Safety Evaluation of Diamond-grade vs. High-intensity Retroreflective Sheeting on Work Zone Drums: A Field Study and Driving Simulator Validation Study

A thesis presented to

the faculty of

the Russ College of Engineering and Technology of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Stephen G. Busam

March 2011

© 2011 Stephen G. Busam. All Rights Reserved.
This thesis titled
Safety Evaluation of Diamond-grade vs. High-intensity Retroreflective Sheeting on Work Zone Drums: A Field Study and Driving Simulator Validation Study

by

STEPHEN G. BUSAM

has been approved for
the Department of Civil Engineering
and the Russ College of Engineering and Technology by

Deborah S. McAvoy
Assistant Professor of Civil Engineering

Dennis Irwin
Dean, Russ College of Engineering and Technology
ABSTRACT

BUSAM, STEPHEN G., M.S., March 2011, Civil Engineering

Safety Evaluation of Diamond-grade vs. High-intensity Retroreflective Sheeting on Work Zone Drums: A Field Study and Driving Simulator Validation (172 pp.)

Director of Thesis: Deborah S. McAvoy

New developments and technologies have paved the way for the creation of diamond-grade sheeting, ASTM Type IX, a new, more retroreflective sheeting which is 6 to 14 times brighter than engineering-grade sheeting, ASTM Type I, and is widely required for use on work zone signs. However, the ASTM Type IX sheeting is not widely required for use on channelizing drums due to the increased cost and concern that the increased retroreflectivity of the sheeting may actually decrease the safety of the work zone when used on closely spaced construction drums.

A comparative parallel study was conducted to compare the safety impacts of the diamond-grade sheeting, ASTM Type IX, with high-intensity sheeting, ASTM Type III, the current MUTCD standard. Driver behavior within the work zone was analyzed in terms of lane placement and traveled speed with respect to the posted speed limit. These data were collected and analyzed to determine the extent to which the behaviors differed between the two traffic control treatments. The results indicate that drivers traveling through work zones with ASTM Type IX sheeting position their vehicle further away from the work zone and abide closer to the posted speed limits when compared to those traveling through work zones with ASTM Type III sheeting on the construction drums.

---

1 This abstract contains adapted writing directly from a report written by the thesis author, Stephen Busam, “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
The second portion of this thesis research involved a simulator study to determine if the simulated environment could adequately reproduce sheeting on construction drums. To determine this, the lane placement and difference in travelled speed from the posted speed limit were compared between sheeting types to determine if the effects in the simulated environment mimicked the responses in the field study. The results of the simulator study indicate that the simulator can reproduce the retroreflectivity of the sheeting, but does not adequately reproduce the fluorescence.

The final portion of this research was a validation study of the O.R.I.T.E. Safety and Human Factors Facility’s driving simulator for speed and lateral lane placement research. This study was performed by comparing the results of the field study with data collected from subjects driving through a similar, simulated work zones with drums utilizing simulated ASTM Type IX and ASTM Type III sheeting. Validation was checked on three levels, absolute validation, relative validation and interactive-relative validation. The results of the lane placement validation indicate the simulator failed to validate at any of the three levels. The speed study indicated that absolute validity was achieved for daytime ASTM Type III work zones as vehicles entered and progressed through the middle of the work zone. Interactive-relative validity was achieved for every time of day and sheeting combination in this study.

Approved: _____________________________________________________________

Deborah S. McAvoy
Assistant Professor of Civil Engineering
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor, Dr. Deborah McAvoy, for her support and encouragement through my Masters of Science program. Without her help and guidance I would not have succeeded in my graduate studies. I would also like to thank my committee members Dr. Lloyd Herman, Dr. Munir Nazzal, and Dr. Wei Lin for their time and help with the completion of my thesis research.

Finally I would like to thank my family and friends and for their love and support through all of my endeavors.
# TABLE OF CONTENTS

Abstract ....................................................................................................................3  
Acknowledgments ....................................................................................................5  
List of Tables ...........................................................................................................9  
List of Figures ........................................................................................................11  
Chapter 1: Introduction ..........................................................................................12  
Chapter 2: Background ..........................................................................................15    
  2.1 Retroreflectivity ..............................................................................................15  
  2.2 Types of Retroreflective Sheeting .................................................................16  
  2.3 Previous Research on the Effects of Different Sheeting Types .....................18  
  2.4 Need for Work Zone Visibility ......................................................................21  
  2.5 Past Research on Driving Simulator Validation ..........................................24    
    2.5.1 Speed Data Validation ..............................................................................25  
    2.5.2 Simulator Lane Placement Validation .....................................................30  
  2.6 Current State-of-the-Practices .......................................................................32    
    2.6.1 Current State-of-the-Practices Results ....................................................34  
Chapter 3: Field Study Site Descriptions ...............................................................37  
  3.1 ASTM Type III Data Collection Sites .........................................................37  
  3.2 ASTM Type IX Sheeting Data Collection Site .............................................42  
  3.3 Field Study Site Summary .............................................................................44  
Chapter 4: Field Study Data Collection .................................................................46  
  4.1 Lane Placement ..............................................................................................46    
    4.1.1 Lane Placement Data Extraction ..............................................................47  
  4.2 Speed ..............................................................................................................49  
  4.3 Sample Size Determination ..........................................................................49  
Chapter 5: Simulator Study ....................................................................................55  
  5.1 Internal Review Board ...................................................................................55  
  5.2 Simulator Scenario Setup ..............................................................................56  
  5.3 Simulator Study Methodology .......................................................................60
9.3 Validation Study ........................................................................................................138
9.4 Recommendations for Future Research ....................................................................141
References ..............................................................................................................143
Appendix A: IRB Documents .....................................................................................148
Appendix B: Simulator Survey ....................................................................................169
Appendix C: State-of-the-Practices Survey ...............................................................170
Appendix D: Road Miles per State ............................................................................172
LIST OF TABLES

Table 1: Retroreflective sheeting type................................................................. 34
Table 2: Reasoning of those requiring ASTM Type IX sheeting.................... 35
Table 3: Summary of field study site characteristics......................................... 45
Table 4: Chi-squared analysis of Illinois and Ohio fatality rates...................... 99
Table 5: Lane placement statistical analysis summary...................................... 101
Table 6: Chi-squared analysis of lateral lane placement standard deviation........ 102
Table 7: Overall Speed Deviation ASTM Type III and ASTM Type IX............ 105
Table 8: Chi-squared analysis of difference in speed standard deviations......... 106
Table 9: Results of the ANOVA analysis of speed deviation from posted speed limits .............................................................................................................. 107
Table 10: Games-Howell post hoc analysis of speed deviation......................... 108
Table 11: Chi-Squared goodness-of-fit analysis............................................... 110
Table 12: Summary of Wilcoxon signed ranks test........................................... 112
Table 13: Summary of Paired-samples t-test...................................................... 115
Table 14: Kruskal-Wallis absolute validity analysis summary for lane position..... 116
Table 15: Lane placement absolute validity Mann-Whitney U analysis............. 117
Table 16: Results of the absolute validity ANOVA analysis of speed deviation from posted speed limits, All Groups, Overall Average......................................................... 119
Table 17: Games-Howell post hoc analysis of speed deviation, All Group, Overall Average............................................................................................................. 119
Table 18: Results of the absolute validity ANOVA analysis of speed deviation from posted speed limits, Daytime, by Location............................................... 120
Table 19: Games-Howell post hoc analysis of speed deviation, Daytime, by Location
........................................................................................................................... 121

Table 20: Results of the absolute validity ANOVA analysis of speed deviation from
posted speed limits, Nighttime, by Location............................................................ 121

Table 21: Games-Howell post hoc analysis of speed deviation, Nighttime, by Location
............................................................................................................................. 122

Table 22: Lane placement relative validity Mann-Whitney U analysis............... 123

Table 23: Relative Validity, Daytime driving conditions......................................... 126

Table 24: Relative Validity, Nighttime................................................................. 127

Table 25: Lane placement interactive relative validity Mann-Whitney U analysis.... 129

Table 26: ANOVA trend analysis for interactive relative speed analysis, Daytime... 130

Table 27: ANOVA trend analysis for interactive relative speed analysis, Nighttime.. 130
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Typical ASTM Type III Work Zone</td>
<td>38</td>
</tr>
<tr>
<td>Figure 2</td>
<td>ASTM Type III data collection site 1</td>
<td>39</td>
</tr>
<tr>
<td>Figure 3</td>
<td>ASTM Type III data collection site 2</td>
<td>40</td>
</tr>
<tr>
<td>Figure 4</td>
<td>ASTM Type III data collection site 3</td>
<td>41</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Typical ASTM Type IX Work Zone</td>
<td>42</td>
</tr>
<tr>
<td>Figure 6</td>
<td>ASTM Type IX data collection site 1</td>
<td>43</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Simulated ASTM Type IX and ASTM Type III barrels</td>
<td>57</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Simulator work zone design diagram</td>
<td>60</td>
</tr>
<tr>
<td>Figure 9</td>
<td>O.R.I.T.E. Safety and Human Factors Facility driving simulator</td>
<td>62</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Frequency by age group</td>
<td>109</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

Each year more than 700 fatalities occur nationally due to vehicular crashes within work zones [2]. In order to guide motorists through work zones in a safe, efficient and smooth manner, various traffic control devices are used including temporary warning signs, pavement markings, channelizing devices such as drums, cones, markers, and barricades. 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 retro-reflective stripes which make them highly visible, even during the nighttime. There are three types of retro-reflective strips or sheeting that can be utilized on the drums, engineering-grade, ASTM Type I, ASTM Type III, ASTM Type III, and ASTM Type IX, ASTM Type IX.

ASTM Type I sheeting is composed of very small glass beads that are enclosed in a translucent substrate with a product life of approximately seven years. ASTM Type III sheeting is composed of at least two layers, an outer translucent layer and an inner reflective layer that includes glass beads. The product life is generally ten years and costs approximately twice the cost for engineering-grade sheeting. Approximately 32 state’s recommend the use of ASTM Type III sheeting on drums in work zones. ASTM Type IX sheeting is made from a micro-prismatic material with a diamond-shaped lattice separating the layers with either a course or fine grain and ranges from six to 14 times brighter than ASTM Type I sheeting and has a ten year product life. Along with the improved retroreflectivity provided by the diamond lattice, ASTM Type IX sheeting is

---

1 This chapter contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
also fluorescent to improve its daytime visibility. The cost for ASTM Type IX sheeting is nearly five times the cost for engineering-grade sheeting.

Concerns have been voiced by transportation engineers as well as local agencies that the retro-reflectivity of the ASTM Type IX sheeting may reflect too much light from the vehicle’s headlights back to the driver, particularly for a string of devices several miles in length spaced at approximately twice the speed limit. Such reflections may cause glare and limit the ability of the driver to continue safely along their travel path. It has been shown in past research that higher retro-reflectivity improves driver visibility of signs in various weather conditions [3]. However, a study has not been conducted comparing the potential safety benefits in terms of driver behavior of ASTM Type IX sheeting on drums with ASTM Type III sheeting on drums.

A comparative parallel study was performed to compare driver behavior in regards to lateral placement within the lane and deviation between travel speed and the posted work zone speed limit between work zones with drums utilizing ASTM Type III sheeting and those utilizing drums with ASTM Type IX sheeting. A current state-of-the-practice survey was distributed to each state department of transportation in order to determine the extent to which ASTM Type IX sheeting is currently being required and utilized. The departments were also asked to respond as to their rationale regarding the requirements or lack thereof for ASTM Type IX sheeting. The survey responses were collected and evaluated.

The first phase of this study included a field study portion of this research was conducted during clear daytime and nighttime weather conditions due to the rarity of rain.
events and the increased safety risk of data collection during adverse weather conditions. During the second phase of this project, the Ohio Research Institute for Transportation and the Environment’s state of the art driving simulator was used to simulate the traffic conditions experienced in the field study. The simulator experiment utilized daytime and nighttime clear weather conditions to mimic the field study conditions. Lastly, a validation study was performed to determine the feasibility and realism of the visual representation of various sheeting materials in the simulator. The simulator validation study was performed by comparing the parameters of vehicle speed and lateral lane placement as collected during the field and simulator studies.
CHAPTER 2: BACKGROUND

2.1 Retroreflectivity

Retroreflectivity refers to the ability of a specially engineered surface to reflect incoming light back in the direction from which it came [4]. It results from the conscious design and precise manufacturing of prismatic structures which comprise modern retroreflective sheeting [5]. This characteristic is essential for nighttime visibility of traffic signs and other traffic control devices and therefore is essential for safe nighttime motor vehicle operation [4]. It is imperative for safe driving conditions that drivers are able to see and read traffic signs or traffic control devices at a sufficient distance to be able to comprehend the meaning of the sign and have sufficient time to make appropriate decisions and adjustments. When geometric sight distance obstructions are not considered, the retroreflectivity, or the amount of light reflected back to the source of the incident light, of the sheeting used on the traffic control device or sign directly relates to a drivers ability to see and comprehend the device or sign, especially during nighttime driving conditions.

Retroreflection is achieved through the combination of specular reflection, the principles behind light reflected from a mirror, refraction, or the change in path of a light source as it passes through a medium, and total internal reflection which occurs when light contacts a transparent material but still reflects rather than passing through. In combination, these three principles cause the initial incoming beam of light to be bounced

---

1 This chapter, sections 2.1-2.4 and 2.6, contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
around within the engineered retroreflective structure, and be transmitted back towards its source along a path parallel to its initial incident path [6].

2.2 Types of Retroreflective Sheeting

The first generation of retroreflective sheeting was introduced by the 3M™ Corporation in the 1920’s. However, the first wide use application of retroreflective sheeting was initiated in 1947 [6]. This sheeting, termed “Engineering-grade” sheeting, later classified as ASTM Type I sheeting, utilized spherical glass beads encased in a transparent polymer. This encasing of the glass beads sealed the glass beads from the elements which would render their visibility lower than that of other materials used for signs at the time. The sealing of the glass beads in a transparent polymer made the ASTM Type I sheeting the brightest available at the time. This sheeting was the dominant traffic sign sheeting around the world for 25 years [6]. Though it set the standard as the most retroreflective material of its time, the use of fully encapsulated spherical beads only transmitted approximately eight percent of the incident light back to the source [6]. Advances in technology which transmit a larger percentage of the incident light back to the source have rendered this sheeting obsolete for use of work zone traffic control devices. ASTM Type I sheeting had a service life of approximately seven years [7]. ASTM Type I sheeting is currently produced by the 3M™ Corporation, Nippon Carbide, American Decal, and Avery-Dennison.

A second generation of retroreflective sheeting technology was initially introduced by the 3M™ Corporation in 1971. This sheeting was termed “High-intensity” sheeting and specified as ASTM Type III sheeting. It continued to use face film in
contact with the glass beads, an air void was induced between the incident surface of the
glass beads and the protective transparent film [6]. Improvements in the reflective
backing material, combined with the introduction of the air void, provided for a new
retroreflective sheeting material which transmits approximately 16 percent of the incident
light back to its source [6]. ASTM Type III sheeting cost approximately twice as much as
the ASTM Type I sheeting and had a ten year service life [7]. The increase in safety from
the increased brightness outweighed the increase in cost of the material and quickly
propelled the sheeting into the forefront for use on highway signs [6]. ASTM Type III
sheeting is currently produced by the 3M™ Corporation, Nippon Carbide, Kiwalite,
ASTM, LG Chem, and Avery-Dennison.

Unfortunately, the use of glass beads had retroreflectivity limitations. The
spherical glass bead has only approximately 28 percent of its area which provides proper
angle for retroreflection. The spherical design of the glass beads also inherently provided
“dead spots” due to its shape and the lack of dense packing abilities of spheres. In order
to significantly increase the amount of light transmitted back to the source a new
technology, prismatic sheeting, was developed. As early as 1963, the Rowland Products
Corporation, now Reflexite, was developing a prismatic retroreflective sheeting [6]. In
1970, Rowland Products Inc. patented a “microprismatic” sheeting which lead to the next
generation of retroreflective sheeting, “Diamond-grade” sheeting, specified as ASTM
Type IX sheeting. This prismatic sheeting incorporates the use of “high accuracy and
high definition cube corners,” which resembled a pyramid shape rather than the round
glass beads. Due to the change in shape of the retroreflective structure from round to a
square base the structure could be much closer packed in the lattice allowing the new
generation of retroreflective sheeting to be nearly six times brighter than the ASTM Type
I sheeting [7]. To enhance its daytime visibility, the ASTM Type IX sheeting has also
incorporated the use of fluorescent sheeting colors. This sheeting cost approximately five
times as much as ASTM Type I sheeting and has a service life of approximately ten
years. ASTM Type IX sheeting is currently being produced by the 3M™ Corporation and
Avery-Dennison.

The newest generation of retroreflective sheeting technology created by the 3M™
Corporation is based on 100 percent efficient optics [6, 8]. Previously the greatest
efficiency achieved in sheeting material was 65 percent; however, and many signs and
devices were utilizing sheeting with only 28 percent efficient optics [8]. The efficiency of
the full cube prismatic reflective sheeting, 3M’s DG3 sheeting, returns almost 60 percent
of the incident light back toward its source. When compared to the spherical glass lens
bead optics, the 3M™ DG3 sheeting provides for the reflection of nearly twice as much
of the incident light [4, 6, 8, 9]. The 3M™ DG3 sheeting is proposed to be an ASTM
Type XI sheeting [10]. This new DG3 sheeting is not currently being used on traffic
control devices and therefore was not considered in this research.

2.3 Previous Research on the Effects of Different Sheeting Types

A study performed by Gatscha et al. studied the eye movement characteristics of
drivers for Type-III sheeting (high-intensity) and Type-XI sheeting (DG3) on signs during
nighttime driving conditions [11]. This study was performed with two groups of
participants, a group of young drivers (20-25 yrs old) and a group of older drivers (50-55
The study was performed using the IView-System of SensoMotoric Instruments. This system utilized a gaze tracking system with two cameras mounted on a bicycle helmet and connected to a computer in the test vehicle [11]. One camera, an infrared camera, recorded one of the participant’s pupils while the second camera captured the scene viewed by the subjects. The test included two tasks, an action task and a navigation task [11]. The action task consisted of signs which told the participant to look at various objects within the test car. A task was considered fulfilled only when the participant focused on the target corresponding to the signs instructions. The navigation task required the participant to navigate the test route using only traffic signs and vague instruction from a co-driver. The signs were all of equal size within each task and used all capital letters [11].

Two types of sheeting were used on the signs in this research: Encapsulated glass bead retroreflective sheeting classified as ASTM Type-III and full cube microprismatic sheeting proposed as ASTM Type-XI [11]. Both of these types of sheeting are designed for permanent highway signing, construction zone devices and delineators. The test results indicated no significant differences between the sheeting types for first glance distances and each sheeting type was easily detected by both age groups [11]. However, the results of the action test showed significant differences with regard to the last glance distances. The test results indicate that the Type XI sheeted signs were viewed an average of 0.3 seconds shorter than the Type III sheeted signs thereby allowing the drivers to read and perceive the displayed information with the Type XI sheeting at a greater distance.
This would allow the drivers to potentially have more time to concentrate on other roadway stimuli [11].

The previous studies were performed comparing sheeting types used for roadway information, regulatory, and warning signs. Little research has been performed to determine the effects of using ASTM Type IX sheeting on work zone traffic control devices. These devices are lower to the ground and in closer proximity to the light source. This changes the incident angle of the incoming light potentially altering the amount of light being retroreflected and therefore may alter the effectiveness of the microprismatic sheeting for use on construction drums and other traffic control devices as compared to its use on traffic signs.

A study performed by the Wisconsin Department of Transportation, published in 2009, studied the effectiveness of ASTM Type IX sheeting on flexible delineator posts as a secondary study objective in their overall evaluation of the use of the flexible delineators [12]. Their findings determined that the ASTM Type IX sheeting was brighter than the ASTM Type III sheeting both in daytime and nighttime conditions but over the course of the year in which they were installed no increased safety effects were noticed. The study estimated that the ASTM Type IX sheeting cost approximately 60 percent more than the ASTM Type III sheeting while only having an expected life of two years greater than that of the ASTM Type III sheeting [12]. Based on the greater expense and the lack of a noticeable increase in safety Bischoff et al. suggested that ASTM Type IX sheeting not be used on the delineators.
The Bishoff study utilized crash and incident reports to determine the safety effects of the flexible delineators [12]. However, crash and incident rates are not the sole indicator of increased or decreased safety of a roadway. The crash and incident rates were not reported in the study. If they were sufficiently low prior to the installation of the ASTM Type IX sheeting on the delineators, the delineators themselves may have no effect at all on the crash occurrence. Other measures such as vehicle travel speed and lane placement can also be used to determine roadway safety attributable to the ASTM Type IX sheeting.

2.4 Need for Work Zone Visibility

In recent years there has been a change in roadway work zone projects from mostly new roadway construction to maintenance and rehabilitation of existing infrastructure. This change in work zone activity has resulted in work zone locations changing from closed with no traffic for the construction of new roadways to existing roadways on which traffic flow must be maintained. Operating work zones on existing roadways while maintaining traffic flow places construction workers at a higher exposure to the driving public as well as putting the driving public at a higher exposure to work zones. The result is a decrease in safety for both the work zone personnel and drivers. While roadway construction is still primarily performed during daylight hours, for reasons of driver safety and project efficiency, work zone lane closures often remain in place throughout the day and night. Nighttime lane closures place drivers at an even greater safety risk due to the combination of altered lane alignments resulting from closed lanes as well as a decrease in available visual cues [13].
The usage of reflective sheeting on traffic control devices was first introduced more than 60 years ago to improve visibility during nighttime driving conditions [8]. In recent years motor vehicles have redesigned, increasing the use of Visually Optically Aimable (VOA) headlamps. According to a study performed at the University of Michigan Transportation Institute by Sivak et al., the overall emitted luminous intensities directed toward signs by VOA headlamps is 53 percent less on a right mounted sign, 28 percent less on an overhead sign, and 42 percent less on a left mounted sign as compared to conventional US headlamps [10, 13]. In order to attain the same “brightness” and therefore the same distance for noticing and comprehending traffic signs and traffic control devices, the retroreflectivity of the sheeting used must be increased [5]. This required increase in retroreflectivity has been made possible through innovations in microprismatic retroreflective sheeting technology [4]. The most significant change made with the VOA headlamps is the reduction in the light emitted above the head light. Work zone traffic control drums or barrels are much lower than post or overhead mounted signs and therefore may not be affected by the change to VOA headlights; however, little research has been done to date to determine this effect.

The National Cooperative Highway Research Program (NCHRP) Report No. 627 identified four main strategies for the safety improvement of work zones [8]. One of those four strategies was to improve the visibility of work zone traffic control devices [9]. One example of such an improvement is the 3M™ DG³ full cube prismatic sheeting (proposed ASTM Type XI) which has been designed to reflect nearly twice as much incident light back toward the light source [8]. This sheeting is designed to perform
efficiently at short and medium sight distances and where signs are placed in non-ideal locations such as overhead or on the left shoulder [8]. The sheeting’s design enables it to reflect nearly twice as much light toward the driver to increase the device “brightness.” Theoretically this increased brightness will increase the distance at which the driver notices the construction barrels thereby allowing more time for the drivers to comprehend and take an appropriate action. Another safety impact of this increased brightness is the improvement of the visibility of solitary traffic signs. One unknown of the increased brightness is what effect it will have when barrels are placed close together along a line in a highway work zone.

An increasing demographic that must be considered and planned for in transportation safety is the older driver demographic. According to the U.S. Census Bureau, the number of drivers over the age of 65 years old in the United States will be approximately 50 million, or 20 percent of the total driving population by the year 2020 [13]. Older drivers show reduced sensitivity to contrast and lower response times than their younger counterparts [14]. Olson (1988) stated that a major problem for traffic safety is the reduced contrast sensitivity experienced during nighttime driving conditions. Objects become hard to see when because they cannot be distinguished from their background. The brightness of a traffic control device is the main factor in its attention-grabbing capability [14]. The brightness of the traffic control device increases its contrast in relation to its surroundings allowing it to more easily be seen, especially during nighttime driving conditions. The brightness or contrast of traffic control devices could, however, have the effect of distracting some driver groups. During a study performed to
assess the benefits of using reflectors on lane markings, the older driver group indicated that the reflectors were beneficial. The younger focus group in the experiment however found the reflectors to be excessively bright and even distracting [15].

2.5 Past Research on Driving Simulator Validation

Driving simulators present a platform through which researchers can safely study a variety of roadway features and characteristics. They provide researchers the ability to conduct studies which would otherwise not be possible due to event rarity or endangerment to participants. The simulator can provide a variety of data in terms of driver reactions to specific stimuli and driving conditions. However, for driving simulators to be a useful tool for researchers they must elicit similar behavior from drivers as the actual driving experience. Simulator validation is typically checked under two conditions: absolute validity and relative validity [16, 17]. Harms originally introduced the idea of absolute and relative validity in her driving simulator validation research performed in Holland in 1994 [16]. She defined absolute validity as the ability of a simulator to produce behaviors which were numerically similar and relative validity as a similarity in effects, magnitude and direction, of different treatments between driving simulators and real world driving. Tornros later proposed that, in order for a simulator to be useful for driving research, only relative validity must be achieved [18]. Since relative validity is achieved when the effect of a treatment is similar in magnitude and direction in a simulator and in the field, and human factors studies on driving behavior are typically concerned with the effect of one treatment over another, only similarity between the effects, or relative validity, is necessary for driving simulators to be useful research tools.
It has been accepted that only relative validity is necessary since research typically pertains to the behavioral effects of independent factors rather than reproduction of specific numerical data [18].

Simulators cannot provide a completely realistic driving scenario. As such each study should ensure that behavior exhibited in a driving simulator is similar to that exhibited in real driving situations and not solely related to characteristics of the simulator [17]. Several studies have been conducted on a variety of driving simulators to determine individual simulator validity for particular driving scenarios. Simulator types include fixed base simulators and non-fixed base simulators and field of views ranging from 40 degrees to 360 degrees. Validation has been studied for the performance of several tasks related to transportation safety research. The safety metrics analyzed in this study are vehicle lane placement and traveled speed. Therefore, only validation studies concerning these metrics will be discussed.

