of Speed Data from Field Sites

LOCATION (FIELD STUDY)	TEST SITE 85TH PERCENTILE SPEED (MPH)			CONTROL SITE 85TH PERCENTILE SPEED (MPH)		
	BEGINNING OF WORK ZONE	MIDDLE OF WORK ZONE	END OF WORK ZONE	BEGINNING OF WORK ZONE	MIDDLE OF WORK ZONE	END OF WORK ZONE
All Sites	53	51	53	64	46	63
Interstate Sites	64	66	66	74	63	71
Freeway Sites	63	57	61	66	55	67
Arterial Sites	47	40	43	50	35	53

Comparisons were also made at specific data points along the work zone configuration for the driving simulator: at the beginning of the work zone lane closure taper, half the distance into the work activity area and at the end of the lane closure. These points are representative of the data point locations for the field experiment work zone speed measurement.

The average 85th percentile speed of all vehicles surveyed at each point of the test and control sites was calculated. Then, a speed profile plot was developed for the two scenarios (drums with lights and drums without lights) using the tenth-mile measurements for plot points on the profiles.

The 85th percentile speeds of the subjects using the driving simulator were higher than the field experiments' 85th percentile speeds. The posted speed limit for the simulator experiment was 70 mph prior to the construction zone and 60 mph in the construction zone in a controlled laboratory experiment, as found also in the Tornros study *(21)*, when all the elements of the driving task such as conflicting traffic, congestion, visual obstructions, and adverse weather are removed, the driver is able to concentrate on only the driving task, thereby increasing their speeds.

The results of the average speeds from the simulator experiment followed similar trends as that obtained in the field experiments on Interstate freeways. The average 85th percentile speeds from the simulator experiment are as follows:

Test Scenario (drums without waning lights)

Beginning of work zone	=	70 mph
Middle of work zone	=	75 mph
End of work zone	=	77 mph

Control Scenario (drums with warning lights)

Beginning of work zone	=	77 mph
Middle of work zone	=	72 mph
End of work zone	=	75 mph

5.1.3.1. Field Speed Data Analysis

In order to test the effectiveness of the drums with and without steady burn warning lights on operating speed, the student's t-test was used to determine if the differences are significant. The student's t-test was used when comparing the mean or 85th percentile speed for a group of test sites with a group of control sites using the 'comparative parallel' evaluation plan. The data used in the statistical analysis is based on the individual observations measured from the data taken in the field. Several comparisons were made to evaluate if the differences in 85th percentile speed were significant between the control and the test sites. The comparisons made include the following: all test and all control sites, interstate test sites and interstate control sites, freeway test sites and freeway control sites, and arterial test sites and arterial control sites. When selecting locations for a comparative parallel study, roadways were selected as pairs based upon a similar roadway category, average daily traffic and posted speed limits. Individual site comparisons were also made including I-75 at M-57 and I-75 at US-10, I-96 and I-94, US-23 and US-131, M-43 to M-89, US-23 and US131, US-10 to Luther, US-12 and Grand River Avenue, and M-39 and Telegraph Road.

The null and alternative hypotheses for the speed studies at the control and test sites are as follows:

H_o (null hypothesis):	There is no difference between the 85th percentile speed at the control and test sites.
H_a (alternative hypothesis):	There is a difference between the 85th percentile speed at the control and test sites.

For the 85th percentile speeds of those segregated into categories of total sites, interstates, freeways, and arterials, the test sites had lower average 85th percentile speeds than similar roadway category control sites. As expected, the interstate category included the highest speeds, while the arterial category had the lowest speeds.

Based on the statistical analysis, the null hypotheses were not rejected for the total control and test site comparisons, the interstate control and test site comparisons, the freeway control and test site comparisons and the arterial control and test site comparisons. Therefore, there was no difference between the 85th percentile speeds of the control sites and test sites at a 95 percent confidence level or alpha equal to 0.05.

