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Demonstration of Innovative Techniques for Work Zone Safety Data Analysis

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DEMONSTRATION OF INNOVATIVE TECHNIQUES FOR WORK ZONE SAFETY DATA ANALYSIS

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Demonstration of Innovative Techniques for Work Zone Safety Data Analysis

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1. INTRODUCTION

1.1. Problem

In 2005, there were 949 fatal crashes in work zones and 1074 fatalities in work zones. Unfortunately, the trend of work zone fatalities over the past six years has not improved, as depicted in Figure 1. Of the 949 fatal crashes, 87 percent were in construction or maintenance work zones (FARS, 2006). This has grown from 693 in 1997, nearly a 55 percent increase (FHWA, 2003). In the year 2005, Ohio work zones alone accounted for 5854 crashes, 1420 injuries, and 20 deaths (ODPS, 2006).

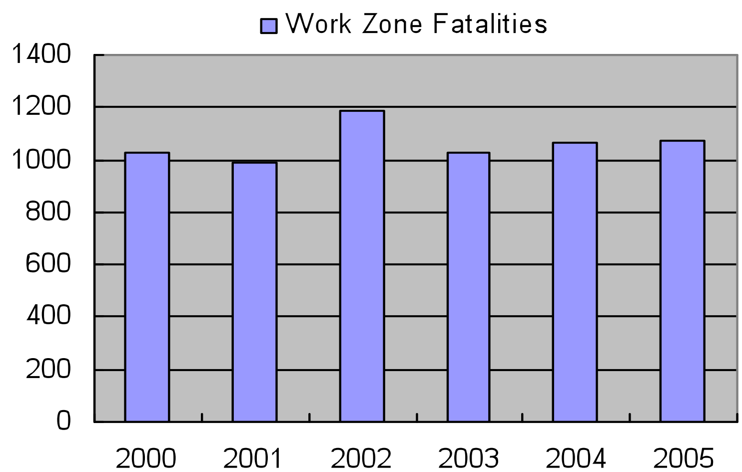

Figure 1. Work Zone Fatalities from 2000 to 2005 (FARS, 2006)

According to the American Society of Civil Engineers' *2005 Report Card*, 34 percent of America's major roads are in poor or mediocre condition. Coupled with this decline in conditions is an increase in vehicle travel. In Ohio alone, travel increased by 25percent from 1990-2003, a statistic that is comparable nationwide. Historical data shows that there were 23,745 miles of roadway improvements underway from 1997 to 2001 and that, on average, motorists drove through one mile of active work zones for every 100 miles driven. In the process of reconstructing our highway system to its optimal condition, the number of temporary and long-term work zones is likely to increase over the next few years (FHWA, 2005). Consequently, as the number of highway work zones increases in the future, more drivers will be exposed to work zones and drivers will encounter work zones more frequently. Thus, the need to improve work zone safety will become even more imperative in the near future and for the long term.

Numerous studies have shown that crash rates increase in work zones compared to the same road during pre-construction conditions (Khattak, Khattak, and Council, 2002). Although many of these studies are not recent (and perhaps are outdated), Khattak, Khattak, and Council (2002) found similar results on California freeways. Despite the knowledge that work zones apparently increase the likelihood of crashes, the precise reasons why this occurs is still not clear.

1.2. Background and Significance of Work

Much effort has been dedicated to collecting work zone crash data in an attempt to identify or classify the causal factors in order to develop appropriate and effective countermeasures. Previous research has cited driver inattention, speed differential, failure to yield, unsafe speed, and following too closely as leading causes of work zone crashes (VTRC, 2002; FHWA, 2005; ODOT, 2005). A 1996 study by Sorock, Ranney, and Lehto found that 50 percent to 75 percent of work zone crashes involved multiple vehicles and the most frequent type of incident was a daytime, rear-end crash. In addition, stopping or slowing in the work zone was the primary pre-crash activity. A 2005 study of work zone accidents at NYSDOT construction projects found that vehicle intrusion into the work area caused the highest percentage of fatal work zone accidents involving construction workers at 35.7 percent (Mohan and Zech, 2005). However, most of the work zone crash data simply describes the type of crash or pre-crash activity, but does not answer the question "What factors (driver, vehicle, organization, environment or otherwise) increase crashes on roadways where a work zone is present?"

In many crashes, both infrastructure and driver-related causes exist. To a limited extent, historical data on work zone crashes and configurations has been used to identify particularly hazardous infrastructure features at work zones in order to make recommendations for enhanced traffic control strategies. In particular, the Ohio Department of Transportation (ODOT) recently received two national safety awards for developing a crash analysis program designed specifically to gather near real-time crash data so that work zone infrastructures can quickly be modified to prevent future crashes (www.governor.ohio.gov). While this approach has shown some success, it is only one approach to improving work zone safety.

Driver behaviors prior to the crash have historically been analyzed based on subjective information from drivers and observers. Surveys have been conducted, narratives from police reports and insurance claims have been studied. However, the usefulness of this information is limited by several factors. First, subjective data is unreliable. Drivers are often unwilling to reveal the true cause of the accident or admit fault to avoid further personal liability. In addition, eyewitness testimony is notoriously inaccurate. Therefore, a critical proportion of work zone crash data is largely unavailable for analysis. Second, databases and police forms often contain incomplete and incorrect data. For example, some questions that might provide valuable information about the true cause of the accident are simply not asked. Furthermore, the actual driver speed is not usually known or recorded because it can only be estimated after the crash. Finally, data is collected for crashes only. Data on near crashes and incidents is not available in databases simply because the data is never reported to police or insurance companies and thus, is not available for analysis. Historically, work zone safety countermeasures have also been developed based on post-crash data collection (e.g., estimates of driver speed prior to crash). While these efforts have produced some success in reducing the frequency of work zone crashes, an unforeseen increase in crash severity (i.e., fatalities) has resulted (Holstein, 2006).