2.5.1 Speed Data Validation

A 1997 study, performed in Sweden by Tornros, aimed to validate the Swedish Road and Transport Research Institute’s driving simulator for speed and lane placement [18]. The researcher compared behavior of drivers in an instrumented car with the behavior of the same participants driving a similar scenario in the simulator. During this study 20 participants each drove through the same section of the Ekeberg tunnel a total of 12 times. The participants began by driving the instrumented car for approximately 20 minutes to get acclimated to the vehicle and traversed the tunnel three times prior to the start of data collection. Each participant then drove through the tunnel twice in each lane
in each direction. To prevent confounding from order effects, the order in which the participants drove in the lanes was balanced through the group. Due to schedule constraints, the order of simulated tunnel and real tunnel driving was not balanced in the study. All participants drove the real tunnel before driving in the simulator. The experimental design was repeated for the simulator portion of the study. For the simulator experiment, the tunnel and all its characteristics were recreated in a virtual environment.

Upon analysis of the speed data, it was determined that participants drove faster in the simulated tunnel as compared to the real tunnel and, based on an ANOVA with a 95 percent level of confidence, the difference in speed between the real tunnel and simulated tunnel was significant [18]. In other words, absolute validity was not achieved. However, a Tukey pair wise comparison of mean speeds was performed to compare the differences mean speed by lane. The analysis indicated the difference in mean speeds from lane to lane between the real tunnel and the simulated tunnel was not significant, or the difference in travel speed between one lane and another were similar in the field and simulated environments. Based on these results, relative validity was confirmed.

In 2001, Godley et al. conducted a similar study comparing the travelled speeds of participants in an instrumented car with travel speeds through a virtual environment using a driving simulator [19]. In both cases, the participants encountered a test route which contained rumble strips on the roadway and a control route which did not utilize rumble strips. Two routes were selected for the field study and were evenly distributed among the participants. To begin the instrumented vehicle segment of the experiment, each participant was provided with a practice route in order to become familiar with the
vehicle. A total of 24 participants took part in the instrumented car study. The routes were exactly recreated in a virtual environment and 20 different participants drove through the scenarios in the driving simulator [19].

For each participant, the impact of the rumble strips on driver speed was determined based on the difference between the mean speeds of the test and control sites [19]. The average differences between test and control sites were then compared between the instrumented vehicle and simulator experiments. A two-factor ANOVA was conducted to determine the relative validity of the simulator results with the instrumented vehicle results [19]. Based on the results of the ANOVA analysis, Godley et al concluded that relative validity was achieved with the driving simulator.

Francesco Bella has conducted many experiments studying the validity of the Inter-University Research Center for Road Safety’s (CRISS) fixed base driving simulator [21, 21]. In 2005, Bella conducted a study to determine the validity of the driving simulator for use in the verification of work zone safety improvements [20]. The travel speed of a vehicle as it progressed through a work zone was utilized as the metric for determining the effectiveness of possible work zone safety countermeasures. A field study was conducted through a work zone on Italy’s Highway A1. The work zone included a median crossover, was approximately 2.7 km in length and had speed reductions from 110 to 90 to 60 kph [20]. Field data was collected at four locations throughout the work zone, in the taper area, and within each median crossover. The work zone was then recreated in the virtual driving simulator environment and 35 participants were selected to drive the simulated work zone. Prior to simulator data collection, the
participants were provided a specific simulated roadway alignment to drive in order to become adapted to the simulator [20].

The speed data collected from the field study was than compared to the participants travelled speed in the simulator. It was found that on average the participants travelled slightly slower in the simulated work zone then in the field study [20]. A bilateral Z-test for non-matched samples was conducted at a 95 percent level of confidence to determine if the differences in speeds between the field and simulator studies were statistically significant. Based on the results of the analysis, the difference in speeds between the field and simulator study were not significant. From this, Bella concluded the simulator provided absolute validity in terms of travel speed within a work zone [20].

In 2007, Bella conducted a study to determine the validity of the CRISS driving simulator speed research on two-lane rural roadways [21]. Validity was determined through the comparison of speeds collected in the field along a two-lane rural roadway with those collected along a similar roadway recreated in the driving simulator. Data was collected at a total of 11 places along the roadway with five locations on curves and the remaining six along tangent sections [21]. The roadway was then recreated within the CRISS driving simulator environment and forty five participants drove the scenario once. A comparison of the speed profiles through the rural roadway indicated that, at nine of the eleven measurement locations, the mean speeds in the simulator were statistically similar to those observed in the field. The means were not statistically significant at two locations; however, they showed good correlation and therefore Bella determined relative
validity was achieved [21]. In both studies performed to determine the validity of driving simulator use in speed research, Bella concluded that the CRISS fixed base driving simulator is a useful tool for speed research [20, 21].

In 2007, McAvoy et al. studied the validity of a driving simulator for work zone research during nighttime driving conditions. The research was aimed to study the effectiveness of construction drums with steady burn warning lights [22]. A “test and control” site comparative parallel study was performed in a field study with speed as the selected metric for evaluation. It was assumed that slower travel speeds within a work zone would create a safer work zone. Speed data was collected at the beginning of the work zone, in the middle of the work zone and at the end of the work zone [22]. Two work zones were then created in the driving simulator, one simulating drums with the steady burn warning lights and the other simulating a work zone utilizing drums without steady burn warning lights. Both simulated work zones were along tangent sections of a two lane divided highway with barrels located on both sides of the travel lane similar to approximately half of the field study sites and included a speed reduction of ten miles per hour through the work zone [22].

A total of 127 participants were utilized in the simulator study. Each participant first drove through a scenario with no work zones present. This scenario was created to allow the participant to adapt to the simulator. This scenario lasted until the participant informed the researcher that they were comfortable with the simulator and ready to proceed with the experiment [22]. On average the adaptation time lasted around 10 minutes. The participant was then presented with the simulated work zones. Speed data
was collected at the beginning, the middle and the end of the work zone [22]. The student’s t-test was utilized to compare the speeds observed in the field with those observed in the simulator at each collection location [22]. An ANOVA was also conducted to determine if the mean speeds varied within the simulator and field studies by location. Based on the results of the statistical analysis, the mean speeds were similar between the simulator study and the field study at the beginning of the work zone. However, the mean speeds were not statistically similar at the middle or end of the work zones [22]. From these results, the absolute validity of the simulator was rejected. Further analysis as to the trends of the data indicated that the simulator failed in terms of relative validity as well [22]. The researchers concluded that driving simulators may not accurately reproduce the perceived risk experienced by drivers traveling through a work zone and therefore may not be a suitable substitute to field data collection during nighttime driving conditions relating to work zones [22].

2.5.2 Simulator Lane Placement Validation

Along with speed, the physical location of a vehicle within the travel lane as it progresses through a work zone is also widely used as a safety metric in transportation research. The placement of a vehicle with respect to a work zone can be used as an indication for possible increased safety of a work zone if drivers tend to position their vehicles further away from a closed lane or shoulder. Lane placement variations has also been well researched as an indication of perceived risk with lower variation indicating less perceived risk. Vehicle placement with respect to the centerline of the travel lane is often considered an indication of driver behavior. Therefore, if vehicle lateral lane
placement is to be used as a metric of safety in a driving simulator study, it too must be validated to ensure the behavior is not caused by the characteristics of the simulator [17]. Lane placement validation research produced mixed results in terms of the achievement of absolute or relative validity.

A study performed by Kappe and Korteling in 1995 found that the difference in behaviors of experienced drivers and inexperienced drivers, in terms of lane placement, was similar on the road and in the driving simulator [23]. Similarly, Tenkink found that, when an obstacle was placed near to the road, participants generally traveled at slower speeds and lateral placement variation decreased in both on road and simulator scenarios [24]. However, Blaauw found that, although the effect trended similarly, drivers tended to drive slightly faster and had higher variation in lane placement when encountering obstacles in the simulator as compared to in field studies [25]. From this, Blaauw concluded that simulators could achieve relative validity but did not achieve absolute validity.

In a study performed by Harms in 1993, speed and lateral position data were collected for participants driving on an actual road as well as on a similar road in a driving simulator environment. In the study, the researcher determined that a strong correlation of vehicle placement within the travel lane between the on road and driving simulator environments could not be found [16]. The study performed by Harms found that participants tended to place their vehicles closer to the centerline of the roadway in the simulator study; however, it was suggested this may have been due to the lack of oncoming traffic present in the driving simulator. Alm replicated Harms’ study in 1995
with the addition of oncoming traffic utilizing a fixed base and motion base simulator conditions [26]. The results indicated that relative validity was achieved with oncoming traffic and under the motion base conditions. Validity was not achieved in the study when the simulator base was fixed. From this, Alm suggested that the motion base increased the validity of the lateral vehicle control behavior [26].

Tornros’ research also included validation for driver behavior in a tunnel considering lane placement with respect to the tunnel walls [18]. Lane placement was analyzed separately for the straight and tangent sections of the roadway in the experiment. Along the straight sections, it was found that in both the simulator and the road scenarios participants positioned their vehicles further from the wall when it was on their left side then when the wall was on the right hand side of the vehicle. The actual lane placement was significantly different between the simulated and road condition; however, relative validity was achieved. In terms of the curved sections of the roadway, relative validity was also achieved [18].

2.6 Current State-of-the-Practices

In this research an evaluation of the current state-of-the-practices of departments of transportation was conducted to determine the extent to which the different types of sheeting are used and required in work zones. It was determined that a current state-of-the-practices survey was the most effective method to determine the current state requirements with regard to the sheeting type used on construction drums within work zones on a state by state basis. A copy of this survey is included in Appendix C. When considering the method of distributing the survey to each department of transportation,
email was deemed the most effective method based on its wide use, and low distribution expense. As such, a current practices survey, along with a letter explaining the purpose and goals of the research, was sent to the individual or office at each state department of transportation which was primarily responsible for work zone design, safety and regulation.

Questions asked in the survey related to the current procedures and devices used for traffic channelization in work zones. These questions included the current types of channelization devices used, the approximate percentage each device constituted, the sheeting type required on construction drums, and why the department did or did not require ASTM Type IX sheeting.

The recipients were given approximately one month to complete and return the survey after which the individuals who did not return the survey were contacted by phone in an attempt to increase the number of returned surveys. Those states which were contacted via phone were allowed an additional three weeks to complete the survey after which a second email and phone call was sent to each of the departments of transportation which had not responded to the survey. At the completion of this research, 40 of the 50, or 80 percent of the states, accounting for approximately 83 percent of public roadways, responded to the survey. A table of the states, and their corresponding percentages of the total public roadway miles is included in Appendix D. Of those returned, many were still not fully completed due to a variety of reasons including, but not limited to, non-applicability to the individual department or possible confusion as to
the question meaning. This was accounted for when analyzing and reporting the results of
the survey.

2.6.1 Current State-of-the-Practices Results

The compiled data provided from the current practices survey regarding the type of
sheeting used is provided in table 1. The total number of states providing a response to
this part of the survey was 40, the percentages reported are the percentages based on
those which responded. Those states which replied that they use both ASTM Type IX and
ASTM Type III sheeting indicated they utilize the ASTM Type IX sheeting for the
orange band and ASTM Type III for the white band on their construction drums.

<table>
<thead>
<tr>
<th>Sheet Type</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM Type III</td>
<td>26</td>
<td>66.70%</td>
</tr>
<tr>
<td>ASTM Type IX</td>
<td>8</td>
<td>20.50%</td>
</tr>
<tr>
<td>ASTM Type III and ASTM Type IX</td>
<td>5</td>
<td>12.80%</td>
</tr>
</tbody>
</table>

As seen in table 1, two thirds of the responding agencies or departments require
ASTM Type III sheeting for use in work zones, one third require at least the orange band
be ASTM Type IX sheeting, and only one fifth of the responding agencies or departments
require ASTM Type IX sheeting for both the white and orange bands. Of those states and
agencies which responded to the current practices survey and do not as of yet require
ASTM Type IX sheeting, 5 of the 26, or 19.2 percent, stated that their departments or agencies do plan to require ASTM Type IX sheeting in the near future.

As part of the survey, each agency or department was requested to indicate the reasons as to why they require ASTM Type IX sheeting or why they do not require the ASTM Type IX sheeting be used on construction drums in work zones. Table 2 below shows the selected reasoning for requiring ASTM Type IX sheeting while Table 3 shows the results reasoning given by those states which do not require that ASTM Type IX sheeting to be used.

<table>
<thead>
<tr>
<th>Reasoning</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visibility</td>
<td>1</td>
<td>7.70%</td>
</tr>
<tr>
<td>Improved Work Zone Delineation</td>
<td>1</td>
<td>7.70%</td>
</tr>
<tr>
<td>Safety, Visibility, and Delineation</td>
<td>9</td>
<td>69.20%</td>
</tr>
<tr>
<td>Visibility and Delineation</td>
<td>2</td>
<td>15.40%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reasoning</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>11</td>
<td>57.90%</td>
</tr>
<tr>
<td>Glare</td>
<td>1</td>
<td>5.30%</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>26.30%</td>
</tr>
<tr>
<td>All the Above</td>
<td>2</td>
<td>10.50%</td>
</tr>
</tbody>
</table>

In table 2 it is apparent that the majority of those departments or agencies which require the use of ASTM Type IX sheeting feel that the sheeting provides a better delineated, more visible, and therefore safer, work zone as opposed to the ASTM Type III sheeting. It is also apparent that the majority of those departments or agencies that do
not require ASTM Type IX sheeting feel the cost of the ASTM Type IX sheeting material outweighs the potential safety improvements of the sheeting.
CHAPTER 3: FIELD STUDY SITE DESCRIPTIONS

The work zone locations chosen for data collection were based on several general criteria. Criteria included: freeway/highway designation with a normal travel speed of 55 mph or greater, closure of at least one travel lane, a lane closure of one mile or greater, a lane closure using construction drums along the tangent sections of the closure, and a lane closure which remained in place overnight. Based on these criteria and with the help of the Ohio Department of Transportation, three sites were selected for data collection for drums with ASTM Type III sheeting, and with the cooperation of the Illinois Department of Transportation, one site was selected for data collection for drums using ASTM Type IX sheeting.

3.1 ASTM Type III Data Collection Sites

As previously mentioned, the ASTM Type III data collection sites were located in Ohio and were set up in accordance with the Ohio Manual on Uniform Traffic Control Devices. Figure 1 provides a general representation of a typical Ohio work zone.

---

1 This chapter, sections 3.1 and 3.2, contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
The first site selected for data collection was along US-50 near Athens, Ohio in Athens County. The work zone began approximately 0.25 miles east of the SR-682 interchange with US-33/SR-32 and continued for approximately 4.60 miles, ending at the interchange of US-50 and East State Street. The terrain along the corridor is rolling with five access points. The average daily traffic (ADT) along this corridor is 18,370 vehicles per day (vpd). Figure 2 presents a map location of the ASTM Type III data collection site.
US-50 is a 4-lane freeway with a speed limit of 55 mph. Lane placement data was collected while the right lane was closed with drums prior to the placement of concrete barriers. This site was a long term construction project and concrete barriers were installed shortly after the initial lane closure rendering the site unsuitable for data collection for this project. Only daytime data was collected from this site. A work zone speed limit was set at 45 mph throughout the work zone.

The second data collection was along SR-32 approximately 13 miles east of Peebles, Ohio in Pike County. The work zone began at County Road 87 on the east and continued west approximately 3.20 miles ending just prior to County Road 16. The terrain along the corridor is hilly with no access points present within the work zone. The
ADT along this corridor is 4,270 vpd. A map of the ASTM Type III data collection site 2 is presented in figure 3.

Figure 3. ASTM Type III data collection site 2.

SR-32 is a 4-lane freeway with a speed limit of 60 mph in this portion of the route. The work zone utilized for data collection consisted of a right lane closure in both directions of travel and included a speed limit reduction to 50 mph through the work zone. Daytime and nighttime lane placement data was collected at this location. This site was not utilized for speed data collection due to the presence of a large vertical curve within the site. No overhead roadway lighting was present along the route. Vehicle headlights were the only illumination of the work zone during nighttime driving conditions.
The third work zone utilized to collect data from ASTM Type III sheeting was a resurfacing project located on SR-32 approximately 5 miles west of Jackson, Ohio in Jackson County. The work zone began just east of SR-776 and continued approximately 2.50 miles to Cove Rd. The terrain along this corridor can be considered rolling terrain with one access point located within the work zone. The ADT along this section of SR-32 is 6,640 vpd. A map of the ASTM Type III data collection site 3 is presents in figure 4.

Figure 4. ASTM Type III data collection site 3.

SR-32 is a 4-lane divided freeway with a posted speed limit of 60 mph. The work zone utilized for lane placement data collection consisted of a left lane closure in both directions of travel with a posted work zone speed limit of 50 mph. No overhead roadway lighting was present along the route. Vehicle headlights were the only illumination of the
work zone during nighttime driving conditions. The terrain at this site was rolling and contained a long straight section of roadway. Because of this speed data collection as well as the lane placement data was collected at this site. Speed data was collected at the east end of the work zone using vehicles traveling west for “entering” speed data and vehicles traveling east for “exiting” speed data. Speed data was also collected at the approximate midpoint of the work zone. Data was collected in the same approximate locations and manner for both daytime and nighttime conditions.

3.2 ASTM Type IX Sheeting Data Collection Site

Based on the results of the current state-of-the-practices survey, it was determined that Illinois currently requires the use of ASTM Type IX sheeting on their work zone drums. A general representation of the Illinois work zone is provided in figure 5.

*Figure 5. Typical ASTM Type IX Work Zone*
Lane placement and speed data collection from a work zone with drums utilizing ASTM Type IX sheeting was performed on Interstate 72 west of Champaign, Illinois. The interstate is a 4-lane corridor of which the right lane in each travel direction was closed at the time of data collection. The work zone began approximately halfway between mile marker 75 and mile marker 74 on the east end and continued west approximately 3.5 miles ending near mile marker 70. The terrain along the corridor was rolling with one access point within the work zone. The ADT for this section of I-72 is 12,000 vpd. A map of the location of the ASTM Type IX data collection site is presented in figure 6.

*Figure 6. ASTM Type IX data collection site 1.*
I-72 was a 4-lane corridor with a speed limit of 65 mph. The work zone closed the right travel lane in each direction and had a posted speed limit of 55 mph when no work was being performed within the work zone and 45 mph when workers were present. Daytime and nighttime lane placement data along with speed data was collected at this site. This section of the interstate was outside of the city limits and had overhead lighting available only at the one access point within the work zone. The only illumination of the work zone was that from a vehicle’s headlights during nighttime driving conditions. Speed data was collected at the east end of the work zone. Data was collected from westbound vehicles as speed entering the work zone and vehicles traveling eastbound as speed exiting the work zone. For the speed data collected within the work zone, a bridge overpass located in the approximate center of the work zone was utilized. The same approximate locations and collection practices were used for both daytime and nighttime speed data collection.

3.3 Field Study Site Summary

Table 3 provides a summary of the characteristics of each of the field data collection sites. Speed data was collected from ASTM Type IX site 3 and ASTM Type III site 1. These sites were both generally level and contained at least one horizontal curve. At both of these sites at least one end of the work zone was along a straight stretch of the site. This end was utilized for entering and exiting speed data collection for this study.
<table>
<thead>
<tr>
<th>Site</th>
<th>No. Lanes per Direction</th>
<th>WZ Speed Limit</th>
<th>Center Median</th>
<th>Lane Width</th>
<th>Lane Closed</th>
<th>Horizontal Curves</th>
<th>Vertical Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM Type IX 1</td>
<td>2</td>
<td>45</td>
<td>Grass</td>
<td>12'</td>
<td>Right</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>ASTM Type IX 2</td>
<td>2</td>
<td>50</td>
<td>Grass</td>
<td>12'</td>
<td>Right</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>ASTM Type IX 3</td>
<td>2</td>
<td>50</td>
<td>Grass</td>
<td>12'</td>
<td>Left</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>ASTM Type III 1</td>
<td>2</td>
<td>55/45</td>
<td>Grass</td>
<td>12'</td>
<td>Right</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
CHAPTER 4: FIELD STUDY DATA COLLECTION

Based on the review of previous research pertaining to driver behavior and driving simulator validation, lateral lane placement and vehicle travel speed were selected as the data collection parameters for this study. These parameters are widely used to when considering driver behavior and are able to be collected without alerting the driver and therefore possibly altering their normal driving behavior.

4.1 Lane Placement

Lane placement data for this research was collected during daytime and nighttime driving conditions in work zones utilizing construction drums for a lane closure. Data was collected from sites with drums using ASTM Type III sheeting on as well as from sites with drums utilizing ASTM Type IX sheeting. Data collection was performed by videotaping a lead vehicle as it entered, progressed through, and exited the work zone. This was accomplished through the use of a camcorder and tripod placed in the front passenger seat of a trailing vehicle. Taping began approximately ½ mile prior to the lane closure and was completed as the vehicle exited the work zone. Efforts were made to assure covert data collection so as not to alter normal driver behavior. These efforts included spotting lead vehicles from entrance ramps and entering the highway behind the selected vehicle in a normal manner, approaching the vehicle at an average speed, merging in behind “lead” vehicles as if it were normal traffic, and keeping as safe of a distance behind the “lead” vehicle as possible while still collecting usable lane placement.

---

1 This chapter contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
data. This was done to help ensure natural driving habits of the leading vehicle when collecting data.

4.1.1 Lane Placement Data Extraction

Upon the collection of lane placement data with a video camera, the extraction of the vehicles actual lane placement was required. The interval at which the lane position data needed to be extracted, 1- 5- or 10-seconds, was unknown. A 1-second interval would provide the most accurate lane placement data however it would require much more time for data extraction then a 5- or 10-second interval and may not provide significantly different results. Conversely, though requiring less time for data extraction then a 1-second extraction interval, a 5- or 10-second data extraction interval may not accurately portray the subject behavior and therefore would not provide accurate experimental results. It was necessary to determine if a significant difference in the average, minimum and maximum lane placements for the subject population existed when considering the 1-, 5-, and 10-second data extraction intervals.

To determine this, a random sample of the collected data was analyzed using a 1-5- and 10-second data extraction interval. The average, minimum, and maximum lane placements were calculated at each interval for each sample. A one-way ANOVA was conducted on the data using SPSS 16.0 statistical software. The ANOVA analysis indicated that there was no significant difference between the data extracted at a 1-, 5- or 10-second interval. Based on these results it was determined that a 10-second interval would be acceptable for lane placement data extraction.
As stated previously, lane placement data was collected by videotaping a lead vehicle from behind as it traveled through a work zone which provided a visual reference of each vehicle but not actual lane placement data. To extract the lane placement data for each car within the work zone at the determined 10-second interval, the video tapes were viewed, pausing as the vehicles entered the work zone and then every ten seconds thereafter to record the vehicles lateral position. Lane placement was taken as the distance a vehicle was away from the center of the traveled lane. A positive value was recorded when the vehicle was located further from the construction drums and negative when the vehicle was closest to construction drum side of the lane. During the data collection process, efforts were made to maintain a relatively constant distance between the lead vehicle and the vehicle collecting the data. However, it was impossible to maintain an exact distance between subject lead vehicles at all times. Due to the changes in distances between the lead vehicle and the data collection vehicle, the horizontal scale of the video was continually changing. In order to account for this varying scale during the data extraction, an object of uniform size on all vehicles was needed as a baseline. It was determined that the standard U.S. state license plate measured approximately one foot in width. To account for the differences in scale between measurements, the license plate of each vehicle, at each interval was used as a 1.0 foot scale. The license plate was used as a measure of the vehicle’s horizontal distance from the center line of the lane and was recorded to the nearest 0.5 ft.
4.2 Speed

Speed data was collected using a Laser Tech Inc. UltraLyte LTI 20-20 laser speed gun. Speed data was collected as vehicles entered the work zone, at the middle of the work zone, and as vehicles were exiting the work zone. During the collection of speed data attempts were made to be out of the vehicles line of sight, so as to not alter normal driving behaviors, while keeping within the required three to five degree angle between the vehicle and speed gun for accurate speed readings. The laser speed gun determines the vehicle speed by calculating the time required for the laser to reflect from the vehicle and return to the speed gun. If data is collected with the laser speed gun at an angle greater than three to five degrees between the collector and the path of travel the length of the laser’s path is increased compared to the parallel distance between the laser gun and the vehicle. This increase in path length artificially inflates the length of time required for laser to reflect and return to its source therefore producing readings which are lower than the actual vehicle speeds. This increase in path length is negligible when the angle is kept to less than three to five degrees. When possible bridge overpasses were utilized for the collection of speed data. When overpasses were not available speed data was taken from shoulder or median locations where the researcher was mostly blocked from the sight of drivers. Attempts to be out of the line of sight of drivers were made in order to assure natural driver behavior of the driver population used for data collection.

4.3 Sample Size Determination

A sample size estimate of approximately 100 vehicles was selected for lane placement and spot speed data based on the approximate sample size required to consider
a 1.0 mile per hour speed difference between groups significant. The initial estimate was later refined based on the data collected and the statistical power desired for this study. Approximately 100 speeds were collected at each location throughout the work zone. Since the actual sample size and corresponding significant error are dependent on the standard deviation of the sample population, this assumption was checked and refined once the initial 100 data points were collected.

Data collection was performed along Interstate 72 near Champaign Illinois at a site with drums utilizing ASTM Type IX sheeting. Lane placement data was collected both during daytime and nighttime driving conditions. The total sample size collected for ASTM Type IX nighttime data lane placement was approximately 120 subjects while the total sample size collected for ASTM Type IX daytime lane placement was approximately 110 subjects. The discrepancy in sample size collected was based solely on chance, and not significant to the study performed.

Lane placement and speed data from work zones with drums utilizing with ASTM Type III sheeting were collected from three separate sites. The locations were all rural 4-lane work zones with two travel lanes in each direction similar to the site utilized for data collection for ASTM Type IX sheeting.