I-75 at US-10, an interstate test site had a higher 85th percentile speed than its interstate control site counterpart, I-75 at M-57. However, I-96, an interstate control site, had a higher 85th percentile speed than its test site counterpart, I-94. Based on the calculations, the null hypotheses were not rejected for the I-75 pair and the I-96/I-94 pair. In other words, the 85th percentile speeds were not statistically different at a 95 percent confidence level or alpha equal to 0.05.

US-23, a freeway control site experienced higher 85th percentile speeds than either of its freeway counterpart test sites along US-131. US-131 had nearly the same 85th percentile speeds between the Kalamazoo area, M-43 to M-89, and the Cadillac area, US-10 to Luther. The null hypothesis was not rejected for the US-23 control site and the US-131, US-10 to Luther in Cadillac. In other words, the 85th percentile speeds were not statistically different at a 95 percent confidence level or alpha equal to 0.05. The null hypothesis was rejected for the 85th percentile speeds for the comparison of US-131 in Kalamazoo, a test site, and US-23 near M-59, a control site. This

indicates a statistically significant difference between the 85th percentile speeds at a 95 percent confidence level or alpha equal to 0.05. The statistical test indicated that vehicles were traveling at slower speeds along the US-131 test site in Kalamazoo than at the US-23 control site.

Sites for arterial comparison could not be selected based upon similar posted speed limits. Therefore, the sites were paired based upon average daily traffic. As the posted speed limits varied, the 85th percentile deviation was chosen as the variable for statistical analysis.

Both of the test sites, Grand River Avenue and Telegraph Road experienced higher speeds than their arterial counterparts, US-12 and M-39. However, the null hypotheses were not rejected for both pairs of control and test sites. In other words, there was no statistical difference between the 85th percentile speeds for the arterial pairs of US-12 with Grand River Avenue and M-39 with Telegraph Road at a 95 percent confidence level or alpha equal to 0.05.

5.1.3.2. Simulator Speed Data Analysis

In order to test the effectiveness of the drums with and without steady burn warning lights for the simulator speed data, the student's t-test was used to determine if the differences are significant. The student's t-test was used to compare the mean speed for the test site scenario with the control site scenario using the 'comparative parallel' evaluation plan.

The null and alternative hypotheses for the speed studies at the control and test site scenarios are as follows:

H_o (null hypothesis):	There is no difference between the 85th percentile speed at the control and test site scenarios.
H_a (alternative hypothesis):	There is a difference between the 85th percentile speed at the control and test site scenarios.

Based on the calculations, the null hypotheses were not rejected for the simulator scenarios. Therefore, the 85th percentile speeds were not statistically different between the control site and the test site scenarios at a 95 percent confidence level or alpha equal to 0.05.

5.1.4 Field and Simulator Lateral Placement Data and Analysis

The lateral placement of vehicles through the work zone was quantified in order to assess the ability of drums with and without lights in guiding motorists through the work zone. Driver behavior and vehicle placement within the lanes was recorded using video cameras. Video data was analyzed in the laboratory in order to obtain quantifiable lateral placement data. When analyzing the video data, the lateral placement of vehicles was determined by locating the vehicle in the center of the lane, in the right third of the lane or in the left third of the lane. An acceptable lateral placement included the two furthest positions from the location of the drums.

The lateral placement data for the field experiments is summarized in Table 5.6.

Table 5.6. Lateral Placement Data Summary

LOCATION (FIELD STUDY)	TEST SITE PERCENTAGE IN ACCEPTABLE LANE POSITION	CONTROL SITE PERCENTAGE IN ACCEPTABLE LANE POSITION
All Sites	94%	92%
Interstate Sites	92%	94%
Freeway Sites	99%	91%
Arterial Sites	97%	95%

When analyzing the video data from the simulator experiment, the lateral placement of vehicles was to be determined by superimposing a calibrated grid system on the monitor during the recording with the driver absent. Similar to the field experiment, lateral placement was determined by locating the vehicle in the center of the lane, in the right third of the lane or in the left third of the lane. For the simulator experiment, the drums were placed along both lane lines indicating an acceptable lateral placement would be the center of the lane. Therefore, any deviation from the center of the lane to either the right third of the lane or the left third of the lane was considered unacceptable.