The required sample size estimate was then refined using a random sampling of the collected data. This was performed through extracting the lane placement data for 5 subjects in each of the four conditions, nighttime with ASTM Type IX sheeting, nighttime with ASTM Type III sheeting, daytime with ASTM Type IX sheeting, and daytime with ASTM Type III sheeting. The lane placement data was extracted for each
separately. The average lane placement throughout the work zone was then combined for each vehicle based on day and nighttime conditions only. The ASTM Type IX and ASTM Type III data were combined in an attempt to attain a sample size which would allow for the consideration of a small difference in lane placement data to be considered significant when analyzing the ASTM Type III work zone data with the ASTM Type IX work zone data. Based on the limitations of the data extraction methods and considering the nature of the lane placement parameter, three inches, or 0.25 feet, would be an adequate limit at which a change in lateral placement could be considered significant.

The daytime data was not analyzed against the nighttime data due to the likelihood of differing subject populations during the different driving conditions. Therefore, daytime and nighttime data were not considered together in the sample size estimation. The nighttime population is less likely to include seniors and will likely include more truck traffic. Since these subject populations are different, an analysis of the difference in lane placement between the two driving conditions would only provide data indicating a possible difference in population behavior. It could not be considered a difference caused by the sheeting.

The two major factors which affect the required sample size are the level of significance and the power of the test [27]. For this study a 95 percent confidence interval, or $\alpha = 0.05$ was desired. Based on this and a 4:1 ratio of $\beta$ to $\alpha$, beta was equal to 0.2, the power of the test was 80 percent.
Sample size is calculated through selecting the acceptable error, the level of confidence desired in the test, and from the sample population standard deviation with the following equation:

\[ n = \frac{Z^2 \sigma^2}{\varepsilon^2} \]  \[27\]

Where: \( Z = 1.96 \)
\( \sigma = \text{Sample Standard Deviation} \)
\( \varepsilon = \text{Acceptable Error} \)

With the following equation, both the power of the test and the level of confidence are considered along with the acceptable error and the standard deviation of the sample population:

\[ n = \frac{(Z_\alpha-Z_{\alpha/2})^2 \sigma^2}{\varepsilon^2} \]  \[27\]

Where: \( Z_{\alpha/2} = 1.96 \)
\( Z_\beta = 0.842 \)
\( \sigma = \text{Sample Standard Deviation} \)
\( \varepsilon = \text{Acceptable Error} \)

The initial estimation of the required sample size is chosen as the greater of the two calculated with the preceding equations.

In the initial sample size estimation based on the random sampling of the collected data, the sample size was known and the error, or significant difference, was
calculated. From this, a reasonable acceptable significant difference was selected and a sample size estimate was calculated.

The sample sizes calculated from these equations are deemed the minimum sample size needed. Being such, the largest of the samples size calculated, either daytime or nighttime, was that selected as the minimum required sample size. Data collection efforts were then aimed to exceed this required minimum size to account for possible differences in overall sample behavior as compared to the random sampling used for the minimum sample size calculation. This method of sample size determination calculated the sample size based on the behavior of the subject population rather than engineering judgment or industry standards.

This process was repeated to determine the sample size needed for speed data collection. Based on the sample data collected, an error of approximately two miles per hour can be considered significant when considering the differences between the ASTM Type III and ASTM Type IX sheeting work zones. Two miles per hour was deemed as an acceptable error because of the practicality of the real effect. A one mile an hour difference in travel speeds between sheeting types would not constitute a significant safety increase.

Upon the completion of the lane placement and speed data collection and extraction the sample size required to meet the 0.25 foot error, the error deemed acceptable at the beginning of this research, was calculated based on the entire populations characteristics. The required sample size was determined to be approximately 25. The actual collected sample size was approximately 200. The beta equation was then
used to calculate the actual error which could be considered significant while still
keeping a level of confidence of 95 percent and the power of the test equal to 80 percent.
It was determined that, based on the sample data collected, an error of 0.15 feet could be
considered statistically significant in this study.
CHAPTER 5: SIMULATOR STUDY

5.1 Internal Review Board

The second phase of this research involved soliciting subjects to drive in the Ohio Research Institute for Transportation and the Environment’s Safety and Human Factors Facility’s state-of-the-art driving simulator. In order to perform research which involves the use of human subjects, the researchers must first receive approval for the research from the university through the Institutional Review Board (IRB). The IRB approval process is aimed to guarantee that any research performed using human or animal subjects is designed to limit any and all possible impacts to participants and to ensure the research is outcomes are of value to society. The researchers must be able to show that the research being performed is safe for participants and will provide a benefit to society which is great enough to offset any possible risk presented to the test subjects. This process includes providing a detailed explanation of the research project including a thorough description of: the project protocol, all aspects of the research in which participants would partake, any and all possible risks to participants during the experiment as well as all precautionary measures taken to reduce the risks, all data analysis procedures, all societal benefits which are likely come from the research, and all measures taken to ensure the confidentiality of any and all participants. During this process the IRB committee also must approve any and all recruitment fliers, questionnaires, and participant compensation if applicable.

Prior to the recruitment of any simulator participants from the university student body or general population the IRB form was completed for the project and submitted to
the review committee. After a series of minor additions and changes to the form, approval was granted for this project to recruit from the general student body at Ohio University and the general Athens population. Upon commencing the simulator study the researchers decided it would be advantageous to utilize the Psychology student research participant pool in this research. The initial IRB was amended to include the use of the Psychology student research pool and to compensate them with one research credit per participant for their participation. The IRB approval and amendment approval along with the final IRB document are available in Appendix A.

5.2 Simulator Scenario Setup

In the second phase of this research, a simulator study was performed to determine the extent to which the driving simulator is able to evoke driver behaviors similar to that exhibited under field driving conditions. While the fidelity of simulators has greatly improved through the years, there are still several factors which impact driver behavior in the real driving task that cannot be reproduced in a driving simulator. As such, in order for a simulator to be a useful research tool, it must first be validated for the type of research being performed. One method of validation which has been widely accepted is a comparison of data collected from drivers in a field study and comparing that with data collected from drivers driving through a simulated scene which replicates the field conditions.

The first task in replicating the field conditions in this study for the simulator scenario was to create construction drums which closely mimicked the characteristics of the ASTM Type IX and ASTM Type III sheeted drums which were used in the field
study. The general physical size and color of the barrels and the width and color orientation of the retroreflective stripes were determined from the manufacturer’s specifications. The colors of the barrel and stripes on the simulated barrels were then matched to the actual barrels. Figure 7 presents the general color combinations used for the simulated barrels.

![Figure 7. Simulated ASTM Type IX and ASTM Type III barrels.](image)

The next task was to determine the brightness of the retroreflective stripes. The simulator is not able to reproduce actual reflectivity. Rather, the simulator program adjusts the luminance properties of simulated entities to mimic the “brightness” of the real entities due to the reflected light. The luminance of the reflective stripes on the construction drums was set by determining the distance at which each sheeting type could
be seen when in line on a construction site spaced at approximately twice the speed limit as per the federal Manual on Uniform Traffic Control Devices (MUTCD). These distances were extracted from the lane placement video collected in the field study at each site. The average distance at which each sheeting type could be seen was determined by counting the approximate number of barrels which was visible on the video while on a relatively level, straight, section of roadway. The luminance of the barrel striping was then set such that the barrels were visible at their corresponding distances along a straight, level roadway under nighttime driving conditions. It was determined that ASTM Type IX barrels could be seen at a distance of approximately 2150 feet while the ASTM Type III barrels were visible at approximately 1600 feet under headlight illumination.

Once the simulated construction drums were created, four simulator scenarios were created to closely mimic environments in which the field study was performed. These included ASTM Type III daytime, ASTM Type III nighttime, ASTM Type IX daytime, and ASTM Type IX nighttime. Each of the scenarios were created on a simulated road similar to those in the field study; a straight four lane rural roadway with two lanes in each direction, no overhead lighting and no access points. Since the purpose of this study was to determine the validity of a driving simulator for this type of research, each of the scenarios were created to simulate clear, dry weather conditions to match the conditions under which the field study data collection was conducted.

The scenarios utilized a straight section of road for this study in an attempt to limit the possibility of participants experiencing simulator sickness which occurs more frequently on simulated curves as compared to straight roadways. In an attempt to limit
any possible influence on driver behavior in the study, there was no ambient traffic on the simulated roadway. The lack of ambient traffic ensured the subjects could travel at a speed they chose rather than possibly getting trapped behind a slower moving vehicle and also prevented the participant from being influenced in terms of lane position by a leading vehicle as well. It was determined that the absence of ambient traffic would not bias the participants when compared to the field study due to the low traffic volumes occurring at the field study sites during the data collection periods.

The speed limit along the roadway was set at 55 mph under normal driving conditions with a reduction to 45 mph through the work zones. Advanced warning signage was placed along the roadway prior to the lane closure in accordance with the standards set forth in the federal MUTCD. In keeping with the majority of the data collection sites utilized for this study, the simulator scenarios all included a right lane closure with a taper length of 540 feet, based on MUTCD taper standards, and a and a closed tangent section of approximately 2100 feet. The tangent length of the closed lane was chosen arbitrarily with the intent to provide a short enough work zone so as to limit the volunteer rime necessary for participants, while still providing a work zone which was long enough to affect the behavior of drivers. Figure 8 below shows the general design for the simulator work zones.
5.3 Simulator Study Methodology

Four separate work zones were required to provide a complete data set for the validation, daytime and nighttime with ASTM Type III sheeting on the construction drums, and daytime and nighttime with ASTM Type IX sheeting on the construction drums. Each separate work zone was identical in terms of spatial layout and grouped by time of day. In an attempt to prevent confounding, two scenarios were created for each time of day with the work zones alternated such that half of the participants encountered ASTM Type III first while the remaining encountered the ASTM Type IX sheeting in the first work zone. A random number generator was utilized to arrange the order of which participants encountered the sheeting types; however, the order at which the time of day was encountered was not random. The random order of the sheeting types was arranged to limit possible confounding due to participants always encountering a certain sheeting
type first. Each participant began the study by driving during daytime hours. By having each participant begin during daytime hours it allowed the subjects to further familiarize themselves with the simulator prior to the change in lighting conditions from the initial adaptation protocols. Confounding due to the non-randomization of the time of day condition was not considered since comparisons were only made within time of day conditions and not between them.

5.4 Simulator Adaptation

The driving simulator used in this study is the Drive Safety DS-605 fully immersive driving simulator which includes a full vehicle cab, a 180 degree field of vision, simulated side and rear view mirrors, two vibration transducers, and a motion base with 2.5 degree of pitch and up to five inches of longitudinal movement. These features combine to provide a driving simulator platform which can closely mirror the feel of real driving and therefore may evoke similar behaviors and reactions. In order to ensure the behaviors of the participants in a driving simulator study were not biased by the differences between real driving and simulated driving, researchers must allow the participants time to adapt to the simulator prior to collecting behavioral data. Similar to the behaviors of a driver during the short period of time after beginning to drive a vehicle they are not used to driving, the participants must be allowed time to adjust to the feel and view of the simulator. Figure 9 displays the O.R.I.T.E. Safety and Human Factors Facility’s driving simulator.
Several adaptation methodologies have been proposed by various researchers for driving simulator research. These methodologies typically fall into two groups: allowing each participant to drive in a simulated scenario similar to the study scenario for a predetermined period of time or distance and assuming they have adapted at the completion of the time or distance, or allowing the participant to drive in a scenario similar to that of the study until they judge themselves comfortable with the controls of the simulator and with the simulated environment. Both of these methodologies have limitations in that neither relies on a finite, scientific, tangible evidence to assure that every participant is adapted to the same degree prior to the start of data collection with the simulator.
While some feel that the set time or distance method for adaptation is appropriate, there has been no commonly recommended time or distance at which adaptation can be considered completed. This method may require some participants to drive much longer than they need during the adaptation portion of the study and may lead to participants rushing the actual study due to boredom. It also may end the adaptation scenario prior to a participant becoming fully comfortable and adapted to the vehicle which could cause data to be skewed due to the participant not being fully adapted to the vehicle and therefore not displaying their normal driving habits. Concerns with the second adaptation methodology of allowing the participant to decide when they are comfortable with the simulator and ready to proceed include participants ending the adaptation scenario quickly just to finish the study quickly.

A few researchers have considered more scientific, calculated measures as a judge of a participant’s adaptation to the simulator with mixed results. Those that have had positive results with more scientific determinations of adaptation however have yet to develop efficient procedures which could be used in real time at the start of a study.

For this research, adaptation began with each participant first driving a brief, timed scenario as an initial introduction to the simulator. This scenario was designed to provide an introduction to the lane placement and speed controls of the vehicle. During this drive the participant was shown five circles on the center screen of the projectors, superimposed on the surroundings. When the participant had the vehicle positioned in the center of the lane the center of the five circles would fill in green. If the participant placed the vehicle to either the left or the right of center in the lane the green circle went clear
and the second circle on that side would fill in yellow. If at any time during the first drive the participant placed their vehicle such that the tire would be traveling on either the left or right lane line the green or yellow circle would clear and the outside circle on that side would display in red. Each participant was also required to maintain a travel speed of plus or minus five miles per hour of the posted speed limit. If they travelled in excess of five miles per hour over the speed limit, a voice automatically sounded saying “Slow Down.” The scenario ended once the participant maintained a lane position within the yellow circles and a speed within five miles per hour of the posted speed limit for a predetermined amount of time. If at any time the participant positioned their vehicle such that a tire would have been on either lane line, a tone sounded and the scenario time restarted. Once the participant stayed within the proper lane orientation and speed range for the predetermined amount of time, a voice came on stating “Practice Complete” and the screens faded to black.

Upon the successful completion of the first adaptation protocol, the participant moved on to a second practice drive. The purpose of this drive was to allow the participant to become comfortable with the actual roadway they were required to drive in the study. Participants drove on a rural 4-lane highway with a concrete center divider with a posted speed limit was 55 mph. Instruction was provided to each participant to practice driving the speed at which they would typically travel on the road type and posted speed limit in order to get used to how that speed felt in the simulated environment. They were also instructed to make at least one lane change to get used to the look and feel of the simulator during lane change events. Completion of this practice
drive occurred at the discretion of the participant. Once they had performed at least one lane change maneuver and felt comfortable with maintaining speed in the simulator they brought the vehicle to a stop and the driving practice was concluded.

Providing both drives within the driving adaptation protocol incorporated parts of both of the commonly practiced driving simulator adaptation protocols. The initial protocol provided the participant with extra speed and lane placement information during their initial experience with driving the simulator. Participants were then provided the opportunity to gain as much extra practice as they felt they needed to be comfortable with the simulated vehicle and environment. On average, the total time spent driving during the adaptation portion of the study was approximately 8-10 minutes.

5.5 Simulator Study Participants

To participate in this study, participants were required to volunteer approximately one hour of their time during which the participant completed a pre-study survey to collect demographic and driving behavior information from the participant, completed the adaptation protocol, and drove through the simulated driving courses. A variety of methods was utilized for recruiting participants in an attempt to recruit a sample population similar to the actual driving population which was sampled during the field study. These recruitment methods included sending mass emails, posting fliers about the study throughout the buildings around campus, and sending targeted emails to invite specific individuals to participate. No compensation was provided to these participants who volunteered for this study though seeing the fliers or emails. This study was also allowed to be included in the Ohio University “Psychology Pool” approved research list.
Research studies included on this list are deemed acceptable for the fulfillment of the research participation requirements for the Psych101 course offered at Ohio University. Students who volunteered to participate as members of the “Psychology Pool” were granted one research credit toward the fulfillment of their course requirements as compensation for their participation. Each participant was limited to participating in the study only once. In order to participate, all subjects were required to meet three basic requirements:

- 18+ years of age
- Possess a valid driver’s license
- Have at least 2 years of driving experience

5.5 Simulator Study Data Collection

The driving simulator used in this research has the ability to collect data on up to 80 parameters at a time and at a speed of up to 60 hertz. The ability of the simulator to collect data at these rates can quickly result in data files which are too large to analyze. Therefore, the data collection parameters should be targeted in line with the purpose of the specific study. In this portion of the study, the researchers were interested in determining the ability of the driving simulator to realistically reproduce retroreflective sheeting. To do so, the field study conditions were replicated within the simulated environment for participants to drive through. The driver behavior while driving in the simulated environment was then compared to the behaviors of drivers in the field study. As such, the data collection parameters for the simulator study were selected to match the field data collection. Speed, lateral placement with respect to the lane center line, and
work zone type were collected for each participant. The data collection rate was set at 60 hertz to help ensure that any minor change in driver behavior would be captured. Upon completion of the data collection portion of this study, a total of 93 participants took part in the driving simulator study.
CHAPTER 6: SIMULATOR VALIDATION THEORY

Driving simulators can provide a very valuable tool for the study of driver behaviors and reactions to a variety of roadway types, treatments, and weather conditions. Simulators provide researchers a platform through which they can safely and efficiently conduct studies using large samples in a variety of settings in a completely controlled environment. Simulators also allow researchers to conduct studies on topics which may be prohibitively expensive or risky to participants or the public to be conducted as a field study. However, in order for these simulators to be valuable they must evoke behaviors and reactions similar to the behaviors and reactions of drivers in the field. The simulator must be validated for the type of research being performed. In a paper published in 1982, Blaauw discussed two types of validity when considering the usefulness of driving simulators in human factors driving research, physical validity and behavioral validity [28]. He defined physical validity as the ability of a simulator to replicate the physical characteristics of an actual vehicle traveling on a roadway. Physical validity is often considered in terms of the fidelity of the simulator. Behavioral validity, as the term implies, refers to the relationship between driver behavior while driving in the real world and in the simulator [28].

Harms expanded upon the idea of behavioral validity for driving simulator research and introduced absolute and relative validity [16]. She defined absolute validity as the ability of a simulator to produce behaviors which were numerically similar and relative validity as a similarity in effects, magnitude and direction, of different treatments between driving simulators and real world driving. Tornros later proposed that, in order
for a simulator to be useful for driving research, only relative validity must be achieved [18]. Since relative validity is achieved when the effect of a treatment is similar in magnitude and direction in a simulator and in the field, and human factors studies on driving behavior are typically concerned with the effect of one treatment over another, only similarity between the effects, or relative validity, is necessary for driving simulators to be useful research tools [18]. In a study conducted in 2001, Godley et al. further expanded the idea of simulator validation and stated that simulator results could still be useful so long as similarity between the driver’s dynamic reactions between field and simulator environments exists [19]. They termed this interactive relative validity and concluded that, due to unavoidable environmental differences between simulated and real world study sites the magnitude of an effect may not be similar between field and simulator studies. However, since human factors studies are concerned with the effects of treatments on behavior, if the reaction is similar between simulator and field data, simulator results can be extended to field behavior [19].
CHAPTER 7: STATISTICAL METHODOLOGY

There were several statistical comparisons to be made in this research. Difference in speed deviation from the posted work zone speed limit and vehicle placement within the lane while in the construction zone were the primary parameters considered to determine if a significant impact on driver behavior was present when traveling through work zones with the different sheeting types. Several comparisons were made between the means of the groups of data collected in the attempt to determine if significant differences in speed or lane placement existed between the sheeting types.

There are four assumptions which must be validated in order to assure statistical power when using parametric tests on sample data. The data must follow a normal distribution, the sample variances between groups must be equal, the data must be type data, and the sample observations must be independent. If any one of these assumptions are invalid for the sample data collected the robustness of the test performed and therefore the significance of the test results could be adversely affected. The magnitude of the effect of an invalid assumption on the test result varies by test and therefore should be considered specifically for each parametric test used in the analysis.

The assumptions of interval data and independence were addressed in the setup of the data collection and extraction processes. Lane placement and speed data was collected from subjects at random during the field study. When collecting data, care was taken so as to collect data without influencing the behavior of the subjects. Speed data was taken from overpasses where possible and attempts were made to remain out of the

---

1 This chapter contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
subjects’ direct line of sight when overpasses were not present. Lane placement data was collected from a tripod mounted camera in the passenger seat of the vehicle trailing the subject. This data was collected from a distance such that the subjects could not see that they were being monitored. Care was also taken to approach leading vehicles and merge with existing traffic such that no suspicion would arise from subjects due to erratic or unusual driving behavior. Extraction of the lane placement was performed beginning at a defined position with respect to the beginning of each work zone and continued at a 10 second interval for every subject providing interval data.

For the simulator validation study, the speed and land placement data was not collected from independent samples. Each participant drove through all four of the study scenarios. This violation of the independence assumption must be considered in the validation analysis.

7.1 Parametric Tests

7.1.1 Normality and Homogeneous Variance

After the data was collected and extracted, validation of the normality and variance homogeneity assumptions was required. Many tests exist to check the normality of sample data. The extracted data was plotted in a histogram to check for any outliers and provide a visual representation of the data behavior. The histogram could be used as a visual check for normality, however, visual analysis of a histogram plot was not deemed accurate enough for this analysis. A box plot was used to determine if any outliers existed within the data. A histogram could also have been used to check for outliers, however, it would not show which data point or points are the outliers. Using the
box plot the outliers were found and further analysis of these data points was performed to determine the validity of each. In this study there was one outlier found in the ASTM Type IX daytime lane placement data. Transformation of the data point was attempted. However, the data point remained an outlier and was therefore removed from the analysis so as to not adversely affect the mean and standard deviation of the remaining data.

Frequency statistics were used to determine the skewedness, the kurtosis and the corresponding standard error of both the combined speed data and the combined lane placement data. The skewedness and kurtosis scores were converted to their corresponding Z-scores using the following:

\[
Z_{skewedness} = \frac{S - 0}{SE_{skewedness}} \quad [29]
\]

\[
Z_{kurtosis} = \frac{K - 0}{SE_{kurtosis}} \quad [29]
\]

Where:

S = Value of skewedness as given from frequency statistics
K = Value of kurtosis as given from frequency statistics

\(SE_{skewedness}\) = Standard Error of skewedness as given from frequency statistics

\(SE_{kurtosis}\) = Standard Error of kurtosis as given from frequency statistics

In this research it was decided to consider the data normal if the Z-score was less than or equal to ±1.96 at a confidence level of 0.05. When the kurtosis or skewedness Z-scores were greater than ±1.96 statistical transformations were performed on the data to attempt to normalize the data. The transformations performed included:
where:

\[ x_{\text{transformed}} = \log x \quad \text{[29]} \]
\[ x_{\text{transformed}} = \sqrt{x} \quad \text{[29]} \]
\[ x_{\text{transformed}} = \frac{1}{x} \quad \text{[29]} \]

Frequency statistics were performed after each transformation and the skewedness and kurtosis Z-scores re-calculated to determine if the data was more or less normal than before the transformation.

Two final statistical tests which can be performed to determine the normality of the data are the Kolmogorov-Smirnov and Shapiro-Wilk tests. These tests compare the values of the experimental data to values that would be expected based on a normally distributed data set with the same mean and standard deviation. If the test result is not significant the experimental sample data does not significantly differ from that of a normal distribution and therefore the sample data is normal [29]. When large sample sizes are considered using this test a significant test result can be produced from small deviations from normality and therefore a significant result may be produced when the data is not non-normal enough to bias analysis. As with all of the tests for normality discussed previously, these tests alone should not be considered as ultimate when determining the normality of data. When the sample data fails tests for normality, the effect of non-normal data any parametric test performed on the data must be considered.
Bias from non-normal data in a parametric test may require the use of non-parametric tests for the analysis of the sample data.

In this research it was determined that the speed data collected was normal data based on the kurtosis Z-score. However, the lane placement, even after log, reciprocal, and square root transformations were performed, did not follow a normal distribution.

Along with normality, homogeneity of variance must also be checked and confirmed in order to guarantee the robustness of a parametric test. Lavene’s test can be used to test for the homogeneity of variances. A significant result from Lavene’s test indicates that the variances between samples are non-homogeneous. This test was selected to be run when performing the one-way ANOVA analysis. As with the Kolmogorov-Smirnov and Shapiro-Wilk tests for normality, this test can produce significant results from small deviations in variances when the sample sizes are large [29].

A second test which can be utilized to check the homogeneity of variance is the ratio test suggested by Box in 1954. This test suggests that the ratio of the larger sample variance to the smaller sample variance should be less than $\sqrt{3}$, or less that 1.73. If the ratio is 1.73 or less the variances can be considered homogeneous [29]. If the variances between samples are not homogeneous it is necessary to consider its effect on the robustness of any parametric test performed on the data and may require the use of non-parametric tests.

In this research, it was determined that, based on the ratio test that the variances of the speed data were likely homogeneous while the variances of the lane placement
were not homogeneous. Based on these findings, non-parametric tests were required to analyze the lane placement data since this data violated both the normality and homogeneous variances assumptions. The speed data however is both normal and by the ratio test the variances are assumed homogeneous. From these findings, the speed data can be analyzed using parametric tests. The tests chosen to analyze the speed data were the one-way ANOVA and the Student’s t-test. Variance homogeneity is a major factor when considering the robustness of this analysis and therefore the Lavene’s test for homogeneous variances will be performed on the data to ensure the variances are homogeneous, the tests will also be performed with the Welch’s modification to maintain statistical power should this assumption be violated.