For each site, the percentage in acceptable position was calculated by dividing the mean time in acceptable position by the mean total time. The mean total time is the average total time spent following each vehicle. The mean time in an unacceptable lane position is simply the difference between the mean time in an acceptable lane position and the total time following. The time in an acceptable lane position was calculated by totaling the amount of time each observed a vehicle occupied in the acceptable lateral position in the traveled lane, while being followed. The mean time in an acceptable lane position was then determined by averaging the time in an acceptable lane position for all the observed vehicles. This same procedure was followed to determine the mean time in an unacceptable lane position and mean total time.

The percentages in the acceptable lane position for the driving simulator experiment were lower than the field experiment. This was due to the fact that acceptable lane positions for the field experiment included the furthest one-third or at the center of the travel lane, whereas the acceptable lane position for the simulator was only the center of the lane as the drums were placed on both sides of the travel lane.

The results of the lateral placement data obtained in the simulator experiments indicated higher percentages of acceptable lane positions in the test scenarios (70 percent), as compared to the control scenarios (58 percent). This result is similar to the field experiments considering all sites combined.

5.1.4.1. Field Lateral Placement Data Analysis

The null and alternative hypotheses for the lateral placement at the control and test sites is as follows:

H_o (null hypothesis):	There is no difference between the lateral placement of vehicles at the control and test sites.
H_a (alternative hypothesis):	There is a difference between the lateral placement of vehicles at the control and test sites.

Based on the statistical analysis, the null hypotheses were not rejected for the total control and test site comparisons, the interstate control and test site comparisons, the freeway control and test

site comparisons and the arterial control and test site comparisons. Therefore, there was no difference between the acceptable lane position percentages for the control sites and the test sites at a 95 percent confidence level or alpha equal to 0.05.

The motorists driving through the I-75 test site near US-10 remained in an acceptable lane position 100 percent of the time in which they were being followed, while the motorists in the I-75 control site near M-57 remained in an acceptable lane position 88 percent of the time followed. The vehicles driving through I-96 and I-94 were in acceptable lane positions nearly the same percentage.

Based on the statistical analyses, the null hypotheses were not rejected for both the I-75 pair and the I-94/I-96 pair at a 95 percent confidence level or alpha equal to 0.05. This means that there was no difference in the acceptable lane position percentages for the I-75 control-test site pair or the I-96 control site and I-94 test site pair.

Motorists traveling along US-131 in Kalamazoo and Cadillac were traveling in an acceptable lane position approximately 99 percent of the time followed. At the control site US-23, motorists maintained an acceptable lane position only 79 percent of the time followed. As a result, the statistical calculations, the null hypothesis was rejected at a 95 percent confidence level or alpha equal to 0.05. This indicates that there was a significant difference in the lateral placement. In other words, the motorists along the test sites of US-131 in Kalamazoo and Cadillac remained in an acceptable lane position more often than those along the control site of US-23.

Motorists driving along US-12 and Grand River Avenue maintained an acceptable lane position 97 percent of the time followed. M-39, a control site, differed from its arterial counterpart, Telegraph Road, by three percent less time in an acceptable lane position. The motorists traveling along Telegraph Road maintained an acceptable lane position 94 percent of the time followed. Based on the statistical analysis, the null hypothesis was not rejected for both arterial pairs. In other words, there was no significant difference in lateral placement between the arterial control and test sites at a 95 percent confidence interval or alpha equal to 0.05.

5.1.4.2. Simulator Lateral Placement Data Analysis

The null and alternative hypotheses for the lateral placement at the control and test scenarios is as follows:

H_o (null hypothesis):	There is no difference between the lateral placement of vehicles at the control and test site scenarios in the driving simulator.
H_a (alternative hypothesis):	There is a difference between the lateral placement of vehicles at the control and test site scenarios in the driving simulator.