7.1.2 Student’s t-test

The Student’s t-test was performed to compare the overall mean speed deviation between sheeting types for each time of day condition. The Students t-test is the best known and most popular method for comparing the means of two groups [30]. In this research the sample data was collected from independent populations and therefore the comparison made between sample groups must be made on a per condition basis rather than on a per participant basis [29]. The differences between the sample group means will be compared as opposed to the differences between pairs of scores [29]. This test uses the standard error of the sampling distributions to assess whether the difference between two sample means is significantly different. There was no assumption made as to how the sheeting type would affect the work zone travel speed of the participants. Since no assumption was made as to the affect the sheeting types would have on the traveled
speed, a two-tailed t-test was performed to compare the mean speed deviation and determine if a difference between speed deviations within the work zones was present. In the Student’s t-test a t-critical statistic was obtained from statistical tables based on the degrees of freedom and the type one error allowed for this analysis. The t-observed was then calculated using the equations presented below. If the t-observed statistic was greater than the t-critical value a significant difference existed in the speed deviation between sheeting types [31].

$$s_p^2 = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2} \quad [30]$$

Where:

- $n_1$ = number of samples in group 1
- $s_1^2$ = variance of group 1
- $n_2$ = number of samples in group 2
- $s_2^2$ = variance of group 2

$$t - observed = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \quad [30]$$

Where:

- $\bar{X}_1$ = average value of sample 1
- $\bar{X}_2$ = average value of sample 2

The Student’s t-test is based on the assumptions of normal data, homogeneous variances, and continuous data [29]. To keep the robustness of the test in the case of non-homogeneous variances the Welch’s modification was performed with the Student’s t-test. With Welch’s test the assumption of normality is retained, however, the assumption of homogeneous variances is no longer made [30]. The Welch’s method calculates a W-observed statistic and W-critical statistic which account for the lack of homogeneous
variances. The $W$-critical statistic is based on a Student’s $t$ distribution but utilizes adjusted degrees of freedom. The $W$-observed and degrees of freedom are calculated using the formulas presented below.

$$W - observed = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad [30]$$

With adjusted degrees of freedom:

$$df = \frac{(q_1 + q_2)^2}{q_1^2 \cdot \frac{1}{n_1 - 1} + q_2^2 \cdot \frac{1}{n_2 - 1}} \quad [30]$$

Where:

$$q_1 = \frac{s_1^2}{n_1}$$

$$q_2 = \frac{s_2^2}{n_2}$$

The Students $t$-test was utilized to compare the following:

Field Study:

Speed data:

ASTM Type IX with ASTM Type III Daytime overall

ASTM Type IX with ASTM Type III Nighttime overall

7.1.3 One Way ANOVA

A one-way ANOVA was used in this research to compare the speed deviations at different locations within the work zones between the types of sheeting. The one-way Analysis of Variance (one-way ANOVA), compares the variances of several groups of data together while controlling the type one error [29]. Using the one-way ANOVA several groups can be compared to each other in all possible comparison scenarios and still retain a type one error of $\alpha = 0.05$. The one-way ANOVA performs the comparison
between groups through the calculation of the Mean Squares Between the groups, MS_B, and the Mean Squares Within the groups, MS_W. The F-statistic for the comparison is then calculated as the ratio of the Mean Squares Between to the Mean Squares Within. This F-statistic is then compared to the F-critical statistic based on the confidence level desired in the test, the number of groups being compared, df_B, and the size of each group df_W [32]. F-critical can be determined from statistical tables using the degrees of freedom and the desired type one error [33].

\[ SS_T = \sum_{i=1}^{n} \sum_{j=1}^{p} (X_{i,j} - \bar{X})^2 \]  

Where:
- \( SS_T \) = total sum of squares
- \( n \) = number of scores
- \( p \) = number of sample groups
- \( \bar{X} \) = average value of samples observations

\[ SS_B = n_j \sum_{j=1}^{p} (\bar{X}_j - \bar{X})^2 \]  

Where:
- \( SS_B \) = sum of squares between groups
- \( \bar{X}_j \) = average value of observations in j\textsuperscript{th} group

\[ SS_W = \sum_{i=1}^{n} \sum_{j=1}^{p} (X_{i,j} - \bar{X}_j)^2 \]  

Where:
- \( SS_W \) = sum of squares within groups
- \( MS_B = \frac{SS_B}{p-1} \)  

Where:
- \( MS_B \) = mean of squares between groups
\[ MS_W = \frac{SS_W}{n-p} \quad [33] \]

Where: \( MS_W \) = mean of squares within groups

\[ F_{obs} = \frac{MS_B}{MS_W} \quad [33] \]

Where: \( F_{obs} \) = F-statistic calculated from sample observations

With degrees of freedom:

\[ df_B = p - 1 \quad [33] \]
\[ df_W = n - p \quad [33] \]

Where: \( df_B \) = degrees of freedom between groups
\( df_W \) = degrees of freedom within groups

If the one-way ANOVA produces an F-observed which is greater than the F-critical value obtained from the tables the test indicates only that there is a significant difference between some of the variances. The ANOVA does not however provide any indication as to where the significant difference exists. To determine where significant differences exist a planned comparison or a post hoc analysis of the data must be performed. A planned comparison breaks down the variance accounted for by the model into component parts. The post hoc test is performed by comparing the means of every group as in using multiple t-tests, but using stricter acceptance criteria to assure the family wise error rate, the type 1 error, does not exceed \( \alpha = 0.05 \) [29]. The difference between the two options for determining where the difference exists is likened to the difference between one- and two-tailed tests [29]. The planned comparison, like a one-tailed test, is performed when a specific hypothesis is being tested. The post hoc test, like
a two-tailed test, is utilized when the hypothesis is that there is a difference between the groups but no specific guess as to what kind of difference is made [29]. The decision as to which type of test will be run must be made prior to data collection. For this research the post hoc test procedure was selected since the hypothesis was there would be a difference between the sheeting types.

When deciding which post hoc procedure to perform three things were considered: control of the Type I error, control of the Type II error, and the reliability of the test when the test assumptions of the ANOVA are violated. In this research the sample sizes varied and the total number of comparisons is low. Based on these criteria, the Gabriel and Games-Howell post hoc procedures were selected [29]. The Games-Howell post hoc procedure was selected in case the variances of the speed data proved to be non-homogeneous in the Lavene’s test [29]. Gabriel’s pair wise test procedure was selected to be performed because its power is retained when sample sizes vary [29].

To account for the possibility of non-homogeneous variances in the speed data which failed to be indicated by Box’s ratio test of variances the Welch’s modification procedure was performed with the ANOVA. This procedure applies a modification to the data and produces a new F-critical and new degrees of freedom from the data to allow a one-way ANOVA to produce robust results for data which violates the homogeneous variances assumption. [30]

\[ w_j = \frac{n_j}{s_j^2} \]  

[30]

Where:  
\( n_j \) = number of samples in a particular group  
\( s_j^2 \) = variance of a particular group
\[ U = \sum_{j=1}^{k} w_j \]  

Where: \( K = \text{number of groups} \)  

\[ \bar{X} = \frac{1}{u} \sum_{j=1}^{k} w_j \bar{X}_j \]  

Where: \( \bar{X}_j = \text{average sample value within a particular group} \)  

\[ A = \frac{1}{K-1} \sum_{j=1}^{k} w_j (\bar{X}_j - \bar{X})^2 \]  

\[ B = \frac{2(K-2)}{K^2 - 1} \sum_{j=1}^{k} \frac{(1-w_j)^2}{n_j-1} \]  

\[ F_w = \frac{A}{1+B} \]  

With Degrees of freedom:  

\[ df_1 = K - 1 \]  

\[ df_2 = \frac{2(K-2)}{3B} \]
The one-way ANOVA was utilized for the following analyses:

Field Study:

*Speed data: (daytime and nighttime)*

- ASTM Type IX entering with ASTM Type III entering
- ASTM Type IX middle with ASTM Type III middle
- ASTM Type IX exiting with ASTM Type III exiting
- ASTM Type IX Entering with Middle with Exiting
- ASTM Type III Entering with Middle with Exiting

Validation Study:

*Speed data:*

*Absolute validity: Overall Average (daytime and nighttime)*

- ASTM Type IX Simulator with ASTM Type IX Field
- ASTM Type III Simulator with ASTM Type III Field

*Absolute validity: ASTM Type IX (daytime and nighttime)*

- ASTM Type IX entering Simulator with ASTM Type IX entering Field
- ASTM Type IX middle Simulator with ASTM Type IX middle Field
- ASTM Type IX exiting Simulator with ASTM Type IX exiting Field

*Absolute validity: ASTM Type III (daytime and nighttime)*

- ASTM Type III entering Simulator with ASTM Type III entering Field
- ASTM Type III middle Simulator with ASTM Type III middle Field
- ASTM Type III exiting Simulator with ASTM Type III exiting Field
Interactive validity: ASTM Type IX (ANOVA Trend) (daytime and nighttime)

Entering-Middle Sim with Entering-Middle Field
Middle-Exiting Sim with Middle-Exiting Field

Interactive validity: ASTM Type III (ANOVA Trend) (daytime and nighttime)

Entering-Middle Sim with Entering-Middle Field
Middle-Exiting Sim with Middle-Exiting Field

7.1.4 One-Sample t-test

The one sample t-test was performed to determine if relative validity existed between the speed collected from the simulator and the field studies by time of day and sheeting type. This test is used to compare sample data to a specific value [34]. In this test, the value, \( \mu_0 \) was considered as the average difference in travelled speed between the field and simulator study at one location within the work zone. The one-sample t-test was utilized to determine if the difference in speed between the field and simulator studies was statistically similar when grouped by time of day and sheeting. This parametric test relies on the assumptions of normal data, homogeneous data, and independent data. The combined data by time of day and sheeting type were normal and, based on the Box analysis, the ratio of variances was less than 1.73 for each group indicating the assumption of homogeneous variances was satisfied. The independent data assumption was maintained since the simulator speeds were compared with the field study data and not with the other simulator speed data collected from each individual.

The t-critical value is obtained based on the degrees of freedom and the type I error determined for the test. The one-sample t-test calculated statistic is calculated using
the equation presented below. This value is then compared with the t-critical value. If the $t_0$ is greater than t-critical, the null hypothesis is rejected indicating the sample population mean does not equal the specified test value.

$$t_0 = \frac{\bar{y} - \mu_0}{S/\sqrt{n}}$$  \[34\]

Where:

$\bar{y} = \text{sample mean}$

$\mu_0 = \text{specified value (Difference between field and simulator speeds at a location)}$

$S = \text{sample standard deviation}$

$n = \text{sample size}$

With degrees of freedom:

$$df = n-1$$

The one sample t-test was utilized for the following analyses:

**Validation Study:**

**Speed data:**

*Relative validity: ASTM Type IX (daytime and nighttime)*

Actual Sim Speed with Exp Sim Speed Entering

Actual Sim Speed with Exp Sim Speed Middle

Actual Sim Speed with Exp Sim Speed Exiting
Relative validity: ASTM Type III (daytime and nighttime)

- Actual Sim Speed with Exp Sim Speed Entering
- Actual Sim Speed with Exp Sim Speed Middle
- Actual Sim Speed with Exp Sim Speed Exiting

7.1.5 Paired-samples t-test

The paired-samples t-test was utilized to determine if a significant difference in speed deviation was present between drivers traveling through the ASTM Type IX and ASTM Type III simulated work zones. Since each simulator study participant drove through both the ASTM Type IX and ASTM Type IX work zones the speed data collected was not independent, but rather, repeated measures data. The dataset therefore violated the independent data assumption of parametric tests. Since each participant drove through each sheeting type, the data set collected is in matched pairs. The paired t-test allows us to test if the mean speeds are equal between each work zone. The assumptions normal data and homogeneous variances must still be met to maintain power with the paired-samples t-test. The simulator speed data was determined to be normal based on the kurtosis and skewness z-scores and the Box ratio indicated the variances were homogeneous.

The paired-samples t-test first determined the difference between the matched pairs of data and then calculated the average difference in matched pairs [30]. The average difference, $\bar{D}$, is the estimation of the average difference in means between the two treatments. This average difference is then used to calculate the t-statistic which is in turn compared to the t-critical value which corresponds to the type one error rate selected
for the test. For this test a type one error rate of 0.05 was selected. The average difference, $\bar{D}$, is computed using the following:

$$\bar{D} = \frac{1}{n} \sum D_i$$  \[30\]

$$D_i = X_{i1} - X_{i2}$$  \[30\]

Where:

$X_{i1} =$ The mean of participant “i” in treatment one

$X_{i2} =$ The mean of participant “i” in treatment two

$n =$ Sample size

Under the paired-samples t-test, conclusions made about $\bar{D}$ are equivalent to conclusions made from the difference in means of two groups \[30\]. The calculated $\bar{D}$ is used to calculate the t-statistic based on the sample variance, and the sample size using the following equation:

$$t = \frac{\sqrt{n} \cdot \bar{D}}{s_D}$$  \[30\]

Where:

$\bar{D} =$ average difference between treatments

$$s_D = \sqrt{\frac{1}{n-1} \sum (D_i - \bar{D})^2}$$

With degrees of freedom:

$$df = n-1$$
The paired-samples t-test was utilized for the following analyses:

Simulator Study:

*Speed data:*

ASTM Type IX with ASTM Type III Daytime overall

ASTM Type IX with ASTM Type III Nighttime overall

### 7.2 Non-Parametric Tests

The robustness of the results of parametric tests relies heavily on whether the data follows the assumptions of normal data, homogeneity of variance within the data, type data and independent samples. While the last 2 criteria listed can be controlled by the experiment setup and data extraction practices, the first two criteria cannot be strictly controlled. The degree to which violating one of the criteria will affect the statistical results varies depending on the test being performed. When the effect of violating these criteria is larger than deemed acceptable for the use of a parametric test for analysis a non-parametric, or assumption free test can be used to analyze the data. Non-parametric tests work by ranking the data with the lowest rank being assigned to the lowest data score and the highest to the greatest data score. The ranks are then analyzed rather than the data itself [29].

Since the analysis is performed on the ranks of the data rather than the data itself many believe that the non-parametric tests have less power than parametric tests. Statistical power is lost when the data is ranked since the ranking provides no information as to the magnitude of the difference between scores. However, for parametric tests to maintain statistical power the assumptions of homogeneous variance and normality must
be met. For data that is normal and has homogeneous variances, the parametric tests have
greater statistical power, while when the normality and variance assumptions are violated
the power the non-parametric test is greater than that of the parametric test [29].

7.2.1 Mann-Whitney U

The lane placement data collected in this research violated both the normality and
homogeneous variance assumptions and therefore parametric tests would not provide an
accurate analysis of the data. Analysis of the lane placement data included a comparison
of the ASTM Type IX sheeting data with the ASTM Type III sheeting data for the
nighttime and daytime driving conditions. This analysis can be performed with one
comparison of means for each driving condition.

In this research the difference in means between the sheeting types were
compared using the Mann-Whitney U comparison of means. The goal of the study was to
determine if there was a significant difference in lane placement of the vehicles in the
travel lane. Data was collected both during daytime driving conditions and nighttime
driving conditions. Since the Student’s t-test performed on the speed deviation data
indicated a significant difference between nighttime and daytime speed deviations it was
assumed that the driving behaviors and driver populations varied between the different
conditions. Because of this, the lane placement of vehicles was only compared within the
daytime and nighttime groupings and not between daytime and nighttime conditions. A
direct comparison with the Mann-Whitney U test was chosen rather than the Kruskal-
Wallis comparison of means due there being only two groups within each driving
condition.
The Mann-Whitney U test, like other nonparametric tests, works by combining the sample data to be analyzed and ranking them from smallest to largest giving no preference to group. The ranks are then separated into their respective groups and summed. The U-statistic is then calculated using the sample sizes and the sum of the ranks of the smaller sample. To determine if the test statistic is significant the mean and standard error are calculated and, since the sample sizes in this research are sufficiently large, then used to calculate the corresponding z-score [33]. Using an $\alpha = 0.05$ and a two tailed analysis, if the calculated z-score is greater than $\pm 1.96$ when considering its absolute value, the U-statistic is significant at $p < 0.05$ [33].

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - W$$  \[33\]

Where:

- $n_1$ = sample size of group 1, the smaller sample
- $n_2$ = sample size of group 2
- $W$ = Sum of the ranks in group 1

$$Z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}}$$  \[33\]

Where:

- $U$ = U-statistic calculated from above
- $n_1$ = sample size of group 1, the smaller sample
- $n_2$ = sample size of group 2
The Mann-Whitney U test was utilized for the following analyses:

**Field Study:**

*Lane Placement* (Mann-Whitney U)

- ASTM Type IX nighttime with ASTM Type III nighttime
- ASTM Type IX daytime with ASTM Type III daytime

**Validation Study:**

*Lane Placement:*

*Absolute validity:* Overall Average (daytime and nighttime)

- ASTM Type IX Simulator with ASTM Type IX Field
- ASTM Type III Simulator with ASTM Type III Field

*Relative validity:* Overall Average (daytime and nighttime)

- Δ ASTM Type IX with Δ ASTM Type III

*Interactive validity:* Overall Average (daytime and nighttime)

- Δ Simulator with Δ Field

**7.2.2 Kruskal-Wallis**

The Kruskal-Wallis test is the non-parametric equivalent of the One-way ANOVA [29]. The Kruskal-Wallis test allows for the comparison between several independent groups of data while controlling the type I error rate. The lane placement data collected in this study failed to satisfy both the homogeneous variances and the normal data assumptions of parametric tests. The One-way ANOVA is fairly robust to violations of these assumptions when equal sample sizes are being considered. However, in this study the sample sizes are different. Due to the violations of the basic assumptions
of the One-way ANOVA, and the different sample sizes, the Kruskal-Wallis non-parametric test will provide a more powerful analysis of the lane placement data.

The Kruskal-Wallis test was utilized to test the absolute validation of lane placement between the simulator and field studies. This test, like the Mann-Whitney U test, is based on ranked data. The analysis is performed by combining the data to be analyzed and ranking it from lowest to highest with no consideration for the group from which the data came [29]. Once ranked, the data is re-sorted into its original groups and the ranks of each group are summed. From this sum of ranks the H-statistic is calculated as shown below. If the H-calculated statistic is greater than the H-critical statistic, as determined from the type I error level and degrees of freedom in the test, than a significant difference exists in at least one of the experiment groups.

\[
H = \frac{12}{N(N+1)} \times \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N + 1) \quad [29]
\]

Where:

\( R_i = \text{Sum of ranks for each group} \)

\( N = \text{Total sample size} \)

\( n_i = \text{Sample size within a group} \)

With degrees of freedom:

\( df = k-1 \)

Where:

\( k = \text{Number of groups in the test} \)

As with the One-way ANOVA test, the Kruskal-Wallis test only indicates that a significant difference exists between one or more of the groups, it does not indicate
where the difference exists. To determine where the difference exists, a post-hoc analysis must be performed. The post-hoc analysis for the Kruskal-Wallis is performed using the Mann-Whitney U analysis. In order to maintain an acceptable type I error the number of total comparisons should be minimized through targeted comparisons between specific groups.

The Kruskal-Wallis test was utilized for the following analyses:

Validation Study:

Lane Placement:

Absolute validity: Overall Average (daytime and nighttime)

Simulator Overall with Field Overall

7.2.3 Wilcoxon Signed Rank Test

The lane placement data collected from the simulator study violated both the normal data and the homogeneous variances assumptions which are fundamental to the parametric tests. Because of this a non-parametric test was required. However, based on the design of the study, the data also violated the independent data assumption. Due to this violation of independent data, the Mann-Whitney U and Kruskal-Wallace non-parametric tests could not be performed to compare the mean lane placement between the ASTM Type IX and ASTM Type III sheeting. To accommodate the violations of the independent data assumptions, the Wilcoxon signed rank test was performed on the simulator lane placement data.

The Wilcoxon signed rank test, like other non-parametric tests is conducted based on some ranking of the experimental data [30]. In the case of the Wilcoxon signed rank
test the rank of the difference between the two treatments per participant, \( D_i \). Once the differences are calculated any \( D_i = 0 \) is removed from the analysis and the absolute values of the remaining differences are ranked. If any of the \( D_i \) values are the same, their rank is computed as the average of the corresponding ranks. These ranks are then given the sign of their original difference. The \( W \)-statistic is then calculated based on the sum of the ranks and compared to the corresponding \( W \)-critical based on the selected type one error rate. In this analysis a type one error rate of 0.05 was selected [30]. If the calculated \( W \)-statistic is less than the \( W \)-critical the null hypothesis is rejected and the alternative hypothesis is accepted. The \( W \)-statistic is calculated using the following equations for a sample size of 40 or greater:

For ranks with ties:  
\[
W = \frac{\sum R_i}{\sqrt{\sum R_i^2}} \quad [30]
\]

Where:

\( R_i = \) Individual ranks of the non-zero differences

For ranks with no ties:  
\[
W = \frac{\sqrt[6]{\sum R_i}}{\sqrt{n(n+1)(2n+1)}} \quad [30]
\]

Where:

\( R_i = \) Individual ranks of the non-zero differences

\( n = \) number of non-zero differences
The Wilcoxon Signed Rank test was utilized for the following analyses:

**Simulator Study:**

*Lane placement data:*

- ASTM Type IX with ASTM Type III Daytime overall
- ASTM Type IX with ASTM Type III Nighttime overall

### 7.2.4 Chi-Squared test

In order to make the comparisons of the field test driver behaviors between Illinois and Ohio drivers to compare determine the effects of the ASTM Type IX and ASTM Type III sheeting types, the driving behaviors of the Ohio and Illinois drivers should be similar. When analyzing the data from the simulator it was also on importance to know how well the simulator population matched the demographics of the general driving population, most specifically in terms of driver age. The chi-squared analysis was utilized to determine the extent to which these populations were similar.

The chi-squared test is an analysis to compare nominal data comparing an observed value with an expected value for the same parameter to determine if the observed and expected values are similar [27]. For this research the chi-squared test was performed at a 0.05 type one error rate, or a level of confidence of 95 percent. The chi-squared statistic is calculated and compared to a critical value based on the type one error rate selected and the degrees of freedom of the test. The chi-squared statistic is calculated as follows:

\[
\chi^2 = \sum \frac{(O-E)^2}{E} \quad [27]
\]
Where:

\[ O = \text{observed frequency} \]
\[ E = \text{expected frequency} \]

With degrees of freedom:

\[ df = n-1 \]

Where:

\[ n = \text{number of observations} \]

7.3 Practical Significance

The statistical tests performed in this research indicated whether the differences in comparisons made were statistically significant. However, a difference being statistically significant indicates only that the probability of the difference between the experimental data and the expected values computed from a given statistical distribution occurring due to chance is less than the significance level, in this research \( \alpha = 0.05 \) [29]. Statistical significance is based on the standard error of the sample which can be controlled by sample size. Large sample sizes lower the standard error and will correspondingly lower the threshold for considering differences to be significant. Conversely, a small sample size can cause a large difference between groups to be statistically insignificant when in reality the difference may be practically significant [30].

One method provided to consider the practical significance of a result is through the calculation of the effect size. By definition the effect size is the degree to which a phenomenon exists [30]. In this research, the phenomenon would be the ASTM Type IX sheeting caused statistically significant differences in lane placement and speed deviation.
within work zones when compared to the ASTM Type III sheeting. The effect size calculated is a measure of the number of standard deviations the difference between the groups is from the null hypothesis [27]. The effect size was calculated for each of the tests performed based on the parameters provided in each test.

For the Student’s T-test:

\[ r = \frac{t^2}{t^2 + df} \]  \[29\]

Where:
- \( r \) = effect size
- \( t \) = t-observed value
- \( df \) = degrees of freedom of the t-test

For the ANOVA:

\[ r = \sqrt{\frac{SS_B}{SS_T}} \]  \[29\]

Where:
- \( r \) = effect size
- \( SS_B \) = sum of squares between groups
- \( SS_T \) = total sum of squares

For the Mann-Whitney U:

\[ r = \frac{Z}{\sqrt{N}} \]  \[29\]

Where:
- \( r \) = effect size
- \( Z \) = z-score calculated from analysis
- \( N \) = total sample size used in the analysis
Based on standards presented by Cohen, the practical significance, or actual difference of the comparisons made, is as follows:

- $r = 0.20 - 0.49$  Small Effect
- $r = 0.50 - 0.79$  Medium Effect
- $r = 0.80 +$  Large Effect
CHAPTER 8: RESULTS

The purpose of this research was to compare work zones utilizing ASTM Type IX sheeting with those using ASTM Type III sheeting on construction drums to determine if a significant difference in driver behavior and therefore difference in safety existed. A comparative parallel experimental design was used for this study to compare driver behavior between work zones using ASTM Type IX sheeting with those using ASTM Type III sheeting on the construction drums utilized for a lane closure. The work zones utilized for data collection all exhibited one a one lane closure, lacked ambient lighting from overhead street lights or businesses, and were of the freeway/interstate functional class. Lane placement and speed data were collected and analyzed based on the type of sheeting used within the work zone. The second phase of this research included the analysis of ASTM Type IX and ASTM Type III sheeting through the use of a state-of-the-art driving simulator. These results were analyzed to determine the extent to which the driving simulator can reproduce the sheeting types and compared with the field study results in a simulator validation study.

8.1 Field Study

Field data was collected at a total of 4 work zones. The ASTM Type IX data was collected from one work zone located on Interstate 72 near Champaign, Illinois. The ASTM III data was collected from three separate sites in southern Ohio. In order to ensure the results of the study were due to the differences in sheeting type and not due to differences in driver behaviors between the states the fatal crash rate per 100 million

---

1 This chapter, introduction and section 8.1, contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
vehicle miles travelled for each state was compared using the chi-squared analysis. Fatal crash rates for Ohio and Illinois were retrieved from the most recent data produced by the Federal Highway Administration (FHWA). According to the FHWA fatality rates for 2008, Ohio drivers had a fatal crash rate of 1.10 fatalities per 100 million vehicle miles travelled (VMT) and Illinois drivers had a fatality rate of 0.98 fatalities per 100 million vehicle miles travelled [35]. The chi-squared analysis indicated that, at a 95 percent level of confidence, the fatality rates were statistically similar. These results indicate that the driver behaviors are similar between Ohio and Illinois drivers. The results of the chi-squared analysis of fatality rates are presented in table 4.

<table>
<thead>
<tr>
<th>State</th>
<th>Crash Rate per 100 Million VMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohio</td>
<td>1.10</td>
</tr>
<tr>
<td>Illinois</td>
<td>0.98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>df</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X^2$-Calc</td>
<td>0.013</td>
</tr>
<tr>
<td>$X^2$-Crit</td>
<td>3.84</td>
</tr>
<tr>
<td>Result: Accept Null: OH = IL</td>
<td></td>
</tr>
</tbody>
</table>

8.1.1 Lane Placement

Lane placement data was collected for each sheeting type during both daytime and nighttime driving conditions. Approximately 100 samples were collected for each driving condition to ensure ample sample size for statistical tests performed with a type one error equal to 0.05. Lane placement data was extracted based on the vehicles position with respect to the lane centerline while traveling through the work zone. It was
determined, through the use of a one way ANOVA that a data extraction interval of 10 seconds would provide for a reasonable data extraction time frame without significantly affecting accuracy of the lane placement data.

The comparison was made between the sheeting types based on the time of day. Daytime conditions were compared together as well as the nighttime conditions. However, the time of day conditions were not combined or compared between groups based on the reasoning that the driver population differs between the nighttime and daytime driving conditions. Therefore a comparison between time-of-day groups would not compare the difference due to sheeting types but rather the differences between driver populations.

A comparison of the lane placement between vehicles traveling through work zones utilizing ASTM Type IX sheeting and that of vehicles traveling through work zones utilizing ASTM Type III sheeting on the construction drums was performed through a two-tailed Mann-Whitney U test at a 95 percent confidence level, or $\alpha = 0.05$. The null hypothesis for each of these comparisons states there is no difference in lane placement between sheeting types. The alternative hypothesis stated that there was a difference in lane placement between the sheeting types.

The Mann Whitney U test determined the calculated $z$–statistic was greater than the critical $z$-score for both time of day groups. From these results it can be determined that, at a 95 percent confidence level, there was a statistically significant difference between lane placement between work zones utilizing ASTM Type IX and ASTM Type III sheeting. In order to standardize the results and determine the practical significance of
the comparison the effect size was calculated. For the lane placement data, the effect size was calculated to be 0.52 for the daytime driving conditions and 0.67 for the nighttime driving conditions. The results from the Mann-Whitney U test are presented in table 5.

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Variable</th>
<th>ASTM Type IX</th>
<th>ASTM Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample Size</td>
<td>109</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>Mean of Ranks</td>
<td>138.19</td>
<td>74.31</td>
</tr>
<tr>
<td></td>
<td>Sum of Ranks</td>
<td>15062.5</td>
<td>7728.5</td>
</tr>
<tr>
<td></td>
<td>Mann Whiney U</td>
<td>2268.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z-score</td>
<td>-7.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effect Size</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Result:</td>
<td>Reject Null:</td>
<td></td>
</tr>
<tr>
<td>Daytime</td>
<td></td>
<td>µDG ≠ µHI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sample Size</td>
<td>119</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Mean of Ranks</td>
<td>146.14</td>
<td>62.32</td>
</tr>
<tr>
<td></td>
<td>Sum of Ranks</td>
<td>17390.5</td>
<td>6045.5</td>
</tr>
<tr>
<td></td>
<td>Mann Whiney U</td>
<td>1292.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z-score</td>
<td>-9.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effect Size</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Result:</td>
<td>Reject Null:</td>
<td></td>
</tr>
<tr>
<td>Nighttime</td>
<td></td>
<td>µDG ≠ µHI</td>
<td></td>
</tr>
</tbody>
</table>

Based on the effect sizes presented by Cohen, the ASTM Type IX sheeting caused a medium effect in vehicle lane placement when compared to the ASTM Type III sheeting.

Upon completing the analysis of the lane placement in terms of average placement with respect to the centerline, the standard deviation for the lane placement
data for each type of sheeting and time-of-day condition was calculated. Previous research performed by Taylor et al. determined that lateral lane placement standard deviation could be directly related to crash rates, at least on horizontal curves [37]. Therefore, the standard deviation of the lane placement for each type of sheeting was compared within time-of-day conditions using the chi-squared test. The results indicate that there was not a significant difference in lane placement standard deviation. The results of the chi-squared analysis are presented in table 6.

Table 6: Chi-squared analysis of lateral lane placement standard deviation

<table>
<thead>
<tr>
<th></th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std. Dev. ASTM Type IX</td>
<td>0.297</td>
<td>0.337</td>
</tr>
<tr>
<td>Std. Dev. ASTM Type III</td>
<td>0.451</td>
<td>0.337</td>
</tr>
<tr>
<td>df</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>X²-Calc</td>
<td>0.079</td>
<td>0.000</td>
</tr>
<tr>
<td>X²-Crit</td>
<td>3.84</td>
<td>3.84</td>
</tr>
<tr>
<td>Result:</td>
<td>Accept</td>
<td>Accept</td>
</tr>
<tr>
<td>Null:</td>
<td>DG = HI</td>
<td>DG = HI</td>
</tr>
</tbody>
</table>

8.1.2 Speed

Speed data was collected at three locations throughout the work zones, as vehicles entered the work zone, at the middle of the work zone, and as vehicles exited the work zone, during both daytime and nighttime driving conditions in work zones with each sheeting type. The work zones utilized for this research had differing posted work zone speed limits. To account for this the deviation from the posted speed limit was compared rather than the actual traveled speed. Approximately 100 sample speeds were collected at
each location based on the sample size required to detect a one mile per hour difference in speed at a 95 percent level of confidence, $\alpha = 0.05$.

The objective of this research was to determine if differences in driver behavior existed between work zones utilizing ASTM Type IX sheeting and those utilizing ASTM Type III sheeting on construction drums. Since the objective was to determine if differences existed between the sheeting types the data in this research was compared only within the time of day conditions and not between the condition groupings when comparing speeds by location within the work zone. This was done based on reasoning that the sample population of drivers would differ between time of day conditions and therefore any comparison of speeds between time of day conditions would provide information as to differences between populations driving behaviors and not differences due to the sheeting types.

Comparisons of speed data were performed between the overall ASTM Type III and ASTM Type IX sheeting by driving condition, as well as ASTM Type III with ASTM Type IX at each separate location within the work zone. The comparison of the overall speed data was performed using a two-tailed Student’s t-test with a level of confidence of 95 percent. The null hypothesis for these comparisons stated that there was no difference in speed between the different sheeting types. The alternate hypothesis stated there was a difference between the speeds traveled through the work zones with the different sheeting types. The two tailed Students t-test determined the calculated t-statistic was greater than the critical t-statistic for both the daytime and nighttime driving conditions. Based on this result, the null hypothesis was rejected indicating a statistically
significant difference between the speed deviations from the posted speed limit between sheeting types exists.

Statistical significance can be manipulated based on the sample size used for analysis, large sample sizes can cause very small actual differences to be considered statistically significant and small sample sizes can conversely cause large actual differences to be deemed non-statistically significant. To determine the actual significance of the statistical comparison the effect size was calculated for the differences in speed. The effect size for the comparison of the overall ASTM Type III speed data with the overall ASTM Type IX sheeting was 0.55. Based on the guidelines presented by Cohen, the sheeting type difference caused a medium effect on deviation from the posted speed limit within the work zones. The statistical results from the comparison of the overall speeds are presented in table 7.
Table 7: Overall Speed Deviation ASTM Type III and ASTM Type IX

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime</th>
<th>Nighttime</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASTM Type IX</td>
<td>ASTM Type III</td>
<td>ASTM Type IX</td>
<td>ASTM Type III</td>
</tr>
<tr>
<td>Sample Size</td>
<td>100</td>
<td>97</td>
<td>99</td>
<td>97</td>
</tr>
<tr>
<td>Mean (MPH)</td>
<td>2.955</td>
<td>-3.919</td>
<td>1.723</td>
<td>-3.433</td>
</tr>
<tr>
<td>Std Deviation (MPH)</td>
<td>2.08</td>
<td>0.45</td>
<td>1.80</td>
<td>0.56</td>
</tr>
<tr>
<td>Std Error</td>
<td>1.2</td>
<td>0.26</td>
<td>1.042</td>
<td>0.322</td>
</tr>
<tr>
<td>Mean Difference</td>
<td>6.874</td>
<td>5.157</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std Error of Difference</td>
<td>1.228</td>
<td>1.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>196</td>
<td>195</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t-calculated</td>
<td>5.597</td>
<td>4.729</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t-critical</td>
<td>1.96</td>
<td>1.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect Size</td>
<td>0.89</td>
<td>0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Result:</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results presented in table 6 indicate a significant difference in the mean difference between traveled speeds and the posted speed limits. The difference is smaller in work zones utilizing ASTM Type IX sheeting and the positive difference indicates the vehicles were traveling at speed less than the posted speed limit. However, it is also apparent in the table that the standard deviation of the difference in travelled speeds is three to four times higher in the ASTM Type IX work zone than it is in the ASTM Type III work zone.

The standard deviation of the differences in speeds were then compared with a chi-squared analysis at a 95 percent level of confidence to determine if they were
significantly different within time-of-day condition between the sheeting types. The analysis indicates that the standard deviation of the daytime speed differences is significantly different with the ASTM Type IX standard deviation being significantly higher than the ASTM Type III. During nighttime driving conditions the standard deviations are not significantly different. The results of the chi-squared analysis are presented in Table 8.

Table 8: Chi-squared analysis of difference in speed standard deviations

<table>
<thead>
<tr>
<th></th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std. Dev. ASTM Type IX</td>
<td>2.08</td>
<td>1.80</td>
</tr>
<tr>
<td>Std. Dev. ASTM Type III</td>
<td>0.45</td>
<td>0.56</td>
</tr>
<tr>
<td>df</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$X^2$-Calc</td>
<td>5.90</td>
<td>2.75</td>
</tr>
<tr>
<td>$X^2$-Crit</td>
<td>3.84</td>
<td>3.84</td>
</tr>
<tr>
<td>Result: Null: DG ≠ HI</td>
<td>Reject</td>
<td>Accept</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Null: DG = HI</td>
</tr>
</tbody>
</table>

The speeds at each location within the work zone were then analyzed separately. Analysis was performed on the pairs as separated out by location and time of day conditions. To keep statistical power this test was performed using a one-way ANOVA. Lavene’s test was performed coincidently with the one-way ANOVA to account for any possible non-homogeneous variances. The results of the Lavene’s test indicated the variances were not homogeneous when considering the speed differences by work zone location. To maintain statistical power in the ANOVA with non-homogeneous variances the Welch’s modification to the ANOVA was used. The F-statistic and degrees of
freedom reported therefore, are those associated with the Welch’s modification. The null hypothesis the one way ANOVA comparison was that as there is no difference in speed variation between the ASTM Type IX and ASTM Type III groups. The ANOVA analysis indicated there was a significant difference between the ASTM Type IX and ASTM Type III sheeting speed data. The effect size of the ANOVA comparison was 0.59 indicating the ASTM Type IX sheeting had a medium practical effect on the deviation between the traveled speed and posted work zone speed limits when compared to ASTM Type III sheeting. The results of the one-way ANOVA are presented in table 9.

Table 9: Results of the ANOVA analysis of speed deviation from posted speed limits

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F-calc</th>
<th>F-crit (p &lt; 0.05)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>12725.85</td>
<td>11</td>
<td>1156.90</td>
<td>62.63</td>
<td>1.79</td>
<td>Reject Null: ( \mu_DG \neq \mu_{HI} ) E.S. = 0.59</td>
</tr>
<tr>
<td>Within Groups</td>
<td>23424.78</td>
<td>1189</td>
<td>19.70</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To determine where the significant difference or differences were present, post hoc analyses were performed. The Gabriel and Games-Howell post hoc analyses were selected for this analysis with a stated null hypothesis that the mean differences in speed from the posted speed limit in the ASTM Type IX sheeting and the ASTM Type III sheeting were equal. Based on the results of the Lavene’s test, the results reported are those from the Games-Howell post hoc since it retains statistical power when the assumption of variance homogeneity is violated. The Games-Howell post hoc indicated a
statistically significant difference at all locations within the work zones for both time of day conditions. The results of the Games-Howell are presented in table 10.

Table 10: Games-Howell post hoc analysis of speed deviation

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference (MPH)</th>
<th>Standard Error</th>
<th>95percent LOC Lower Bound</th>
<th>95percent LOC Upper Bound</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime Entering Work Zone HI vs. DG</td>
<td>5.07</td>
<td>0.69</td>
<td>2.80</td>
<td>7.36</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
<tr>
<td>Nighttime Entering Work Zone HI vs. DG</td>
<td>5.58</td>
<td>0.61</td>
<td>3.45</td>
<td>7.61</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
<tr>
<td>Daytime Middle Work Zone HI vs. DG</td>
<td>8.29</td>
<td>0.57</td>
<td>6.41</td>
<td>10.18</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
<tr>
<td>Nighttime Middle Work Zone HI vs. DG</td>
<td>3.47</td>
<td>0.61</td>
<td>1.46</td>
<td>5.47</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
<tr>
<td>Daytime Exiting Work Zone HI vs. DG</td>
<td>7.28</td>
<td>0.68</td>
<td>5.03</td>
<td>9.53</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
<tr>
<td>Nighttime Exiting Work Zone HI vs. DG</td>
<td>6.42</td>
<td>0.61</td>
<td>4.40</td>
<td>8.45</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
</tbody>
</table>

8.2 Simulator Study

A total of 93 subjects participated in this driving simulator portion of this research. Of those, 59, or 63.4 percent, were male and 34, or 36.63 percent, were female. As might be expected when considering the main source of subjects being a college
campus, 72 percent of participants were 16-20 years old and another 16.1 percent of subjects were 21-25 years old. A majority of the subjects spend a total of 0.5-1.0 hours driving to work or school each day and typically commute 10-20 miles round trip. A summary of the subject ages is provided in figure 10.

![Figure 10. Frequency by age group](chart)

The sample population in the simulator study was compared to the overall driving population to determine how well the simulator population matched the actual driving population. The expected number of participants in each age group was calculated based the proportions of licensed drivers in each age category as determined from the Federal Highway Administration statistics [36]. A chi-squared goodness-of-fit test was performed, at type one error rate of 0.05 or 95 percent level of confidence, to determine how well the simulator population represented actual driving population. The chi-squared analysis is presented in table 11.
Table 11: Chi-Squared goodness-of-fit analysis

<table>
<thead>
<tr>
<th>Age</th>
<th>Observed</th>
<th>Expected</th>
<th>$X^2$-Calc</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-20</td>
<td>67</td>
<td>9</td>
<td>348.59</td>
</tr>
<tr>
<td>21-25</td>
<td>15</td>
<td>9</td>
<td>3.28</td>
</tr>
<tr>
<td>26-35</td>
<td>2</td>
<td>18</td>
<td>14.16</td>
</tr>
<tr>
<td>46-60</td>
<td>3</td>
<td>34</td>
<td>27.79</td>
</tr>
<tr>
<td>61-70</td>
<td>3</td>
<td>14</td>
<td>8.85</td>
</tr>
<tr>
<td>71-80</td>
<td>3</td>
<td>8</td>
<td>3.48</td>
</tr>
<tr>
<td>Total</td>
<td>93</td>
<td>93</td>
<td>406.15</td>
</tr>
</tbody>
</table>

$X^2$-Crit ($\alpha = 0.05$) = 116

Result: Reject Null: sim $\neq$ actual

The results of the chi-squared goodness-of-fit analysis indicate that, at a 95 percent level of confidence, the simulator sample population did not accurately represent the actual driving population. Based on the analysis, the 16-20 year old driver age group was heavily overrepresented in the study. However, this age group is also overrepresented in terms of fatal crashes indicating it is a high risk driver age group. The results of a National Highway Traffic Safety Administration report on fatal crashes involving young drivers indicated that drivers aged 16-20 years old accounted for only six percent of total licensed drivers in 2007 but represented 19 percent of all fatal crashes [37]. Therefore the overrepresentation of younger drivers in the simulator study population can be considered a worst case scenario in regards to driver behavior.

The results of the simulator study were analyzed to determine if a significant difference in driver behavior existed between the simulated work zones utilizing drums
with ASTM Type IX and ASTM Type III sheeting. Similar to the field study analysis, difference in travel speed from the posted speed limit and lateral lane position with respect to the lane centerline were used as the analysis parameters. These results were then also compared with those of the field study to determine if the simulator could adequately reproduce the work zone drum sheeting types. Results similar to the field study, i.e. significant differences in lane placement with ASTM Type IX lateral placement further from the work zone, and significant differences in difference in travel speed from the posted work zone speed limit, with ASTM Type IX speeds being closer to the posted speed limit, would indicate that the simulated environment is able to adequately simulate the sheeting types.

8.2.1 Lane Placement

Lane placement data was collected for each sheeting type, during both daytime and nighttime driving conditions for each participant. A total of 93 sample sets were collected from each sheeting type and time of day condition. The lane placement data was collected at a rate of 60 hertz to ensure adequate sampling to detect even small variations in lane position. Lane placement data was compared between sheeting types within each time of day condition, it was not compared between time-of-day conditions because, even though the population was the same for each time of day in this portion of the study, the experimental design did not randomize the time-of-day conditions which would confound any conclusions drawn from any analysis performed between time-of-day conditions.
The participants in the simulator study each drove through every sheeting and time of day condition in the study. Therefore, the data collected constituted matched pairs data. As such, the Mann-Whitney U test, which was used for the field data would not maintain its statistical power for this analysis. Instead, the analysis was performed using the Wilcoxon signed ranks test. This analysis was performed at a type one error rate of 0.05, or a 95 percent level of confidence, with a null hypothesis that the mean lateral lane placement was equal between sheeting types. The alternative hypothesis stated that there was a difference in average lane placement between the work zones utilizing drums with ASTM Type IX and ASTM III sheeting.

The results of the Wilcoxon signed rank test indicate that, at a 95 percent confidence level, there was no significant difference in the lateral lane placement between work zones with ASTM Type IX and ASTM Type III sheeting during either the daytime or nighttime driving conditions. The null hypothesis was therefore accepted for both time-of-day driving conditions. The results of the Wilcoxon signed ranks test are presented in table 12.

### Table 12: Summary of Wilcoxon signed ranks test.

<table>
<thead>
<tr>
<th></th>
<th>Difference</th>
<th>Ranks</th>
<th>N</th>
<th>Mean Rank</th>
<th>Sum of Ranks</th>
<th>W-calc</th>
<th>W-crit</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Daytime</strong></td>
<td>ASTM Type III-ASTM Type IX</td>
<td>Negative</td>
<td>42</td>
<td>44.94</td>
<td>1887.5</td>
<td>-0.293</td>
<td>287</td>
<td>Accept Null : ( \mu_{DG}=\mu_{HI} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive</td>
<td>46</td>
<td>44.10</td>
<td>2028.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ties</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>88</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nighttime</strong></td>
<td>ASTM Type III-ASTM Type IX</td>
<td>Negative</td>
<td>45</td>
<td>42.84</td>
<td>1928.0</td>
<td>-1.477</td>
<td>287</td>
<td>Accept Null : ( \mu_{DG}=\mu_{HI} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive</td>
<td>35</td>
<td>37.49</td>
<td>1312.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ties</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.2.2 Speed

Travel speed data was collected for each sheeting type, during both daytime and nighttime driving conditions for each participant. A total of 93 sample sets were collected from each sheeting type and time of day condition. The speed data was collected at a rate of 60 hertz to ensure adequate sampling to detect even small changes in travel speed. Speed data was compared between sheeting types within each time-of-day condition. It was not compared between time-of-day conditions because, like for the lateral lane placement data, the experimental design did not randomize the time of day condition which would confound any conclusions drawn from the analysis between time-of-day conditions. Upon the completion of the simulator study the speed data was averaged over the first 200 feet of the work zone, the middle 200 feet of the work zone and the exiting 200 feet in an attempt to group the simulator data similar to that collected in the field. 200 feet was selected based on the estimated range within which the vehicle spot speeds were collected for each location in the field study.

Each participant in the simulator study drive through every sheeting type and time of day combination. As such, the speed data collected between sheeting types was dependent data. The one-way ANOVA and Student’s t-tests utilized to analyze the field speed data are based on the assumption of independent data. The simulator speed data adhered to the normal data and homogeneous variances assumptions of the ANOVA and Student’s t-test. However, it violated the independent data assumption. To account for this violation, the speed data was analyzed using the paired-samples t-test. The paired-
samples t-test was performed at a type one error rate of 0.05, or a level of confidence of 95 percent, with the null hypothesis stating that the mean difference in travel speed from the posted speed limits was equal. The alternative hypothesis stated that the mean speed differences were not equal between the sheeting types.

The results of the paired-samples t-test for the daytime driving condition indicate that, at a 95 percent level of confidence, there was not a significant difference in overall mean deviation from the posted speed limit. The null hypothesis was accepted for the daytime driving condition. The results for the nighttime driving conditions indicate that a significant difference in overall mean deviation from the posted speed limit did exist between work zones utilizing drums with ASTM Type IX and ASTM Type III sheeting. Based on these results the null hypothesis for the nighttime driving conditions was rejected and the alternative hypothesis was accepted. The results of the paired-samples t-test analysis are presented in table 13.
### Table 13: Summary of Paired-samples t-test

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASTM Type IX</td>
<td>ASTM Type III</td>
</tr>
<tr>
<td>Sample Size</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Mean (MPH)</td>
<td>-5.72</td>
<td>-5.62</td>
</tr>
<tr>
<td>Std Deviation (MPH)</td>
<td>4.97</td>
<td>5.35</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>Mean Difference</td>
<td>-0.100</td>
<td>0.792</td>
</tr>
<tr>
<td>Std Error of Difference</td>
<td>0.297</td>
<td>0.271</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>92</td>
<td>79</td>
</tr>
<tr>
<td>t-calculated</td>
<td>-0.338</td>
<td>2.92</td>
</tr>
<tr>
<td>t-critical</td>
<td>±1.96</td>
<td>±1.96</td>
</tr>
<tr>
<td>Result</td>
<td>Accept Null: $\mu_{DG} = \mu_{HI}$</td>
<td>Reject Null: $\mu_{DG} \neq \mu_{HI}$</td>
</tr>
</tbody>
</table>

8.3 Validation Study

The simulator study data was then compared with the field data to determine the extent to which the simulated environment was able to reproduce the field test conditions and therefore driver behavior. In order for simulators to be a useful tool for transportation research they must mimic the real world environment such that they evoke at least similar driver behaviors and reactions. The validation study compared the driver behavior data from the field test with that of the drivers in the simulator test to determine if absolute, relative, or interactive-relative validity was achieved for the study of sheeting on construction drums.
8.3.1 Absolute Validity:

*Lane Placement*

The Kruskal-Wallis test was performed to determine if absolute validity was achieved for lateral lane placement. The Kruskal-Wallis test was chosen to be performed due to the violation of the homogeneous variances and normal data assumptions of parametric tests. This test was performed for all of the data within each time of day grouping. The results of the analysis are presented in table 14.

Table 14: Kruskal-Wallis absolute validity analysis summary for lane position

<table>
<thead>
<tr>
<th>Variable</th>
<th><strong>Daytime</strong></th>
<th></th>
<th><strong>Nighttime</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulator</td>
<td>Field</td>
<td>Simulator</td>
<td>Field</td>
</tr>
<tr>
<td>Sample Size</td>
<td>179</td>
<td>213</td>
<td>166</td>
<td>215</td>
</tr>
<tr>
<td>Mean of Ranks</td>
<td>92.45</td>
<td>283.94</td>
<td>84.58</td>
<td>273.17</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$X^2$-Calc</td>
<td>277.83</td>
<td></td>
<td>274.7</td>
<td></td>
</tr>
<tr>
<td>$X^2$-Crit</td>
<td>3.841</td>
<td></td>
<td>3.841</td>
<td></td>
</tr>
<tr>
<td>Result:</td>
<td>Reject Null:</td>
<td></td>
<td>Reject Null:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu_{\text{simulator}} \neq \mu_{\text{field}}$</td>
<td></td>
<td>$\mu_{\text{simulator}} \neq \mu_{\text{field}}$</td>
<td></td>
</tr>
</tbody>
</table>

Similar to the results of an ANOVA analysis, the Kruskal-Wallis indicates if a difference exists between any of the groups in the analysis, but does not indicate where the difference occurs. To determine where the difference exists Mann-Whitney U analyses should be performed. Although the Kruskal-Wallis analysis compared lane placement within and between sheeting types and simulator and field groups, only the comparisons within sheeting type and between simulator and field groups is of interest to
the validation study. As such, to prevent inflation of the type I error, Mann-Whitney U analyses were performed only within sheeting types to compare the lane placement data between the simulator and field studies. The results of the Mann-Whitney U tests are presented in Table 15.