Based on the statistical analysis, the null hypothesis was not rejected for the simulator control and test site scenario lateral placement. Therefore, the lane positioning was not statistically different between the control site and the test site scenarios at a 95 percent confidence level or alpha equal to 0.05.

Thus, the field and driving simulator experiments produced similar results.

5.1.5 Field and Simulator Steering Reversal Data and Analysis

The steering reversal of vehicles through the work zone was quantified in order to assess the ability of drums with and without lights in guiding motorists through the work zone. Driver performance and vehicle placement within the lanes was recorded using video cameras. Video data was analyzed in the laboratory in order to obtain quantifiable steering reversal data. When analyzing the video data, the lateral placement of vehicles in time was determined by locating the vehicle in the center of the lane, in the right third of the lane or in the left third of the lane. For each site, the mean number of steering reversals per vehicle, was calculated as simply the average number of steering reversals observed per vehicle, per site. The mean number of steering reversals per minute was calculated by dividing the number of steering reversals per vehicle by the total time following and then averaging the number of steering reversals per minute per vehicle for each site.

The steering reversal data for the field experiments are summarized in Table 5.7.

Table 5.7. Steering Reversal Data Summary

LOCATION (FIELD STUDY)	TEST SITE MEAN NUMBER OF STEERING REVERSALS PER VEHICLE PER MINUTE	CONTROL SITE MEAN NUMBER OF STEERING REVERSALS PER VEHICLE PER MINUTE
All Sites	1.84	2.54
Interstate Sites	2.34	3.08
Freeway Sites	1.35	2.72
Arterial Sites	1.47	1.64

For the driver simulator, the mean number of steering reversals per vehicle was calculated as simply the average number of steering reversals observed per subject per site. The mean number of steering reversals per minute was calculated by dividing the number of steering reversals per subject, by the total time and then averaging the number of steering reversals per minute, per subject for each site. Although the absolute values of the number of steering reversals differ from the field results, similar trends were observed. That is, in the simulator experiment, the average frequency of steering reversals was higher for the control scenarios (6.69) as compared to the test scenarios (6.42).

5.1.5.1. Field Steering Reversal Data Analysis

The null and alternative hypotheses for the steering reversals at the control and test sites is as follows:

H_o (null hypothesis): There is no difference between the number of steering reversals per vehicle at the control and test sites.

H_a (alternative hypothesis): There is a difference between the number of steering reversals per vehicle at the control and test sites.

The number of steering reversals per vehicle observed was lower for the test sites than the control sites as shown in Table 5.8. This was true for the total site, interstate, freeway and arterial comparisons.

Based on the statistics, the null hypothesis was not rejected for all scenarios. There was no significant difference in the number of steering reversals per vehicle, per minute between the control and test sites at a 95 percent confidence level or alpha equal to 0.05.

The number of steering reversals per vehicle observed was lower for both I-75 at US-10 and I-94 than at the control sites of I-75 at M-57 and I-96. This would indicate the potential for a crash was lower for both test sites. Based on the statistical analysis, the null hypothesis was not rejected for either scenario. There was no significant difference in the number of steering reversals per vehicle between the control and test sites for the I-75 pair or the I-96 and I-94 pair at a 95 percent confidence interval or alpha equal to 0.05.

The number of steering reversals per vehicle observed was substantially lower at both of the US-131 sites than at the control site of US-23 as shown in Table 5.37. Based on the statistical calculations, the null hypothesis was not rejected for either scenario. In other words, there was no significant difference in the number of steering reversals per vehicle between the control site of US-23 and test sites of US-131 at a 95 percent confidence interval or alpha equal to 0.05.

The number of steering reversals per vehicle, per minute observed was lower at the Grand River Avenue site than its control site counterpart of US-12, while Telegraph Road, the test site experienced higher steering reversals than its arterial counterpart control site, M-39. However, based on the calculations, the null hypothesis was not rejected for either scenario. There was no significant difference in the number of steering reversals per vehicle, between the control and test sites at a 95 percent confidence interval or alpha equal to 0.05.