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Variable</th>
<th>ASTM Type III</th>
<th>ASTM Type IX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulator</td>
<td>Field</td>
</tr>
<tr>
<td>Daytime</td>
<td>Sample Size</td>
<td>91</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>Mean of Ranks</td>
<td>46.78</td>
<td>142.82</td>
</tr>
<tr>
<td></td>
<td>Sum of Ranks</td>
<td>4257.00</td>
<td>14853.00</td>
</tr>
<tr>
<td></td>
<td>Mann Whiney U</td>
<td>71.00</td>
<td>126.00</td>
</tr>
<tr>
<td></td>
<td>Z-score</td>
<td>-11.86</td>
<td>-11.74</td>
</tr>
<tr>
<td></td>
<td>Result:</td>
<td>Reject Null:</td>
<td>Reject Null:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu_{\text{simulator}} \not= \mu_{\text{field}}$</td>
<td>$\mu_{\text{simulator}} \not= \mu_{\text{field}}$</td>
</tr>
<tr>
<td>Nighttime</td>
<td>Sample Size</td>
<td>86</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Mean of Ranks</td>
<td>43.52</td>
<td>134.48</td>
</tr>
<tr>
<td></td>
<td>Sum of Ranks</td>
<td>3743.00</td>
<td>12910.00</td>
</tr>
<tr>
<td></td>
<td>Mann Whiney U</td>
<td>2.00</td>
<td>55.00</td>
</tr>
<tr>
<td></td>
<td>Z-score</td>
<td>-11.63</td>
<td>-11.81</td>
</tr>
<tr>
<td></td>
<td>Result:</td>
<td>Reject Null:</td>
<td>Reject Null:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu_{\text{simulator}} \not= \mu_{\text{field}}$</td>
<td>$\mu_{\text{simulator}} \not= \mu_{\text{field}}$</td>
</tr>
</tbody>
</table>

Based on these results, it was determined that absolute validity was not achieved for any time of day or sheeting combination in the simulator study.
Absolute validity for the speed data collected from the simulator is accomplished only if the field study and simulator study speeds were statistically similar by location throughout the work zone for each time of day and sheeting combination. This analysis was performed in two stages using a one-way ANOVA. Since the comparisons to be made are between the simulator and field data by time of day and sheeting group, and not between simulator groups, the independent data assumption of the ANOVA is fulfilled. Two stages of analysis were chosen due to the nature of the comparisons to be made. The comparisons of interest were between the simulator and field data, within the time of day and sheeting groups. Since there was no interest in comparing between groups of data, a single ANOVA analysis of all of the data would reduce the type I error rate to an unacceptable level while providing results which are of no use. To prevent this, an initial ANOVA was performed using only the overall average speed deviation throughout the work zones to determine if differences existed between the simulator and field data by group. The ANOVA results indicate if a difference exists within one or more of the groups included in the test, however it does not indicate where the difference exists. The results of this initial ANOVA analysis are presented in table 16. To determine this, the Games-Howell post-hoc analysis was performed. The Games-Howell post-hoc was selected for its power when sample sizes differ. The results of the Games-Howell post hoc analysis are presented in table 17.
Table 16: Results of the absolute validity ANOVA analysis of speed deviation from posted speed limits, All Groups, Overall Average

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F-calculated</th>
<th>F-critical (p &lt; 0.05)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>24953.80</td>
<td>7</td>
<td>3564.83</td>
<td>164.73</td>
<td>1.79</td>
<td>Reject Null: ( \mu_{\text{sim}} \neq \mu_{\text{field}} )</td>
</tr>
<tr>
<td>Within Groups</td>
<td>53649.55</td>
<td>940.55</td>
<td>24.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 17: Games-Howell post hoc analysis of speed deviation, All Group, Overall Average

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference (MPH)</th>
<th>Standard Error</th>
<th>95% LOC Lower Bound</th>
<th>95% LOC Upper Bound</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime DG Field vs Sim</td>
<td>-8.64</td>
<td>0.39</td>
<td>-9.83</td>
<td>-7.46</td>
<td>Reject Null: ( \mu_{\text{Field}} \neq \mu_{\text{Sim}} )</td>
</tr>
<tr>
<td>Daytime HI Field vs Sim</td>
<td>-1.80</td>
<td>0.44</td>
<td>-3.13</td>
<td>-0.47</td>
<td>Reject Null: ( \mu_{\text{Field}} \neq \mu_{\text{Sim}} )</td>
</tr>
<tr>
<td>Nighttime DG Field vs Sim</td>
<td>-6.92</td>
<td>0.43</td>
<td>-8.22</td>
<td>-5.62</td>
<td>Reject Null: ( \mu_{\text{Field}} \neq \mu_{\text{Sim}} )</td>
</tr>
<tr>
<td>Nighttime HI Field vs Sim</td>
<td>-2.49</td>
<td>0.44</td>
<td>-3.82</td>
<td>-1.17</td>
<td>Reject Null: ( \mu_{\text{Field}} \neq \mu_{\text{Sim}} )</td>
</tr>
</tbody>
</table>

Based on the results of the initial ANOVA and post-hoc analysis, separate ANOVA analyses were performed for each group which indicated a significant difference in average speed deviation. Based on the Games-Howell post-hoc analysis initially performed, a significant difference was present between the simulator and field study average speed deviation for every group. Therefore a separate ANOVA and Games-Howell post-hoc was performed for each time of day and sheeting group to compare the speed deviation by location within the work zone to determine where the
significant differences occurred. Based on the results of the ANOVA and post-hoc analysis presented in tables 18-21 below, significant differences in speed deviation were present between the simulator and field data at every location in every group. These results indicate that absolute validity was achieved with the driving simulator for the daytime ASTM Type III group as vehicles entered and were in the middle of the work zone. Absolute validity was also achieved for the nighttime ASTM Type III group as vehicles were progressing through the middle of the work zone. Absolute validity was not achieved for any other groups or locations.

Table 18: Results of the absolute validity ANOVA analysis of speed deviation from posted speed limits, Daytime, by Location

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F-calc</th>
<th>F-crit (p &lt; 0.05)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM Type IX</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>11629.11</td>
<td>5</td>
<td>2325.82</td>
<td>120.70</td>
<td>1.79</td>
<td>Reject Null: $\mu_{\text{sim}} \neq \mu_{\text{field}}$</td>
</tr>
<tr>
<td>Within Groups</td>
<td>11433.86</td>
<td>262.78</td>
<td>19.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Type III</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>616.31</td>
<td>5</td>
<td>123.26</td>
<td>5.58</td>
<td>1.79</td>
<td>Reject Null: $\mu_{\text{sim}} \neq \mu_{\text{field}}$</td>
</tr>
<tr>
<td>Within Groups</td>
<td>14876.90</td>
<td>258.88</td>
<td>26.71</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 19: Games-Howell post hoc analysis of speed deviation, Daytime, by Location

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference (MPH)</th>
<th>Standard Error</th>
<th>95% LOC Lower Bound</th>
<th>95% LOC Upper Bound</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM Type IX</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime DG Entering WZ Field vs Sim</td>
<td>-6.36</td>
<td>0.69</td>
<td>-8.35</td>
<td>-4.37</td>
<td>Reject Null: $\mu_{Field} \neq \mu_{Sim}$</td>
</tr>
<tr>
<td>Daytime DG Middle WZ Field vs Sim</td>
<td>-10.17</td>
<td>0.61</td>
<td>-11.92</td>
<td>-8.42</td>
<td>Reject Null: $\mu_{Field} \neq \mu_{Sim}$</td>
</tr>
<tr>
<td>Daytime DG Exiting WZ Field vs Sim</td>
<td>-9.42</td>
<td>0.66</td>
<td>-11.34</td>
<td>-7.51</td>
<td>Reject Null: $\mu_{Field} \neq \mu_{Sim}$</td>
</tr>
<tr>
<td><strong>ASTM Type III</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime HI Entering WZ Field vs Sim</td>
<td>-1.39</td>
<td>0.83</td>
<td>-3.77</td>
<td>0.98</td>
<td>Accept Null: $\mu_{Field} = \mu_{Sim}$</td>
</tr>
<tr>
<td>Daytime HI Middle WZ Field vs Sim</td>
<td>-1.46</td>
<td>0.72</td>
<td>-3.53</td>
<td>0.60</td>
<td>Accept Null: $\mu_{Field} = \mu_{Sim}$</td>
</tr>
<tr>
<td>Daytime HI Exiting WZ Field vs Sim</td>
<td>-2.55</td>
<td>0.72</td>
<td>-4.62</td>
<td>-0.48</td>
<td>Reject Null: $\mu_{Field} \neq \mu_{Sim}$</td>
</tr>
</tbody>
</table>

Table 20: Results of the absolute validity ANOVA analysis of speed deviation from posted speed limits, Nighttime, by Location

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F-calc</th>
<th>F-crit (p &lt; 0.05)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM Type IX</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>7489.33</td>
<td>5</td>
<td>1497.87</td>
<td>65.09</td>
<td>1.79</td>
<td>Reject Null: $\mu_{Sim} \neq \mu_{Field}$</td>
</tr>
<tr>
<td>Within Groups</td>
<td>12341.31</td>
<td>248.38</td>
<td>22.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Type III</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>1142.94</td>
<td>5</td>
<td>228.59</td>
<td>8.29</td>
<td>1.79</td>
<td>Reject Null: $\mu_{Sim} \neq \mu_{Field}$</td>
</tr>
<tr>
<td>Within Groups</td>
<td>12731.61</td>
<td>242.87</td>
<td>23.93</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 21: Games-Howell post hoc analysis of speed deviation, Nighttime, by Location

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference (MPH)</th>
<th>Standard Error</th>
<th>95% LOC Lower Bound</th>
<th>95% LOC Upper Bound</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM Type IX</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime DG Entering WZ</td>
<td>-8.10</td>
<td>0.78</td>
<td>-10.35</td>
<td>-5.86</td>
<td>Reject Null: ( \mu_{Field} \neq \mu_{Sim} )</td>
</tr>
<tr>
<td>Field vs Sim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime DG Middle WZ</td>
<td>-3.91</td>
<td>0.71</td>
<td>-5.95</td>
<td>-1.87</td>
<td>Reject Null: ( \mu_{Field} \neq \mu_{Sim} )</td>
</tr>
<tr>
<td>Field vs Sim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime DG Exiting WZ</td>
<td>-8.87</td>
<td>0.67</td>
<td>-10.79</td>
<td>-6.94</td>
<td>Reject Null: ( \mu_{Field} \neq \mu_{Sim} )</td>
</tr>
<tr>
<td>Field vs Sim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASTM Type III</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime HI Entering WZ</td>
<td>-3.38</td>
<td>0.79</td>
<td>-5.67</td>
<td>-1.08</td>
<td>Reject Null: ( \mu_{Field} \neq \mu_{Sim} )</td>
</tr>
<tr>
<td>Field vs Sim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime HI Middle WZ</td>
<td>-1.45</td>
<td>0.73</td>
<td>-3.56</td>
<td>0.66</td>
<td>Accept Null: ( \mu_{Field} = \mu_{Sim} )</td>
</tr>
<tr>
<td>Field vs Sim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime HI Exiting WZ</td>
<td>-3.70</td>
<td>0.72</td>
<td>-4.77</td>
<td>-0.63</td>
<td>Reject Null: ( \mu_{Field} \neq \mu_{Sim} )</td>
</tr>
<tr>
<td>Field vs Sim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.3.2 Relative Validity:

Lane Placement

Relative validation of the lane placement data between the simulator and field tests was determined by testing if the difference in lane placement from the simulator and field tests was similar by sheeting type for each time of day. To do this, the simulator and field data was pared randomly and the difference of each pair determined. The Mann-Whitney U test was then performed to determine if the differences calculated from the ASTM Type IX field and simulator studies was statistically similar to that calculated from the ASTM Type III field and simulator studies. The Mann-Whitney U test was performed separately for the daytime and nighttime conditions with the null hypothesis
that the difference in between the field and simulator study for ASTM Type IX sheeting is equal to the difference in lane placement between the field and simulator study for ASTM Type III sheeting. The non-parametric Mann-Whitney U test was chosen for this analysis due to the non-normal data, and non-homogeneous variances occurring in the lane placement data. Results of this analysis are presented in table 22. Based on these results, it is seen that relative validity was not achieved in the simulator study for either time of day.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASTM Type IX</td>
<td>ASTM Type III</td>
</tr>
<tr>
<td>Sample Size</td>
<td>88</td>
<td>91</td>
</tr>
<tr>
<td>Mean of Ranks</td>
<td>74.38</td>
<td>105.11</td>
</tr>
<tr>
<td>Sum of Ranks</td>
<td>6545.00</td>
<td>9565.00</td>
</tr>
<tr>
<td>Mann Whiney U</td>
<td>2629.00</td>
<td></td>
</tr>
<tr>
<td>Z-score</td>
<td>-3.97</td>
<td></td>
</tr>
<tr>
<td>Result:</td>
<td>Reject Null:</td>
<td>Reject Null:</td>
</tr>
<tr>
<td></td>
<td>$\mu_{DG} \neq \mu_{HI}$</td>
<td>$\mu_{DG} \neq \mu_{HI}$</td>
</tr>
</tbody>
</table>

**Speed**

To determine if relative validity was achieved for speed deviation from the posted speed limit the simulator data was compared against the corresponding field data for each sheeting type and time of day combination. The field speed deviation data was selected as the control data and the simulator speed deviation data as treatment. For each location
throughout the work zone the expected average simulator speed was calculated based on
the difference in simulator and field deviation from the posted speed limit at one of the
other locations within the work zone and the average field travel speed deviation from the
posted speed limit at that location using the equations presented below.

Using the difference in deviation as vehicles entered the work zone:

\[
\tilde{V}_{\text{BField}} - \tilde{V}_{\text{BSimulator}} = \Delta_B
\]

\[
\tilde{V}_{\text{MSimulator(Expected)}} = \tilde{V}_{\text{MField}} - \Delta_B
\]

\[
\tilde{V}_{\text{ESimulator(Expected)}} = \tilde{V}_{\text{EField}} - \Delta_B
\]

Where:

\[
\tilde{V}_{\text{BField}} = \text{Actual average deviation from the posted speed limit}
\]

(field data, as vehicle entered the work zone)

\[
\tilde{V}_{\text{BSimulator}} = \text{Actual average deviation from the posted speed limit}
\]

(simulator data, as vehicle entered the work zone)

\[
\tilde{V}_{\text{MSimulator(Expected)}} = \text{Expected average deviation from the posted speed limit}
\]

(simulator data, middle of the work zone)

\[
\tilde{V}_{\text{MField}} = \text{Actual average deviation from the posted speed limit}
\]

(field data, middle of the work zone)

\[
\tilde{V}_{\text{ESimulator(Expected)}} = \text{Expected average deviation from the posted speed limit}
\]

(simulator data, as vehicle exited the work zone)

\[
\tilde{V}_{\text{EField}} = \text{Actual average deviation from the posted speed limit}
\]

(field data, as vehicle exited the work zone)
These calculations were repeated for the middle of the work zone and as vehicles exited the work zone.

The one way t-test was then performed to determine if the actual simulator speeds recorded at the middle and as vehicles exited the work zone were statistically similar to the calculated expected speed. This process was repeated for each sheeting and time of day combination, daytime ASTM Type IX, daytime ASTM Type III, nighttime ASTM Type IX, and nighttime ASTM Type III. In order to achieve relative validity, the expected and actual difference in speeds should be statistically similar for every test within the sheeting and time of day combination. The results of the one-way t-test are presented in tables 23 and 24.
### Table 23: Relative Validity, Daytime driving conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\Delta_B$</th>
<th>$\Delta_M$</th>
<th>$\Delta_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Middle</td>
<td>Exiting</td>
<td>Beginning</td>
</tr>
<tr>
<td>$\bar{V}_{\text{Sim Expected}}$</td>
<td>-1.58</td>
<td>-3.10</td>
<td>-9.4</td>
</tr>
<tr>
<td>$\bar{V}_{\text{Sim Actual}}$</td>
<td>-5.39</td>
<td>-6.16</td>
<td>-5.59</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>4.71</td>
<td>4.97</td>
<td>5.24</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.494</td>
<td>0.521</td>
<td>0.556</td>
</tr>
<tr>
<td>Mean Difference</td>
<td>-3.81</td>
<td>-3.06</td>
<td>3.81</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>90</td>
<td>90</td>
<td>88</td>
</tr>
<tr>
<td>$t_{\text{calc}}$</td>
<td>-7.71</td>
<td>-5.88</td>
<td>6.85</td>
</tr>
<tr>
<td>$t_{\text{critical}}$</td>
<td>±1.664</td>
<td>±1.664</td>
<td>±1.664</td>
</tr>
<tr>
<td>Result</td>
<td>Reject</td>
<td>Reject</td>
<td>Accept</td>
</tr>
</tbody>
</table>

**ASTM Type IX**

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\mu_{\text{exp}} \neq \mu_{\text{act}}$</th>
<th>$\mu_{\text{exp}} \neq \mu_{\text{act}}$</th>
<th>$\mu_{\text{exp}} = \mu_{\text{act}}$</th>
<th>$\mu_{\text{exp}} = \mu_{\text{act}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{V}_{\text{Sim Expected}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{V}_{\text{Sim Actual}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std Deviation</td>
<td>5.40</td>
<td>4.56</td>
<td>6.01</td>
<td>4.56</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.566</td>
<td>0.478</td>
<td>0.630</td>
<td>0.478</td>
</tr>
<tr>
<td>Mean Difference</td>
<td>-0.07</td>
<td>-1.16</td>
<td>0.07</td>
<td>-1.09</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$t_{\text{calc}}$</td>
<td>-0.127</td>
<td>-2.430</td>
<td>0.110</td>
<td>-2.284</td>
</tr>
<tr>
<td>$t_{\text{critical}}$</td>
<td>±1.664</td>
<td>±1.664</td>
<td>±1.664</td>
<td>±1.664</td>
</tr>
<tr>
<td>Result</td>
<td>Reject</td>
<td>Reject</td>
<td>Accept</td>
<td>Reject</td>
</tr>
</tbody>
</table>

**ASTM Type III**

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\mu_{\text{exp}} \neq \mu_{\text{act}}$</th>
<th>$\mu_{\text{exp}} \neq \mu_{\text{act}}$</th>
<th>$\mu_{\text{exp}} = \mu_{\text{act}}$</th>
<th>$\mu_{\text{exp}} = \mu_{\text{act}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{V}_{\text{Sim Expected}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{V}_{\text{Sim Actual}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.3.3 Interactive Validity:

As defined by Godley et al., interactive relative validity is achieved if the simulated environment evokes similar dynamic response to that experienced in the field.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\Delta_B$</th>
<th>$\Delta_M$</th>
<th>$\Delta_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Middle</td>
<td>Exiting</td>
<td>Beginning</td>
</tr>
<tr>
<td>$\vec{V}_{\text{Sim Expected}}$</td>
<td>-8.13</td>
<td>-4.63</td>
<td>-2.41</td>
</tr>
<tr>
<td>$\vec{V}_{\text{Sim Actual}}$</td>
<td>-3.94</td>
<td>-5.40</td>
<td>-6.61</td>
</tr>
<tr>
<td><strong>ASTM Type IX</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Std Deviation</strong></td>
<td>5.09</td>
<td>4.81</td>
<td>6.01</td>
</tr>
<tr>
<td><strong>Std Error</strong></td>
<td>0.562</td>
<td>0.531</td>
<td>0.660</td>
</tr>
<tr>
<td><strong>Mean Difference</strong></td>
<td>4.19</td>
<td>-0.77</td>
<td>-4.20</td>
</tr>
<tr>
<td><strong>Degrees of Freedom</strong></td>
<td>81</td>
<td>81</td>
<td>82</td>
</tr>
<tr>
<td>$t_{\text{calc}}$</td>
<td>7.46</td>
<td>-1.44</td>
<td>-6.36</td>
</tr>
<tr>
<td>$t_{\text{critical}}$</td>
<td>$\pm 1.663$</td>
<td>$\pm 1.663$</td>
<td>$\pm 1.663$</td>
</tr>
<tr>
<td><strong>Result</strong></td>
<td>Reject: $\mu_{\text{exp}} \neq \mu_{\text{act}}$,</td>
<td>Accept: $\mu_{\text{exp}} = \mu_{\text{act}}$</td>
<td>Reject: $\mu_{\text{exp}} \neq \mu_{\text{act}}$,</td>
</tr>
<tr>
<td>$\vec{V}_{\text{Sim Expected}}$</td>
<td>-6.87</td>
<td>-5.93</td>
<td>-5.41</td>
</tr>
<tr>
<td>$\vec{V}_{\text{Sim Actual}}$</td>
<td>-4.94</td>
<td>-5.54</td>
<td>-7.34</td>
</tr>
<tr>
<td><strong>ASTM Type III</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Std Deviation</strong></td>
<td>5.38</td>
<td>5.10</td>
<td>5.89</td>
</tr>
<tr>
<td><strong>Std Error</strong></td>
<td>0.591</td>
<td>0.560</td>
<td>0.66</td>
</tr>
<tr>
<td><strong>Mean Difference</strong></td>
<td>1.93</td>
<td>0.39</td>
<td>-1.93</td>
</tr>
<tr>
<td><strong>Degrees of Freedom</strong></td>
<td>82</td>
<td>82</td>
<td>79</td>
</tr>
<tr>
<td>$t_{\text{calc}}$</td>
<td>3.26</td>
<td>0.69</td>
<td>-2.93</td>
</tr>
<tr>
<td>$t_{\text{critical}}$</td>
<td>$\pm 1.663$</td>
<td>$\pm 1.663$</td>
<td>$\pm 1.662$</td>
</tr>
<tr>
<td><strong>Result</strong></td>
<td>Reject: $\mu_{\text{exp}} \neq \mu_{\text{act}}$,</td>
<td>Accept: $\mu_{\text{exp}} = \mu_{\text{act}}$</td>
<td>Reject: $\mu_{\text{exp}} \neq \mu_{\text{act}}$,</td>
</tr>
</tbody>
</table>
In order to determine if interactive validity was achieved, the trends of the data between the field and simulator studies were compared to determine if they were similar. Similar trends would imply similar response to a particular treatment or event occurring in both the field and simulated environments and therefore confirm interactive relative validity.

*Lane Placement*

In order to determine if interactive validity was achieved with the simulator for the vehicle lateral lane placement, a Mann-Whitney U analysis was performed to compare the differences in lateral lane position between ASTM Type III sheeting and ASTM Type IX sheeting between the field and simulator study results. The average lateral lane position of each participant in the simulator experiment was calculated for each work zone. The difference between the average ASTM Type IX lateral lane position data and the average ASTM Type III lateral lane position data was then determined for each participant. The average field ASTM Type IX and ASTM Type III lateral lane position data for each participant was then paired randomly for each time of day condition. The Mann-Whitney U test was performed with the null hypothesis that the difference in lane placement between the ASTM Type IX and ASTM Type III sheeting in the road study was equal to the difference in lane placement between sheeting types in the simulator study. The results of the Mann-Whitney U analysis are presented in table 25.
Table 25: Lane placement interactive relative validity Mann-Whitney U analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field</td>
<td>Simulator</td>
</tr>
<tr>
<td>Sample Size</td>
<td>104</td>
<td>88</td>
</tr>
<tr>
<td>Mean of Ranks</td>
<td>81.22</td>
<td>114.56</td>
</tr>
<tr>
<td>Sum of Ranks</td>
<td>8447.00</td>
<td>10081.00</td>
</tr>
<tr>
<td>Mann Whiney U</td>
<td>2987.00</td>
<td></td>
</tr>
<tr>
<td>Z-score</td>
<td>-4.14</td>
<td></td>
</tr>
<tr>
<td>Result:</td>
<td>Reject Null: μ_simulator ≠ μ_field</td>
<td>Reject Null: μ_simulator ≠ μ_field</td>
</tr>
</tbody>
</table>

Based on the results of the analysis, interactive relative validity for lateral lane position was not achieved with the simulator for either time of day condition.

**Speed**

Interactive relative validity for the speed data was checked through the use of the ANOVA trend analysis. This analysis contrasts the data and determines if a statistically significant trend exists between the data sets, in this case the simulator and field speed data. For this study, the linear, quadratic, and cubic trends were considered, higher order trends were not considered due to their complexity. A separate analysis was performed for each time of day and sheeting combination with the null hypothesis being: no trend exists. A significant result in this analysis indicates the presence of a trend between the data and, accordingly, confirms interactive relative validity. The results of the analysis are presented in tables 26 and 27.
Table 26: ANOVA trend analysis for interactive relative speed analysis, Daytime

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Trend Type</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F-calc</th>
<th>F-crit</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM Type IX</td>
<td>Between Groups</td>
<td>Quadratic</td>
<td>474.3</td>
<td>1</td>
<td>474.28</td>
<td>21.08</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>-</td>
<td>8525.7</td>
<td>379</td>
<td>22.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM Type III</td>
<td>Between Groups</td>
<td>Linear</td>
<td>333.5</td>
<td>1</td>
<td>333.5</td>
<td>11.02</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>-</td>
<td>11224.2</td>
<td>371</td>
<td>20.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on these results, there is a significant linear trend between the in the daytime ASTM Type III, a significant quadratic trend in the nighttime ASTM Type III and a significant quadratic trend in both the daytime and nighttime ASTM Type IX sheeting. These results indicate that, while the difference in speed from the posted speed limit was not similar in magnitude, it was similar in direction, greater difference or lesser
difference, between the simulator and field studies for each sheeting type and time of day combination as subjects traveled through the work zone.
CHAPTER 9: CONCLUSIONS

9.1 Field Study

The objective of this research was to determine if a significant difference in driver behavior exists between work zones utilizing ASTM Type IX sheeting and ASTM Type III sheeting on construction drums. A comparative parallel study was performed using work zones along SR-32, US-50 and SR-33 in Ohio, and I-72 in Illinois. All study locations were 4-lane corridors with a one lane closure and limited or no overhead lighting. The data collected included lateral placement within the lane and traveled speed within the work zone at three locations throughout the work zone. The lane placement data was extracted in terms distance away from the lane centerline either toward the closed lane, negative, or away from the closed lane, positive. The posted speed limit varied between data collection sites and therefore the speed data was analyzed in terms of the difference in traveled speed from the posted speed limit with positive deviations indicating traveled speed less than the posted speed limit and negative deviations indicating traveled speed greater than the posted speed limit.

Past research has considered lateral lane placement standard deviation as an indication of increased crash risk [38]. Taylor et al. conducted a study of nine rural two lane curves in Pennsylvania. As part of this study, lateral lane placement data was collected and upon analysis of the lateral lane placement data, the researchers determined that crash rates along the horizontal curves could be directly related to the standard deviation of the lane placement data. It was determined that higher variation in lane

---

1 This chapter, sections 9.1 and 9.4, contains adapted writing directly from a report written by the thesis author, Stephen Busam. “Determination of Traffic Control Device Selection for Nighttime Maintenance of Traffic” [1].
placement, or higher lane placement standard deviation, led to higher crash rates along the curves [38].

When considering the lane placement data collected in this research, the standard deviation of the lane placement decreased in work zones with drums utilizing ASTM Type IX sheeting as compared to drums utilizing ASTM Type III sheeting during the daytime driving condition but the decrease was not significant. During the nighttime driving conditions, the standard deviation of the lateral lane placement of vehicles in the work zone with drums utilizing ASTM Type IX sheeting was equal to that of work zones with drums utilizing ASTM Type III sheeting. Based on these results and the research performed by Taylor et al. it was determined that, during the daytime driving condition the drums with diamond grade sheeting may slightly lower the crash rate within the work zone. During the nighttime driving condition it can be assumed that the crash rate would not be negatively affected by the drums utilizing ASTM Type IX sheeting.

The results of the lateral lane placement analysis indicate that the average lane placement of vehicles traveling through work zones with drums utilizing ASTM Type IX sheeting is significantly different that of work zones with drums utilizing ASTM Type III sheeting. Vehicles traveling through work zones with drums utilizing ASTM Type IX sheeting were placed further from the work zone as compared to drums utilizing ASTM Type III sheeting. This was apparent in both driving conditions with the greatest difference in mean lateral lane placement being present during the nighttime driving condition.
While little research has been performed to link the increased lateral distance between the work zone and the vehicle to decreased crash rates, it can be assumed that the greater separation of vehicle and work zone could decrease the crash rate and increase work zone safety for both drivers and the construction workers. However, these results indicate a general trend of drivers shying away from the brighter barrels. While this places the vehicles further from the closed lane, on a roadway with three lanes of travel per direction and one lane closed for construction it could lead to drivers crowding the outer open lane which may cause a decrease in work zone safety for drivers. Further research should be conducted to determine if this crowding behavior occurs before the ASTM Type IX sheeting is recommended for work zones on roadways with more than two travel lanes in each direction.