5.1.5.2. Simulator Steering Reversal Data Analysis

The null and alternative hypotheses for the number of steering reversals at the control and test site scenarios is as follows:

H_o (null hypothesis):	There is no difference between the lateral placement of vehicles at the control and test site scenarios in the driving simulator.
H_a (alternative hypothesis):	There is a difference between the lateral placement of vehicles at the control and test site scenarios in the driving simulator.

Based on the statistical analysis, the null hypothesis was not rejected for the simulator control and test site scenario steering reversals. Therefore, the driver performance of steering reversals was not statistically different between the control site and the test site scenarios at a 95 percent confidence level or alpha equal to 0.05.

5.1.6 Physical Investigation of Drums Data

Another surrogate measure used in this study was the inspection of the work zones at the test and control sites in order to identify vehicle contact with traffic control devices. Specifically, drums being knocked-down, dirty, and/or misaligned was investigated. For drums with warning lights, the functionality of the light was also noted.

A survey of the work zone study sites included identifying the approximate location and the physical condition of the drums. For the control sites, details regarding the type of warning light used and power source was identified, as well as the operational and physical characteristics of the steady burn warning lights (burned out, and orientation being turned and not properly visible, etc.). In addition, a digital video was taken of the drums and the surrounding traffic control devices for documentation and verification purposes. Table 5.8 summarizes the physical evidence data found for each study site.

Table 5.8. Work Zone Physical Evidence Data Summary

(As observed in a given instance in time)

LOCATION	NUMBER OF TOTAL DRUMS	NUMBER OF KNOCKDOWN DRUMS	NUMBER OF STEADY BURN WARNING LIGHTS NOT FUNCTIONING	NUMBER OF DIRTY DRUMS	PERCENTAGE OF DRUMS IN ACCEPTABLE ALIGNMENT
I-96, Control Site	450	1	20	29	88.89%
US-23, Control Site	449	36	118	115	59.91%
M-10, Control Site	388	0	6	13	95.10%
US-12 (Michigan Avenue), Control Site	393	6	16	52	81.17%
M-39 (Southfield Road), Control Site	156	1	2	34	76.28%
I-94, Test Site	710	1	Not Relevant (NR)	312	44.08%
I-75 at US-10, Test Site	72	0	NR	2	97.22%
I-69, Test Site	358	0	NR	4	98.89%
US-131; M-43 to M-89, Test Site	1158	1	NR	7	99.31%
US-131; US-10 to Luther, Test Site	800	0	NR	10	98.75%
US-10, Test Site	560	7	NR	2	98.39%
Grand River Avenue, Test Site	192	1	NR	5	96.88%
Telegraph Road, Test Site	188	0	NR	24	87.23%
Bus. US-10 (Main St.), Test Site	241	3	NR	0	98.80%

6.0 CONCLUSIONS

The basic objective of this study was to determine the effectiveness of drums with and without steady burn warning lights in work zones with regard to delineation and safety. A field experiment as well as driving simulator experiment was conducted to assist in the determination of effectiveness. Traffic operational and safety data was collected for each site and each simulator scenario including traffic crash data, speed through the work zone, lateral placement of vehicles and the number of steering reversals. The statistical significance of the effectiveness of the drums with and without steady burn warning lights was tested in order to better understand whether the changes observed in the measures of effectiveness of crash data, speed, lateral placement, and steering reversals are attributable to the steady burn warning lights on the drums. Several hypotheses were presented and tested for significance. A summary of the associated field experiment findings are as follows:

- An analysis of all the field study sites indicated that there was no difference between the crash rate 'before' and 'after' the installation of the construction zone traffic control, both the 'control' (work zones with steady burn warning lights) and the 'test' (work zones without steady burn warning lights) sites for all the sites combined, and interstate, freeway and arterial sites were considered separately.
- The statistical analysis of the speed data showed no difference between 85th percentile speeds at the control and test sites for most of the study locations. However, for the comparison of the control site, US-23, with the test site US-131 in Kalamazoo, a significant difference was found in the 85th percentile speeds. The test site utilizing drums without steady burn warning lights had lower 85th percentile speeds than the control site utilizing drums with steady burn warning lights.
- For the analysis of the lateral placement data for the field experiment, no significant difference between the lateral placement of vehicles while driving through the control and test scenarios was found for most of the paired comparisons. However, for most of the grouped comparisons, a significant difference was found in the lateral placement analysis. In the cases where a significant difference was found, the test sites that utilized drums without steady burn warning lights had a higher percentage

of vehicles maintaining an acceptable lane position, that is, a safer driver behavior was observed.

- The statistical analysis of the steering reversal data for the field studies showed no difference between the control and test sites for most of the paired comparisons. However, for most of the grouped comparisons, a significant difference was found in the steering reversal rates. In the cases where a significant difference was found, the test sites that utilized drums without steady burn warning lights had a lower number of steering reversals per vehicle per minute, which can be considered a safer driver performance.

A summary of the associated findings of the driving simulator study is as follows:

- For the simulator experiment, a significant difference was found between the control and test site scenarios in terms of crashes. The actual number of crashes observed for the test (drums without warning lights) sites was lower than expected by slightly more than 71 percent than the control (drums with warning lights) site scenario. The control site scenario had significantly greater crashes than the test site scenario.
- The speed data for the simulator experiment showed no difference between the 85th percentile speed at the control and test site scenarios.
- For the analysis of the lateral placement data for the simulator experiment, no significant difference between the lateral placement of vehicles while driving through the control and test scenarios was found.
- The statistical analysis of the steering reversal data for the simulator experiment showed no difference between the control and test sites.

Some significant differences were found between the sites utilizing drums with and without steady burn warning lights for some of the various comparisons analyzed as a part of this study. The sites utilizing drums without steady burn warning lights had better indications such as lateral placement, speed, steering reversals and crashes, as compared to sites utilizing drums with steady burn warning lights.

Based upon the field and simulator experiment's statistical analysis presented in this report, overall there was no significant difference in delineation and safety between drums with steady burn warning lights and drums without steady burn warning lights. These findings are consistent with the study by Pant and Park *(12)* which found that steady burn warning lights had little impact on a driver's speed, lateral placement, or weaving along tangential sections of rural four-lane divided roadways. Pant performed a second study *(13)* which determined that steady burn warning lights had little impact on a driver's speed, lateral placement, weaving and traffic conflict along divided and undivided highways at horizontal and vertical curves, with and without ambient lighting, ramps, tapers and crossovers. Although the study performed by the WSU-TRG did not specifically address horizontal or vertical curves due to the lack of field conditions to collect an adequate sample size, the findings of such a study may parallel the Pant study *(13)* as this study performed by the WSU-TRG paralleled the Pant and Park study *(12)*.

Although the simulator experiment produced different values for the 85th percentile speed, average lateral placement and average number of steering reversals, it was assumed that the drivers would behave similarly in a simulator as in a real-world scenario. This was supported in a study performed by Godley et al. *(22)* which found when comparing a total of forty-four drivers in a real-world scenario to a simulator scenario, the motorists act similarly in a simulator as compared to an instrumented car. It can then be stated that the results from the WSU-TRG simulator experiment, where 89 drivers were utilized, supplement the field experiment portion of this study.

The results of this study indicated there is no significant difference in delineation and safety between drums with steady burn lights and without steady burn lights.

Therefore, these study results should be considered in making any policy decisions relative to future delineation strategies for work zone traffic control.