Previous research aimed at studying the relationship between vehicle speed and roadway safety has indicated that elevated mean travel speed impacts roadway safety less than the deviation of vehicles’ speeds from the mean travel speed. This phenomenon was discovered by Solomon who found increased crash rates as individual vehicular travel speeds deviated further from the mean travel speed along the roadway [39]. The increased crash rates were present for deviations above and below the mean traveled speed. Research performed in 1971 by West and Dunn confirmed the results attained by Solomon who found that vehicles traveling much faster or much slower than the mean travel speed had six times the crash risk as those traveling closer to the speed limit. In their research they found the largest increase in crash risk occurred at two standard deviations from the mean travel speed [40]. More recently, research performed by Garber
et al. studied the effects of speed, traffic flow, and geometrics on crash frequency along two-lane highways in Virginia [41]. Garber et al. concluded that, as the speed deviation increased in either direction from the mean travel speed the crash rate also increased for all flow rates.

The results of this research indicate that vehicles tended to, on average, differ less from the posted speed limit in work zones with drums utilizing ASTM Type IX sheeting when compared to ASTM Type III sheeting indicating that drivers in work zone utilizing drums with ASTM Type IX sheeting, on average, drove closer to the posted speed limits. However, the data also indicated that the standard deviation of the differences in speed in the work zones utilizing ASTM Type IX sheeting were higher than those in the work zones utilizing ASTM Type III sheeting. The results of the chi-squared test indicate that the difference was not statistically significant during nighttime driving conditions. However it was statistically significant during daytime driving conditions. In both conditions the standard deviation of the difference from the posted speed limit was three times larger than that in the ASTM Type III work zones. Based on these results it can be concluded that, though the average travel speed is closer to the posted speed limit in the ASTM Type IX work zones, the range of travel speeds is much greater. Considering past research this indicates that the ASTM Type IX sheeting may increase the crash risk due to speed deviation.

The lateral lane placement and speed deviation differences apparent in the daytime driving condition indicate that the fluorescent nature of the ASTM Type IX sheeting has a significant effect on daytime driver behavior. During daytime driving
hours sunlight provides ample light for drivers to see the barrels along the work zone. The available ambient light from the sun during daytime driving conditions reduces the effectiveness of headlights. The abundance of ambient light present also eliminates the retroreflectivity of the sheeting which makes the fluorescent property of the ASTM Type IX sheeting the only difference between the sheeting types. Therefore, with all other features being equal, any difference in daytime speed or lane placement can be directly attributed to the fluorescence of the ASTM Type IX sheeting.

During the nighttime driving conditions in the field study there was very little ambient light present. Therefore the work zone and corresponding drums were illuminated solely by the vehicle headlights rendering the fluorescence of the ASTM Type IX sheeting unnoticeable. During nighttime driving conditions the work zone barrels are visible due to their ability to redirect the incoming light from vehicle headlights back toward the vehicles. Therefore, any difference in nighttime speed and lane placement is attributed directly to the differences in the retroreflective properties of each sheeting type.

9.2 Simulator Study

The second task of this study was to determine if the ASTM Type IX and ASTM Type III sheeting could be adequately reproduced in the driving simulator environment. This was accomplished through the analysis of the simulator speed and lateral lane placement data for differences in means between the sheeting types similar to the field study analysis. The results indicate that there was not a significant difference in lateral lane placement in the simulated environment for either time of day condition. The field
study data did indicate a significant difference in lateral lane placement of vehicles between the sheeting types for both daytime and nighttime driving conditions. However, the absence of a significant difference in the simulator could be due to many factors other than being directly related to the simulators ability to simulate the sheeting.

The simulated environment is created through projecting a scene on screens in front of and to the side of the driver. Due to the nature of a simulated environment, the projected surroundings are two-dimensional. The sense of speed is achieved by “moving” the environment with varying quickness in a direction opposite to the direction of travel, and proportional to the vehicle “travel speed” which gives the participant the perception of moving through an actual three-dimensional environment. However, the subjects view perpendicular to the direction of travel remains two-dimensional. The lack of depth in the environment to the periphery of the vehicle makes it difficult for participants to accurately judge the lateral lane position of their vehicle.

When considering the deviation from the posted speed limit data, the results of the paired-samples t-test indicated that there was no significant difference between the sheeting types during daytime driving conditions. In comparison, there was a significant difference present during daytime conditions in the field study. During the daytime driving conditions the difference between sheeting is due to the ASTM Type IX sheeting being fluorescent and the ASTM Type III sheeting not utilizing fluorescent colors. The retroreflective properties of the sheeting types only apply when light is incident on the retroreflective structure. During daylight driving conditions the environment is lit indirectly by sunlight and therefore vehicle headlights are not needed. The ambient light
also negates the impact of daytime running lights for those vehicles so equipped.
Therefore, during daytime driving conditions the only difference in sheeting types is the
fluorescence of the ASTM Type IX sheeting. The speed data in the simulator study not
producing a significant difference in speed reduction during daytime driving conditions
indicates that the simulator may not adequately reproduce fluorescent colors.

The results of the paired samples t-test for the nighttime simulator speed data
indicate there was a significant difference in speed deviation from the posted speed limit
between the work zones utilizing drums with ASTM Type IX sheeting and ASTM Type
III sheeting. The results indicate that, similar to the field study results, participants
traveled closer to the posted speed limit in the work zones with ASTM Type IX sheeting.
During nighttime driving conditions the fluorescence of the ASTM Type IX is not
noticeable since there is little or no ambient light. The difference in sheeting types during
nighttime driving conditions is due to the retroreflective properties of the sheeting. The
barrels are able to be scene only due to the retrorefection of light incoming from the
vehicles headlights. The significant difference in simulator travel speed difference from
the posted speed limit, and its being closer to the posted speed limit as in the field study,
indicate that the simulated environment is capable of reproducing retroreflectivity.

9.3 Validation Study

The final portion of this research was to determine the extent to which the
O.R.I.T.E Safety and Human Factors Facility’s driving simulator evokes behavior similar
to that in real world driving scenarios. In order for driving simulators to be a valuable
tool for driving research they must be able to simulate the real driving experience
accurately enough produce behavior similar to that occurring in the field. While several studies have been performed to test the ability of a simulator to produce similar behavior responses for a variety of conditions, simulator validation should be performed for each condition and with each simulator separately. Since driver safety research is often performed through field data collection, it is only necessary that the simulator behaviors be as accurate as field behavior. As such, validation is often performed through comparing behavioral data collected through a field study with that collected in a similar simulator study.

Many of the previous validations studies were performed using focus groups. Researchers collected and compared behavior data from the same cohort of participants while driving an instrumented vehicle on a closed track with their behavior while driving in a driving simulator in a virtually recreated environment similar to the field environment. Validation through this method may indicate that the simulator evokes similar behaviors as an instrumented car. However, this does not guarantee that the behaviors of drivers in a simulator are similar to normal, field driving behavior. The instrumented vehicle allows participants to feel the typical vehicle responses in normal driving conditions but it may also induce a bias due to the participants knowing their behavior is being studied.

In an attempt to alleviate this possible bias and ensure validation with actual field driving behaviors, field data was collected from participants at random without their knowing and compared to data collected from subjects driving through several similar simulated environments. Validation was considered for both lateral lane placement and
speed deviation from the posted speed limit at three levels; absolute validity, relative validity, and interactive-relative validity.

The results of the validation analysis indicate that the simulator was not validated for lateral lane placement at any of the three validation levels considered. Under every driving combination, participants in the simulator study positioned their vehicles much further away from the work zone than those in the field study. This is likely due to simulator drivers not experiencing the same level of risk as those driving in the field and therefore not being concerned with their vehicle lateral placement since there was no run-off-the-road risk. The lack of depth perception in the periphery as previously discussed and the lack of a general sense of the vehicle on a real road in the simulator is likely also a contributing factor.

When considering travel speed within the work zone, the simulator did achieve absolute validation for daytime driving conditions for the work zone with drums utilizing ASTM Type III sheeting for vehicles as they entered the work zone and progressed through the middle of the work zone. Absolute validity was also achieved for the nighttime driving condition in the ASTM Type III work zone as subjects progressed through the middle of the work zone. These results indicate that the simulator likely recreates the ASTM Type III work zone during daytime driving conditions. Absolute validity was not achieved as vehicles exited the work zone. The data show that participants driving in the simulator travelled more in excess of the speed limit than the field subjects when approaching the end of the work zone which could be attributable to their having a greater anticipation for the end of the work zone due to the lesser
distractions experienced by drivers in the simulator as compared to the field study subjects. The simulation was set up to allow the subjects to concentrate only on the driving task, no radio or cell phones could be used during the study and there was no ambient traffic present to possibly distract the drivers.

Interactive-relative validity was achieved for difference in travel speed from the posted speed limit for every driving combination in this study. This implies that the overall effect of the sheeting types on speed was similar when comparing the simulator study and field study for daytime and nighttime driving conditions. Based on these results and the observations of Tornros and Blaauw, the O.R.I.T.E. Safety and Human Factors Facility driving simulator produced similar behavioral effects and therefore is a viable tool for studying the effects of ASTM Type IX sheeting when used on construction drums for difference in travel speed from the posted speed limit.

9.4 Recommendations for Future Research

The rural nature of the sites selected for data collection could be considered the worst case scenario for roadway work zones, especially during nighttime driving conditions due to the lack of ambient lighting along the roadway to illuminate the work zone. The only light present during nighttime driving conditions were the vehicles' headlights. However, the rural nature of the work zones utilized also limited the complexity of the driver’s surroundings. The results of this study indicate an improvement in the safety of work zones with drums utilizing ASTM Type IX sheeting as opposed to ASTM Type III sheeting. Future research should consider work zones located in settings which are more complex such as urban or suburban work zones to
determine if the safety improvements associated with drums utilizing ASTM Type IX sheeting remain.

This research was also limited in the number of work zones considered for the field study. Future research should consider a broader array of work zone locations and a greater number work zones to ensure that the effects universal for the driving public instead of just the fairly limited population utilized in this study. There remain concerns from transportation professionals that the increased amount of retroreflected light may cause problems of glare. To address this concern future research should consider performing data collection during adverse weather conditions, especially during nighttime rain events and immediately following nighttime rain events, during the “wet response” period when roadway glare is especially prevalent.

Finally, the lane placement results of the field study performed in this research indicate that drivers in work zones utilizing drums with ASTM Type IX sheeting tended to shy away from the increased brightness and fluorescence of the sheeting. In these work zones drivers placed their vehicles further from the closed lane. When one lane of a two lane roadway is closed, as in this study, this presents only the concern of run off the road crashes into the median. However, if this crowding continued when one lane of a three lane roadway was closed it could lead to a greater rate of side swipe crashes in the two non-closed lanes. Future research should consider the driver behaviors in work zones utilizing drums with ASTM Type IX sheeting on roadways with three or more lanes with one lane closed.
REFERENCES


APPENDIX A: IRB DOCUMENTS

Project Title: Safety Evaluation of Diamond Grade vs. High Intensity Retroreflective Sheeting on Work Zone Fences

Primary Investigator: Stephen G. Busam
Co-Investigator(s):

Faculty Advisor: Deborah McAvey
Department: Civil Engineering

Rebecca Cale, AAB, CIP
Office of Research Compliance

Approval Date 08/26/10
Expiration Date 08/25/11

The following research study has been approved by the Institutional Review Board at Ohio University for the period listed below. This review was conducted through an expedited review procedure as defined in the federal regulations as Category(ies).

This approval is valid until expiration date listed above. If you wish to continue beyond expiration date, you must submit a periodic review application and obtain approval prior to continuation.

Adverse events must be reported to the IRB promptly, within 5 working days of the occurrence.

The approval remains in effect provided the study is conducted exactly as described in your application for review. Any additions or modifications to the project must be approved by the IRB (as an amendment) prior to implementation.
The amendment, detailed below, and submitted for the following research study has been approved by the Institutional Review Board at Ohio University.

**Project:** Safety Evaluation of Diamond-Grade vs. High-Intensity Retroreflective Sheeting on Work Zone Drums

**Amendment:** Recruit from Psychology Pool; Add Co-investigator (Griffeth)

**Primary Investigator:** Stephen G. Busam

**Co-Investigator(s):** Rodger Griffeth

**Advisor:** Deborah McAvoy

**Department:** Civil Engineering

**Rebecca G. Cale, AAB, CIP**
Office of Research Compliance

**Protocol Expiration Date:** 8/25/2011

**Date:** 10/04/10
**Proposal Title**  
Safety Evaluation of Diamond-Grade vs. High-Intensity Retroreflective Sheeting on Work Zone Drums

Investigator(s) Information

<table>
<thead>
<tr>
<th>First</th>
<th>Middle</th>
<th>Last</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stephen</td>
<td>G.</td>
<td>Busam</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Department</th>
<th>Stocker 308</th>
</tr>
</thead>
<tbody>
<tr>
<td>Email</td>
<td><a href="mailto:sb389704@ohio.edu">sb389704@ohio.edu</a></td>
</tr>
<tr>
<td>Phone</td>
<td>513-410-1002</td>
</tr>
<tr>
<td>Training Module Completed?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Co-investigators

<table>
<thead>
<tr>
<th>Name</th>
<th>Department</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodger Griffeth</td>
<td>Psychology</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Address</th>
<th>Email</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>213 Porter Hall</td>
<td><a href="mailto:griffeth@ohio.edu">griffeth@ohio.edu</a></td>
<td>740-593-1069</td>
</tr>
<tr>
<td>Training Module Completed?</td>
<td>Yes</td>
<td>x</td>
</tr>
</tbody>
</table>

Advisor Information (if applicable)

<table>
<thead>
<tr>
<th>Name</th>
<th>Department</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deborah McAvoy, Ph.D., P.E., P.T.O.E</td>
<td>Civil Engineering</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Address</th>
<th>Email</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stocker 118</td>
<td><a href="mailto:mcavoy@ohio.edu">mcavoy@ohio.edu</a></td>
<td>740-593-1468</td>
</tr>
<tr>
<td>Training Module Completed?</td>
<td>Yes</td>
<td>x</td>
</tr>
</tbody>
</table>
2. Study Timeline

a. Anticipated Starting Date (Study, including recruitment, cannot begin prior to IRB approval. This date should never precede the submission date)  
   September 7, 2010

b. Duration of Study  
   Years: 4  
   Months: 0

3. Funding Status

a. Is the researcher receiving support or applying for funding?  
   Yes  
   No  
   X

If YES

<table>
<thead>
<tr>
<th>List Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Describe any consulting or other relationships with this sponsor.</td>
</tr>
</tbody>
</table>

Funding will be used for:

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paying Participants (Provide further details in compensation section)</td>
</tr>
<tr>
<td>Researcher Expenses (Postage, Equipment, Travel, etc.)</td>
</tr>
<tr>
<td>Other Research Project – Wages and Salary for Staff</td>
</tr>
</tbody>
</table>

4. Review Level

Based on the definition in the guidelines, do you believe your research qualifies for?

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exempt Review – See description of categories at: <a href="http://www.ohio.edu/research/compliance/Exemption-Categories.cfm">http://www.ohio.edu/research/compliance/Exemption-Categories.cfm</a></td>
</tr>
<tr>
<td>Full Board Review</td>
</tr>
</tbody>
</table>

5. Recruitment/Selection of Subjects

a. Maximum Number of Participants to be Enrolled – If screening occurs, include number that will need to be screened in order to get the N necessary for statistical significance.  
   400

b. Characteristics of subjects (check as many boxes as appropriate).

<table>
<thead>
<tr>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minors</td>
</tr>
<tr>
<td>Disabled (Physically or Mentally)</td>
</tr>
<tr>
<td>Elementary School Students</td>
</tr>
<tr>
<td>Adults</td>
</tr>
<tr>
<td>Legally Incompetent</td>
</tr>
<tr>
<td>Middle School Students</td>
</tr>
<tr>
<td>Prisoners</td>
</tr>
<tr>
<td>Cognitively Impaired</td>
</tr>
<tr>
<td>High School Students</td>
</tr>
<tr>
<td>Pregnant</td>
</tr>
<tr>
<td>Non-English Speaking</td>
</tr>
<tr>
<td>University Students</td>
</tr>
<tr>
<td>x</td>
</tr>
</tbody>
</table>

x
c. Briefly describe the criteria for selection of subjects (inclusion/exclusion). Include such information as age range, health status, etc. Attach additional pages if necessary.

| Criteria for selection of subjects | 18 years or older, two years of driving experience, and a valid driver’s license. The subjects are limited to 18 years and older with two years of driving experience due to the inexperience levels of new drivers. |

d. Please describe how you will identify and recruit prospective participants.

| Identification and Recruitment | Participants for the study will be solicited on voluntary basis by the PI working on the research study through direct person to person contact or by phone from the community-at-large. Flyers will be posted throughout the university requesting participants. Individuals will also be recruited at businesses and community centers through the use of a pamphlet that will be left at the front desk or with the business administrator. Participants will also be recruited from the Psych Pool. The flyer/pamphlet has been provided in Appendix B. It is anticipated approximately 50 individuals will be recruited per month. |

e. Records

<table>
<thead>
<tr>
<th>Accessing private records</th>
<th>Yes</th>
<th>No</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are you accessing private, i.e. medical, educational, or employment records?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

f. Please describe your relationship to the potential participants, i.e. instructor of class, co-worker, etc. If no relationship, state no relationship.

<table>
<thead>
<tr>
<th>Relationship</th>
<th>No Relationship</th>
</tr>
</thead>
</table>

| Attach copies of all recruitment tools (advertisements, posters, etc.), label as APPENDIX B |

g. Performance Sites/Location of Research

<table>
<thead>
<tr>
<th>Performance Sites/Location of Research</th>
<th>Ohio University Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Public Location</td>
</tr>
<tr>
<td></td>
<td>Other – Describe below and provide letters of cooperation and/or support</td>
</tr>
</tbody>
</table>
6. Project Description

a. Please provide a brief summary of this project, using non-technical terms that would be understood by a non-scientific reader. Please limit this description to no more than one page, and provide details in the methodology section.

Traffic safety along the nation’s roadways is a major concern for traffic and safety professionals. Engineering, educational and enforcement efforts have reduced the fatality rate from 5.5 deaths per 100 million miles of travel in 1966 to 1.41 deaths in 2006.

Temporary traffic control devices are utilized to safely and efficiently guide motorists through construction work zones. Drums are the most common temporary traffic control device used for channelization. The drums have alternating orange and white retroreflective stripes which make them visible, particularly during nighttime hours. Over the past two decades, improvements to the retroreflective sheeting have been made to enhance detection distance and guidance through the work zone to reduce work zone crashes and fatalities.

In recent years there has been a change in roadway work zone projects from new roadway construction to maintenance and rehabilitation of the existing infrastructure. This change in construction activity has required work zone locations in which traffic flow must be maintained. Operating work zones on existing roadways while maintaining traffic flow places construction workers at a higher exposure to vehicle intrusion as well as exposing the driving public to unexpected roadway conditions. The result is a decrease in safety for both the work zone personnel and drivers. While roadway construction is still primarily performed during daylight hours, for reasons of driver safety and project efficiency, work zone lane closures often remain throughout a 24-hour period. Nighttime lane closures place drivers at an even greater safety risk due to the combination of a changed roadway alignment as well as the decreased in visual cues. Advances in technology have helped to reduce the number of fatalities occurring due to the maintenance of traffic through active work zones. However, there are still over 700 fatalities in work zones every year.

Recently, technological advances have allowed for the creation and introduction of the new, more retroreflective diamond-grade sheeting for use on construction drums. This sheeting utilizes microprismatic crystal structures which has increased the sheeting brightness six to 14 times over previous sheeting types. Field research conducted to determine the effects of this increased brightness has determined that the diamond-grade sheeting does provide a safer work zone in terms of driver behavior during daytime and nighttime driving conditions and clear, dry environmental conditions. However, due to the nature of the field study data collection practices, no data is available pertaining to the performance of the diamond-grade sheeting under fog and rain conditions. It is proposed in this research that a driving simulator be used to determine if an increase in work zone safety is provided through the use of diamond-grade sheeting compared to the conventional high-intensity sheeting.

Driving simulators have been utilized for human factors and transportation engineering research where they have proven to be a valuable and valid tool for understanding human performance for a variety of applications. They are an especially...
effective tool when the simulation model is able to represent, as closely as possible, real-world driving conditions while allowing for accurate driver performance measurements.

It is proposed to use a high-fidelity driving simulator (recently acquired by McAvoy through an NSF Grant) to determine the extent to which work zone safety may be increased through the use of the new diamond-grade sheeting.

b. Please describe the specific scientific objectives (aims) of this research and any previous relevant research.

The objective of this research is to compare driver performance, and therefore work zone safety, in work zones with drums utilizing diamond-grade sheeting with those utilizing high-intensity sheeting. In order to fulfill the objectives of the research needs, the project has been subdivided into two phases, each with individual tasks culminating with a report outlining the results of the research conducted in the phase and direction for the research in the subsequent phase. The phases and tasks to fulfill the objectives of this research are as follows:

**PHASE I: Literature Review**
Perform a review of previous research and other literature pertaining to simulator validation for work zone safety research.

**PHASE II: Driving Simulator Study**
Conduct a field study assessing the detectable distances of the high-intensity and diamond-grade materials when used on standard construction drums for daytime and nighttime driving conditions with clear, dry environmental conditions in order to develop the simulated, virtual environment
Conduct a simulator study to examine the daytime and nighttime driving conditions with clear, dry environmental conditions and compare the results with the field research to validate the simulator for the study.
Conduct a simulator study to examine the daytime and nighttime driving conditions with rain and fog environmental conditions to determine possible safety increases of diamond-grade sheeting as compared to high-intensity sheeting for use on construction drums.
c. Methodology: please describe the procedures (sequentially) that will be performed/followed with human participants.

After recruitment, the participants will be introduced to the project using the following narrative paragraph.

You have volunteered to be in a research study to compare the relative driving performance of drivers in a controlled laboratory environment to understand the impact of various traffic control devices on driver behavior. The driving simulator has been built to represent the interior of a standard size passenger automobile, including dashboard, steering wheel, gas pedal, and brake pedal. As you drive the simulator, operate it as if you were driving an actual automobile. The computer screens are intended to represent the actual images you would encounter while looking through the windshield, door windows, and rear view mirrors. The scenes have been programmed with images to replicate typical features encountered on the roadway, including other vehicles present on the road, pedestrians, lane markings, traffic signs, traffic signals, etc.

You will drive through two scenarios. The first one is merely to get you acclimated to the vehicle controls and computer-generated images. The first scenario should take about 15 minutes. Altogether, you will be driving for about 45 minutes. Your total time commitment for this study is approximately 60 minutes; 45 minutes for driving and 15 minutes to answer the questionnaire. Your driving performance will be monitored and statistics will be recorded on the computer and quantified. Your name will remain confidential in the study and your performance will be identified by a subject number only. Your participation in this study will be greatly appreciated and may be a valuable benefit to society. Through your participation the safety consequences along roadways will be quantified and the results may serve to influence legislation in the State of Ohio as well as across the nation, which ultimately aim to reduce traffic crashes on road and highways as well as reduce taxes.

The participants will then be asked to fill out the informed consent form and the pre-test questionnaire.

The participants will drive in the simulator for approximately fifteen minutes in order to become accustomed to the motion platform and simulated world. If the participants desire to continue they will drive in the simulator for an additional 30 minutes. If the participants do not desire to continue in the study, they will be thanked for their time and leave the study.

After completing the simulation participants will be informed of the scope of the project as well as where and when they will be able to find the results of the study.
d. Describe any potential risks or discomforts of participation and the steps that will be taken to minimize them.

The risks involved in this experiment are minimal. Some participants may experience simulator sickness after driving in the simulator for extended periods of time; mainly for driving periods greater than one hour. Based upon previous studies conducted by the PI, it is anticipated that approximately one percent of the participants will experience slight to moderate simulator sickness. If a participant indicates at any time that they are too uncomfortable to continue, they will be released from the experiment. Also, crackers and water will be available for the participants to help with any simulator sickness.

e. Describe the anticipated benefits to the individual participants. If none, state that. (Note that compensation is not a benefit, but should be listed in the compensation section on the next page.)

The benefits for the individual participants will be the same as those for society.

f. Describe the anticipated benefits to society and/or the scientific community in lay language. There must be some benefit to justify the use of human subjects.

Engineering, educational and enforcement efforts have reduced the fatality rate along the nation’s highway from 5.5 deaths per 100 million miles of travel in 1966 to 1.41 deaths in 2006; however, there are still more than 700 fatalities each year in work zones across the nation. The trend of roadway construction toward rehabilitation of existing infrastructure and away from building new roadways has placed work zone personnel and the driving public at an increased risk. The aim of this research is to compare the high-intensity sheeting with the new diamond-grade sheeting in terms of work zone safety. These findings will allow state departments of transportation and industry officials a tool with which they can create or change policies to require that construction drums utilize the sheeting which provides the safest work zone. This in turn will increase the safety of roadway work zones for both the driving public and work zone personnel and, ultimately, reduce work zone crashes and save lives.

7. Confidentiality
   a. Check all that apply

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data is collected anonymously</td>
<td></td>
</tr>
<tr>
<td><strong>x</strong> Data will be recorded without possibility of identification</td>
<td><em>(Computerized Data)</em></td>
</tr>
<tr>
<td><strong>x</strong> Data will be recorded with a code replacing identifiers and a master list connecting the code and the identifier exists for some period of time</td>
<td></td>
</tr>
<tr>
<td>Data will be recorded with identifying information, e.g. name, SSN, oak id, etc.</td>
<td></td>
</tr>
<tr>
<td>Nature of data makes it potentially identifiable (e.g. material with DNA, photographs)</td>
<td></td>
</tr>
</tbody>
</table>
b. If master code list is used (3rd option); please provide detail, such as how/where code list is securely stored, when it will be destroyed, etc.).