REFERENCES

1. Work Zone Safety Fact Sheet, National Work Zone Awareness Week 2004, Federal Highway Administration.
2. 1997-2003 Michigan Work Zone Crash Comparison, Michigan State Police.
3. *Manual on Uniform Traffic Control Devices, 2003 Edition*. U.S. Department of Transportation, Federal Highway Administration, Washington D.C., 2003.
4. *Michigan Manual of Uniform Traffic Control Devices, Part 6 Construction and Maintenance.* Michigan Department of Transportation, 2001.
5. (2002). "RSF Wins Retroreflectivity Contract." *The Roadway Safety Reporter* (2nd Quarter).
6. Khattak, A. J., Aemal J. Khattak, and Forest M. Council. (2000). "Effects of Work Zone Presence on Injury and Non-injury Crashes." *Accident Analysis and Prevention 34*, 34, 19-29.
7. Graham, J. L., R.J. Paulsen, and J.C. Glennon. (1978). "Accident Analysis of Highway Construction Zones." Transportation Research Board, National Research Council, Washington D.C.
8. Garber, N. J., and Ming Zhao. (2002). "Crash Characteristics at Work Zones." Virginia Transportation Research Council, Charlottesville, Virginia.
9. Bryden, J. E. "Crash Tests of Work Zone Traffic Control Devices." *Transportation Research Record 1254*, 26-35.
10. King, G. F. and M. Lunenfeld. (1971). "Development of Information Requirements and Transmission Techniques for Highway Users." Washington D.C.
11. (1992). "Steady-Burn Warning Lights Executive Summary." KLD Associates, Inc., Huntington Station, New York.

12. Pant, P. D., and Yongjin Park. "Effectiveness of Steady Burn Lights for Traffic Control in Tangent Sections of Highway Work Zones." Transportation Research Board, National Research Council, Washington D.C.

13. Pant, P. D., Xiao H. Huang, and Sundaresan A. Krishnamurthy. (1991). "Steady Burn Lights in Highway Work Zones: Further Results of Study in Ohio." University of Cincinnati, Department of Civil and Environmental Engineering, Cincinnati, Ohio.

14. Shepard, F. D. "Improving Work Zone Delineation on Limited Access Highways." *Transportation Research Record 1254*, 36-43.

15. Lafferty, A. and J. Pennington. (1995). "Type "C" Steady Burn Warning Lights on Temporary Concrete Barrier Wall in Active Work Zones." Florida Department of Transportation, Office of Construction/Product Evaluation.

16. Pain, R. F., H.W. McGee, and B.G. Knapp. (1981). "Evaluation of Traffic Controls For Work Zones." Transportation Research Board, Washington D.C.

17. Chiu, S. A., R.R Mourant, A. Belambe, and B.K. Jaeger. (1997). "A Study of Nighttime Highway Lane Shifts." Northeastern University, Boston, Massachusetts.

18. “The American Traffic Safety Services Association Policy on Use of Flashing and Steady Burn Lights."

19. The American Traffic Safety Services Association of Michigan. (1995). "Reasons to Use Flashing and Steady Burn Lights in Michigan Road Construction Projects."

20. Blaauw, G. J. (1982). "Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study." *Human Factors 24*, 473-486.

21. Tornros, J. (1998). "Driving Behaviour in a Real and a Simulated Road Tunnel - A Validation Study." *Accident Analysis and Prevention 30*, 497-503.

22. Godley, S. T., Triggs, Thomas J., Fildes, Brian N. (April 2001). "Driving Simulator Validation for Speed Research." *Accident Analysis and Prevention 34*, 34, 589-600.

23. Klee, H., C. Bauer, E. Radwan and H. Al-Deek. (1999). "Preliminary Validation of Driving Simulator Based on Forward Speed." *Transportation Research Record 1689*, 33-39.

24. Burns, P.E. and D. Saluaar. "Intersections Between Driving in Reality and Virtual Reality." Volvo Technological Development Corporation, Goteborg, Sweden.

25. Ha, Tae-Jun and Zoltan A. Nemeth (1995). "Detailed Study of Accident Experience in Construction and Maintenance Zones." *Transportation Research Record 1509*, 38-45.

26. Garrett, Robert M. (1992). "ATSSA: Ohio Wrong in Steady-Burn Light Ban." *Roads and Bridges.* 30-32.

27. "Work Zone Safety", Oregon.

28. U.S. Census Bureau – State of Michigan

APPENDIX I – SURVEY INSTRUMENT