To protect participants’ privacy, certain measures will be taken to ensure that no sensitive information will be disclosed. Participant data obtained from the driving simulator and questionnaire will be tagged by number and date, not by participant name. Simulator data will be stored in a password protected computer file and only stored by number (date-time format). Questionnaires and informed consent will be stored in a separate office from the driving simulator and will be in a locked file cabinet until three years after the project has been completed.

c. If data is stored with identifiers, please provide details of how data will be stored securely (i.e. locked cabinet, password protected, etc.) as well as timeframe of when data will be de-identified.

N/A

d. Data Sharing

| Will identifiable data be shared with anyone outside the immediate research team? | Yes | No | x |

e. Recording

| Will participants be Audio recorded? | Yes | No | x |
| Will participants be Video recorded? | Yes | No | x |

f. Additional Details (if needed)

---

8. Compensation

| a. Will participants receive a gift or token of appreciation? | Yes | No | x |
| b. Will participants receive services, treatment or supplies that have a monetary value? | Yes | No | x |
| c. Will participants receive course credit? | Yes | x | No |

If YES, please describe non-research alternatives to earn the credit, the number of points awarded and what percentage of total points for the course it represents. If you are using the Psychology Pool, which has already established guidelines that provide these details to the IRB, simply write Psych Pool.

Psych Pool, Non-Psych Pool participants will not receive compensation
d. Will participants receive monetary compensation (including gift cards)?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
<th>X</th>
</tr>
</thead>
</table>

* If University funds are used to compensate participants, minimally, the name and address of participants will need to be provided to the Finance Office at OU. If participants will be paid $100 or more in a calendar year, participant social security numbers must be provided to Finance. The consent form must reflect this.

9. **Instruments**

a. List all questionnaires, instruments, standardized tests below, with a brief description, and provide copies of each, labeled as APPENDIX C.

<table>
<thead>
<tr>
<th>Experiment Questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>The experiment questionnaire will be used as a pre-test survey to ask participants about their driving experiences in terms of visibility of emergency vehicles. The participants will also be asked to supply demographic information to determine the representative nature of the participants with the population in terms of age, gender, etc.</td>
</tr>
</tbody>
</table>

10. **Data Analysis**

How will the data be analyzed? What statistical procedures will be used to test hypotheses; if qualitative, how will data be coded, etc.

<table>
<thead>
<tr>
<th>Demographic Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>This analysis will allow the researchers the ability to determine the extent to which the sample population is representative of the overall driving population. The observed frequency distribution or percentage of participant demographics will be compared with the corresponding values of the expected distribution of the nation’s demographics. The intent of the comparison will be to test whether the discrepancies between the observed and expected frequencies or percentages were attributable to chance or were significantly different. If the discrepancies were attributable to chance, then the differences between the two percentages can be deemed statistically insignificant. The statistical analysis to determine if the demographic data (gender or age) in the sample population was significantly different than the population will be the test of goodness-of-fit or the chi-square test. The null hypothesis for the chi-square test will be as follows: There was no difference between the demographic data (gender or age) of the field experiment sample and the nation’s population.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speed Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>The analysis of speed data will be used as an indication of a motorist’s perceived risk of traveling along a roadway. The speed data will be analyzed and the overall mean speed and the mean speeds at the beginning, middle and end of the work zone, as well as the variance of the speeds will be calculated. Statistical tests will be used to determine if the mean speeds and speed variances between the scenarios are statistically significant. The null hypothesis for the scenarios speed analysis will be that there is no difference between the mean speeds of the scenarios. The Paired t-test will be utilized to determine the effectiveness of the sheeting based upon the comparison of the test and control scenario overall mean speeds and speed variances. If the data collected violates normality for the speed data, the mean speeds will be compared</td>
</tr>
</tbody>
</table>
with the Paired t-test’s nonparametric counterpart, the Mann-Whitney U Test. To compare the mean speeds at the beginning, middle and end of the work zone a one-way ANOVA will be utilized to ensure the type one error is preserved. If the data collected violates normality for the speed data, the mean speeds will be compared with the one-way ANOVA’s nonparametric counterpart, the Kruskal-Wallis Test.

Lateral Placement Data
The lateral placement for each participant will be quantified to assess the ability of the sheeting type in dictating the placement and behavior of the participant as they traverse through the work zone. The lane offset is recorded on the simulator control station similar to that of the speed. The lane offset is recorded in relationship to the centerline of the roadway where a positive number indicates traveling to the right of center and a negative number indicates traveling to the left of center. The average lateral position and lateral position variance for each participant will be calculated for each work zone. The lateral placement data for each scenario will be analyzed. Statistical tests will be conducted to determine if the mean percentage in acceptable lane position between the test scenario and the control scenario are statistically significant. The null hypothesis for the lateral placement through the control and test scenarios is that there is no difference between the lateral placement of vehicles for the control and test scenarios. The Paired t-test will be utilized to determine the effectiveness of the sheeting type based upon the comparison of the test and control scenario lateral placement. If the data collected violates normality for lateral placement, the lateral placement data will be compared with the Paired t-test’s nonparametric counterpart, the Mann-Whitney U test.

11. Informed Consent Process

Select One of the Following Options

<table>
<thead>
<tr>
<th></th>
<th>I am obtaining signed consent for this study (Attach copies of all consent documents as Appendix A, using the template provided at the end of this document.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>I am requesting a waiver or alteration of Informed Consent (provide details below and attach information that will be provided to participants regarding the study (email, cover letter) as Appendix A.)</td>
</tr>
</tbody>
</table>

Waiver of signature
___ Exempt study
___ Waiver needed to protect the privacy of participants
___ Waiver needed due to cultural norms (e.g. wary of forms needing signatures)
___ Impracticable (online or phone study)
___ Other

Deception (incomplete disclosure)
___ Necessary to avoid participants altering behavior (e.g. not informing of 2 way mirror; providing cover story)

___ Complete waiver of consent
Provide additional information regarding the waiver, if needed.

Attach copies of all consent documents or text and label as APPENDIX A. Please use the template provided at the end of this document.

b. How and where will the consent process occur? Will participants have an opportunity to ask questions and have them answered? What steps will be taken to avoid coercion or undue influence?

The potential participants in the study will be debriefed regarding the study as outlined above and in the Appendices. They will be given the informed consent form to read, review and signed, if so desired. Prior to signing the document, they will be allowed to ask any questions regarding the experiment with appropriate, honest answers provided. The participants will not be forced or asked to proceed with the experiment unless they are completely comfortable with the task.

The consent process will occur in the Driving Simulator Laboratory (Stocker 308) after the participant has initially agreed to participate in the study. The participant will be given a verbal briefing regarding the project and experiment. At that point, the participant will be provided the informed consent form to read, review and sign. The participants will be encouraged to ask any questions that they may have regarding the experiment and the task they may be completing before they sign the consent form and throughout the study. The participants will also be made aware that at any time they may withdraw from participating in the project without ramifications.

c. Will the investigator(s) be obtaining all of the informed consents?  Yes  x  No

d. Will all adult participants have the capacity to give informed consent?  Yes  x  No

*Yes. This is demonstrated by their ability to obtain a driver’s license.*

e. Will any participants be minors?  Yes  No  x

f. Will participants be deceived or incompletely informed regarding any aspect of the study?  Yes  No  x
Investigator Assurance

I certify that the information provided in this outline form is complete and correct.

I understand that as Principal Investigator, I have ultimate responsibility for the protection of the rights and welfare of human subjects, conduct of the study and the ethical performance of the project.

I agree to comply with Ohio University policies on research and investigation involving human subjects (O.U. Policy # 19.052), as well as with all applicable federal, state and local laws regarding the protection of human subjects in research, including, but not limited to the following:

The project will be performed by qualified personnel, according to the OU approved protocol. No changes will be made in the protocol or consent form until approved by the OU IRB. Legally effective informed consent will be obtained from human subjects if applicable, and documentation of informed consent will be retained, in a secure environment, for three years after termination of the project. Adverse/Unexpected events will be reported to the OU IRB promptly. All protocols are approved for a maximum period of one year. Research must stop at the end of that approval period unless the protocol is re-approved for another term.

I further certify that the proposed research is not currently underway and will not begin until approval has been obtained. A signed approval form, on Office of Research Compliance letterhead, communicates IRB approval.

Primary Investigator Signature_____________________ Date ________________

(Please print name) ___________________________

Co-Investigator Signature_____________________ Date ________________

(Please print name) ___________________________
Faculty Advisor/Sponsor Assurance

By my signature as sponsor on this research application, I certify that the student(s) or guest investigator is knowledgeable about the regulations and policies governing research with human subjects and has sufficient training and experience to conduct this particular study in accord with the approved protocol. In addition:

I agree to meet with the investigator(s) on a regular basis to monitor study progress. Should problems arise during the course of the study, I agree to be available, personally, to supervise the investigator in solving them.
I assure that the investigator will report adverse/unexpected events to the IRB in writing promptly.
If I will be unavailable, as when on sabbatical or vacation, I will arrange for an alternate faculty sponsor to assume responsibility during my absence.

I further certify that the proposed research is not currently underway and will not begin until approval has been obtained. A signed approval form, on Office of Research Compliance letterhead, communicates IRB approval.

Advisor/Faculty Sponsor Signature _______________ Date _______________

(Please print name) __

*The faculty advisor/sponsor must be a member of the OU faculty. The faculty member is considered the responsible party for legal and ethical performance of the project.
Ohio University Consent Form
Non-Psych Pool Participants

Title of Research: Safety Evaluation of Diamond-Grade vs. High-Intensity Retroreflective Sheeting on Work Zone Construction Drums

Researcher: Stephen Busam, Graduate Research Assistant, Deborah McAvoy, Ph.D., P.E., P.T.O.E.

You are being asked to participate in research. For you to be able to decide whether you want to participate in this project, you should understand what the project is about, as well as the possible risks and benefits in order to make an informed decision. This process is known as informed consent. This form describes the purpose, procedures, possible benefits, and risks. It also explains how your personal information will be used and protected. Once you have read this form and your questions about the study are answered, you will be asked to sign it. This will allow your participation in this study. You should receive a copy of this document to take with you.

Explanation of Study
You have volunteered to be in a research study to compare the relative driving performance of drivers in a controlled laboratory environment to understand the impact of various traffic control devices on driver behavior. The driving simulator has been built to represent the interior of a standard size passenger automobile, including dashboard, steering wheel, gas pedal, and brake pedal. As you drive the simulator, operate it as if you were driving an actual automobile. The computer screens are intended to represent the actual images you would encounter while looking through the windshield, door windows, and rear view mirrors. The scenes have been programmed with images to replicate typical features encountered on the roadway, including other vehicles present on the road, pedestrians, lane markings, traffic signs, traffic signals, etc. You will drive through two scenarios. The first one is merely to get you acclimated to the vehicle controls and computer-generated images. The first scenario should take about 15 minutes. Altogether, you will be driving for about 45 minutes. Your driving performance will be monitored and statistics will be recorded on the computer and quantified. Your name will remain confidential in the study and your performance will be identified by a subject number only. Your participation in this study will be greatly appreciated and may be a valuable benefit to society. Through your participation the safety consequences along roadways will be quantified and the results may serve to influence legislation in the State of Ohio as well as across the nation, which ultimately aim to reduce traffic crashes on roads and highways as well as reduce taxes.

We are also requesting that you fill out a questionnaire regarding your demographics and past driving habits. We will use the demographic data to determine if the results from this study can be applied to the nation’s population. If the demographic data for the survey participants are significantly different than the nation’s demographic data, we may not be able to generalize the results of this project. We are attempting to assure we have an adequate representation so that
we can draw significant conclusions from this project. Your total time commitment for this study is approximately 60 minutes; 45 minutes for driving and 15 minutes to answer the questionnaire.

Risks and Discomforts
The risks to which you will be exposed by participating in the experiment are minimal. The risks are as follows:
Simulator sickness due to driving in a simulator; generally one percent of participants experience nausea and a headache at the onset of driving or after driving for an hour or more.
Discomfort while sitting in the simulator for an extended period of time.

While these risks generally occur in less than one percent of participants, the following precautions will be taken to ensure minimal risk to you:
You have the right to withdraw from the experiment at any time.
You will be allowed to take up to a two-minute break in between driving sessions to alleviate any discomfort you may experience due to sitting for an extended period of time.
The length of the driving simulation has been kept to one hour.
Crackers and water will be available to participants who experience motion sickness.

Benefits
The National Safety Council releases data every year regarding the economic cost of crashes. The approximate cost for each fatal crash is over $1.5 million. The cost of these crashes is offset by taxpayers and drivers. Therefore, this project will assist in reducing the economic cost of crashes on society and providing safe travel for motorists.

Confidentiality and Records
The data collected from the experiment will be identified by a time stamp including date and time of travel run. Your completed questionnaire will be also be linked by a time stamp that will correspond to the collected data. Your name will not appear in any document or tape related to this research. Participation in this study is completely confidential.

Additionally, while every effort will be made to keep your study-related information confidential, there may be circumstances where this information must be shared with:
* Federal agencies, for example the Office of Human Research Protections, whose responsibility is to protect human subjects in research;
* Representatives of Ohio University (OU), including the Institutional Review Board, a committee that oversees the research at OU.

Compensation
No compensation will be provided.

Contact Information
If you have any questions regarding this study, please contact:
Steve Busam, Graduate Research Assistant, by email: sb389704@ohio.edu
Deborah McAvoy, Ph.D., P.E., P.T.O.E.by email: mcavoy@ohio.edu
If you have any questions regarding your rights as a research participant, please contact Jo Ellen Sherow, Director of Research Compliance, Ohio University, (740)593-0664.

By signing below, you are agreeing that:
you have read this consent form (or it has been read to you) and have been given the opportunity to ask questions and have them answered
you have been informed of potential risks and they have been explained to your satisfaction.
you understand Ohio University has no funds set aside for any injuries you might receive as a result of participating in this study
you are 18 years of age or older
your participation in this research is completely voluntary
you may leave the study at any time. If you decide to stop participating in the study, there will be no penalty to you and you will not lose any benefits to which you are otherwise entitled.

Signature_____________________ Date__________

Printed Name_________________________
Ohio University Consent Form
Psych Pool Participant

Title of Research: Safety Evaluation of Diamond-Grade vs. High-Intensity Retroreflective Sheeting on Work Zone Construction Drums

Researcher: Stephen Busam, Graduate Research Assistant, Deborah McAvoy, Ph.D., P.E., P.T.O.E.

You are being asked to participate in research. For you to be able to decide whether you want to participate in this project, you should understand what the project is about, as well as the possible risks and benefits in order to make an informed decision. This process is known as informed consent. This form describes the purpose, procedures, possible benefits, and risks. It also explains how your personal information will be used and protected. Once you have read this form and your questions about the study are answered, you will be asked to sign it. This will allow your participation in this study. You should receive a copy of this document to take with you.

Explanation of Study
You have volunteered to be in a research study to compare the relative driving performance of drivers in a controlled laboratory environment to understand the impact of various traffic control devices on driver behavior. The driving simulator has been built to represent the interior of a standard size passenger automobile, including dashboard, steering wheel, gas pedal, and brake pedal. As you drive the simulator, operate it as if you were driving an actual automobile. The computer screens are intended to represent the actual images you would encounter while looking through the windshield, door windows, and rear view mirrors. The scenes have been programmed with images to replicate typical features encountered on the roadway, including other vehicles present on the road, pedestrians, lane markings, traffic signs, traffic signals, etc. You will drive through two scenarios. The first one is merely to get you acclimated to the vehicle controls and computer-generated images. The first scenario should take about 15 minutes. Altogether, you will be driving for about 45 minutes. Your driving performance will be monitored and statistics will be recorded on the computer and quantified. Your name will remain confidential in the study and your performance will be identified by a subject number only. Your participation in this study will be greatly appreciated and may be a valuable benefit to society. Through your participation the safety consequences along roadways will be quantified and the results may serve to influence legislation in the State of Ohio as well as across the nation, which ultimately aim to reduce traffic crashes on roads and highways as well as reduce taxes.

We are also requesting that you fill out a questionnaire regarding your demographics and past driving habits. We will use the demographic data to determine if the results from this study can be applied to the nation’s population. If the demographic data for the survey participants are significantly different than the nation’s demographic data, we may not be able to generalize the results of this project. We are attempting to assure we have an adequate representation so that
we can draw significant conclusions from this project. Your total time commitment for this study is approximately 60 minutes: 45 minutes for driving and 15 minutes to answer the questionnaire.

Risks and Discomforts
The risks to which you will be exposed by participating in the experiment are minimal. The risks are as follows:

* Simulator sickness due to driving in a simulator; generally one percent of participants experience nausea and a headache at the onset of driving or after driving for an hour or more.
* Discomfort while sitting in the simulator for an extended period of time.

While these risks generally occur in less than one percent of participants, the following precautions will be taken to ensure minimal risk to you:

* You have the right to withdraw from the experiment at any time.
* You will be allowed to take up to a two-minute break in between driving sessions to alleviate any discomfort you may experience due to sitting for an extended period of time.
* The length of the driving simulation has been kept to one hour.
* Crackers and water will be available to participants who experience motion sickness.

Benefits
The National Safety Council releases data every year regarding the economic cost of crashes. The approximate cost for each fatal crash is over $1.5 million. The cost of these crashes is offset by taxpayers and drivers. Therefore, this project will assist in reducing the economic cost of crashes on society and providing safe travel for motorists.

Confidentiality and Records
The data collected from the experiment will be identified by a time stamp including date and time of travel run. Your completed questionnaire will be also be linked by a time stamp that will correspond to the collected data. Your name will not appear in any document or tape related to this research. Participation in this study is completely confidential.

Additionally, while every effort will be made to keep your study-related information confidential, there may be circumstances where this information must be shared with:

* Federal agencies, for example the Office of Human Research Protections, whose responsibility is to protect human subjects in research;
* Representatives of Ohio University (OU), including the Institutional Review Board, a committee that oversees the research at OU.

Compensation
For participation in this study you will receive one research credit. This credit will be received even if you withdraw from the study prior to its completion.
Contact Information
If you have any questions regarding this study, please contact:
Steve Busam, Graduate Research Assistant, by email: sb389704@ohio.edu
Deborah McAvoy, Ph.D., P.E., P.T.O.E. by email: mcavoy@ohio.edu

If you have any questions regarding your rights as a research participant, please contact Jo Ellen Sherow, Director of Research Compliance, Ohio University, (740)593-0664.

By signing below, you are agreeing that:
you have read this consent form (or it has been read to you) and have been given the opportunity to ask questions and have them answered
you have been informed of potential risks and they have been explained to your satisfaction.
you understand Ohio University has no funds set aside for any injuries you might receive as a result of participating in this study
you are 18 years of age or older
your participation in this research is completely voluntary
you may leave the study at any time. If you decide to stop participating in the study, there will be no penalty to you and you will not lose any benefits to which you are otherwise entitled.

Signature________________________ Date__________
Printed Name_______________________
APPENDIX B: SIMULATOR SURVEY

Driver Profile

Date: __________

1. Gender: Male Female


3. How much total time do you spend driving on a typical day on your way to and from work/school?
   - 0-0.5 hours
   - 0.5 – 1.0 hours
   - 1.0 – 1.5 hours
   - 1.5 – 2.0 hours
   - 2.0 – 2.5 hours
   - Over 2.5 hours

4. How many miles do you drive in one direction on a typical day to arrive at work/school?
   - Less than 5 miles
   - 5 – 10 miles
   - 11 – 20 miles
   - 21 – 30 miles
   - 31 – 40 miles
   - Over 41 miles

5. How often did you encounter a work zone while driving over the past six months?
   - None
   - Rarely (less than 5 occurrences)
   - Occasionally (once or twice per week)
   - Frequently (almost every day while driving to and from work/school)

6. Have you ever been involved in an accident within a work zone?
   - Yes
   - No

   If yes, how many?
   - 1
   - 2
   - 3
   - 4+

7. Have you received a speeding ticket over the past five years?
   - Yes
   - No

   If yes, how many?
   - 1
   - 2
   - 3
   - 4+
APPENDIX C: STATE-OF-THE-PRACTICES SURVEY

Current Practices Survey:

For each question please check all answers which apply to your agency.

1) What type of channelization devices does your agency require for freeway work zones?
   a. Cones
   b. Drums
   c. Barricades
   d. Tubular Markers

2) What percentage of the total uses does each constitute?
   a. Cones
   b. Drums
   c. Barricades
   d. Tubular Markers

3) What grade sheeting does your agency currently require for use on your construction drums?
   a. Engineering Grade
   b. High-Intensity
   c. Diamond Grade

4) Has your agency ever used Diamond Grade sheeting on construction drums?
   a. Yes
   b. No

5) If your agency does require Diamond Grade Sheetin on its construction drums, why?
   a. Safety
   b. Visibility
   c. Improved Delineation of Work Zone
   d. Other
      i. Reason: ________________________________

6) If your agency does not require Diamond Grade sheeting on its construction drums, why not?
   a. Cost
   b. Safety Concerns
   c. Glare
   d. Other
      i. Reason: ________________________________
7) Does your agency have plans to begin requiring Diamond Grade sheeting on their construction drums?
   a. Yes
      i. If yes, when? __________
   b. No

8) Has your agency conducted any studies to determine the effectiveness of Diamond Grade sheeting over High-Intensity or Engineering Grade sheeting on construction drums?
   a. Yes
   b. No

9) Would your agency be willing to provide help in obtaining work zone traffic crash data?
   a. Yes
   b. No
## APPENDIX D: ROAD MILES PER STATE

### Public Roads by State 2008

**OCTOBER 2009**

<table>
<thead>
<tr>
<th>State</th>
<th>Total</th>
<th>Percent of Total</th>
<th>State</th>
<th>Total</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>97,325</td>
<td>2.41%</td>
<td>Montana</td>
<td>74,173</td>
<td>1.83%</td>
</tr>
<tr>
<td>Alaska</td>
<td>15,329</td>
<td>0.38%</td>
<td>Nebraska</td>
<td>93,615</td>
<td>2.32%</td>
</tr>
<tr>
<td>Arizona</td>
<td>60,440</td>
<td>1.50%</td>
<td>Nevada</td>
<td>33,907</td>
<td>0.84%</td>
</tr>
<tr>
<td>Arkansas</td>
<td>99,814</td>
<td>2.47%</td>
<td>New Hampshire</td>
<td>16,005</td>
<td>0.40%</td>
</tr>
<tr>
<td>California</td>
<td>172,511</td>
<td>4.27%</td>
<td>New Jersey</td>
<td>38,753</td>
<td>0.96%</td>
</tr>
<tr>
<td>Colorado</td>
<td>88,265</td>
<td>2.18%</td>
<td>New Mexico</td>
<td>68,384</td>
<td>1.69%</td>
</tr>
<tr>
<td>Connecticut</td>
<td>21,363</td>
<td>0.53%</td>
<td>New York</td>
<td>114,471</td>
<td>2.83%</td>
</tr>
<tr>
<td>Delaware</td>
<td>6,282</td>
<td>0.16%</td>
<td>North Carolina</td>
<td>105,104</td>
<td>2.60%</td>
</tr>
<tr>
<td>Florida</td>
<td>121,387</td>
<td>3.00%</td>
<td>North Dakota</td>
<td>86,842</td>
<td>2.15%</td>
</tr>
<tr>
<td>Georgia</td>
<td>121,873</td>
<td>3.01%</td>
<td>Ohio</td>
<td>122,973</td>
<td>3.04%</td>
</tr>
<tr>
<td>Hawaii</td>
<td>4,365</td>
<td>0.11%</td>
<td>Oklahoma</td>
<td>113,323</td>
<td>2.80%</td>
</tr>
<tr>
<td>Idaho</td>
<td>47,790</td>
<td>1.18%</td>
<td>Oregon</td>
<td>59,252</td>
<td>1.47%</td>
</tr>
<tr>
<td>Illinois</td>
<td>139,491</td>
<td>3.45%</td>
<td>Pennsylvania</td>
<td>121,771</td>
<td>3.01%</td>
</tr>
<tr>
<td>Indiana 1/</td>
<td>95,613</td>
<td>2.37%</td>
<td>Rhode Island</td>
<td>6,403</td>
<td>0.16%</td>
</tr>
<tr>
<td>Iowa</td>
<td>114,223</td>
<td>2.83%</td>
<td>South Carolina</td>
<td>66,255</td>
<td>1.64%</td>
</tr>
<tr>
<td>Kansas</td>
<td>140,611</td>
<td>3.48%</td>
<td>South Dakota</td>
<td>82,147</td>
<td>2.03%</td>
</tr>
<tr>
<td>Kentucky</td>
<td>78,748</td>
<td>1.95%</td>
<td>Tennessee</td>
<td>92,175</td>
<td>2.28%</td>
</tr>
<tr>
<td>Louisiana</td>
<td>61,095</td>
<td>1.51%</td>
<td>Texas</td>
<td>306,404</td>
<td>7.58%</td>
</tr>
<tr>
<td>Maine</td>
<td>22,828</td>
<td>0.56%</td>
<td>Utah</td>
<td>44,706</td>
<td>1.11%</td>
</tr>
<tr>
<td>Maryland</td>
<td>31,386</td>
<td>0.78%</td>
<td>Vermont</td>
<td>14,421</td>
<td>0.36%</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>36,105</td>
<td>0.89%</td>
<td>Virginia</td>
<td>73,902</td>
<td>1.83%</td>
</tr>
<tr>
<td>Michigan</td>
<td>121,667</td>
<td>3.01%</td>
<td>Washington</td>
<td>83,526</td>
<td>2.07%</td>
</tr>
<tr>
<td>Minnesota</td>
<td>138,242</td>
<td>3.42%</td>
<td>West Virginia</td>
<td>38,452</td>
<td>0.95%</td>
</tr>
<tr>
<td>Mississippi</td>
<td>74,887</td>
<td>1.85%</td>
<td>Wisconsin</td>
<td>114,844</td>
<td>2.84%</td>
</tr>
<tr>
<td>Missouri</td>
<td>129,718</td>
<td>3.21%</td>
<td>Wyoming</td>
<td>28,106</td>
<td>0.70%</td>
</tr>
</tbody>
</table>

| Percent Not Responding: | 17.31% |
| Percent Responding:     | 82.69% |


**Note:** Highlighted states did not reply to the state-of-the-practices survey.