1.3. Research Need

Due to the limitations of existing work zone crash data as well as the complexity involved in producing effective countermeasures based on incomplete or inaccurate data, it is not surprising that work zone safety is still a critical issue. To address these concerns, CSU proposes an innovative approach to investigate the underlying causal factors that lead to increased crashes and fatalities in work zones before attempting to develop additional or modified countermeasures. Thus, CSU proposes using a macroergonomic (or sociotechnical systems) approach to analyzing naturalistic work zone driving data and using this analysis as the basis of human factors recommendations for work zone safety improvements. This is an innovative approach for two reasons. First, a macroergonomic approach has not previously been taken when analyzing work zone safety data and, second, a large naturalistic driving dataset has not previously been analyzed with respect to work zones.

1.4. Literature Review

A literature review was performed to examine work zone regulations, safety initiatives, data collection methods, and crash causation research. In order to identify past results related to the proposed research, literature searches were conducted through Internet queries and traditional library resources. The findings of the literature review identified gaps in the knowledge base which were utilized to formulate the research conducted in this study. The following sections summarize the research papers reviewed, by subject area, as a part of this research.

1.4.1. Work Zone Regulations and Standards

Work zone basic principles and standards for work zone traffic control are set forth in Part 6 of the Manual of Uniform Traffic Control Devices (MUTCD) published by the Federal Highway Administration (FHWA). In addition, 23 CFR 630 Subpart J entitled "Traffic Safety in Highway and Street Work Zones" established a work zone safety and mobility policy to which all states must adhere.

To update and broaden federal regulations on traffic safety in work zones (23 CFR 630 subpart J), the Rule on Work Zone Safety and Mobility was published in 2004. The goal of the rule is to incorporate broader consideration of work zone safety and mobility into work zone policies and procedures as well as to develop a management strategy to minimize the impacts of work zones. The main components of the rule include the following:

- Development and implementation of an overall, agency-level work zone safety and mobility policy to institutionalize work zone processes and procedures.
- Development of agency-level processes and procedures to support policy implementation, including procedures for work zone impacts assessment, analyzing work zone data, training, and process reviews.
- Development of procedures to assess and manage work zone impacts of individual projects. (Rule FAQ, 2004)

1.4.2. Work Zone Safety Initiatives

In addition to simply adhering to federal and state regulations, work zone safety initiatives at the state and federal level have been established in an effort to improve work zone safety. In response to work zone safety issues, the Federal Highway Administration (FHWA) developed the National Highway Work Zone Safety Program in 1995 with the goal of improving safety and operational efficiency of highway work zones for highway users and workers (Federal Register, 1995). The program has four main components: standardization, compliance, evaluation, and innovation. The program updated work zone safety standards and implemented new standards to include updating federal regulations and the MUTCD as well as developing a methods for testing the crashworthiness of work zone traffic control devices. The compliance portion of the program emphasized improving both contractor compliance with existing guidelines and also improving driver compliance with work zone speed limits and traffic control. The evaluation component focused, in part, on improving the accuracy and sufficiency of work zone crash data. Lastly, the innovation portion of the program was intended to promote the adoption of new and/or improved work zone safety technology as well as to establish an ongoing research program aimed at improving work zone safety. Overall, the program was published as a guide to be used in planning, developing, implementing, and monitoring work zone safety and operational activities nationally.

The Midwest States Smart Work Zone Deployment Initiative (MwSWZDI) was created in 1999 by the states of Iowa, Kansas, Missouri, and Nebraska (http://www.ctre.iastate.edu/smartwz). The name has subsequently changed to Smart Work Zone Deployment Initiative (SWZDI). The goal of the initiative was to research traffic control and safety in work zones. Since its inception, over 50 projects have investigated the effectiveness of work zone-related products and evaluated the application of intelligent transportation system (ITS) devices to traffic control in work zones in order to improve safety and efficiency.

Other smaller scale work zone safety initiatives have been established at the federal, state, and local levels. As an example, the federal government sponsors a work zone safety awareness week and many state and law enforcement agencies collaborate to develop work zone safety awareness campaigns as well. Effective initiatives were also successfully proposed in Ohio during past few years. In 2004, the Ohio Department of Transportation (ODOT) initiated a new crash analysis program designed to identify work zone configurations that contribute to crash problems (National Roadway Safety Award, 2005). The historical and near real-time crash data are used in this program to prevent crashes and detect problems in the field. Through the analysis of crashes using this program, authorities can modify work zones designs accordingly. In addition, ODOT spent $35 million in 2005 to reduce work zone congestion and accidents by conducting more work at night and on weekends, and it also initiated a pilot program to increase law enforcement in work zones statewide in the same year (ODOT, 2006).

1.4.3. Work Zone Crash Causation

Despite a significant effort to improve work zone safety and reduce the number and severity of work zone crashes, the precise reasons why work zones crashes occur is still not clear. Much effort has been dedicated to collecting work zone crash data in an attempt to identify or classify the causal factors and then develop appropriate and effective countermeasures. Previous research has cited driver inattention, speed differential, failure to yield, unsafe speed, and following too closely as leading causes of work zone crashes specifically (VTRC, 2002; FHWA, 2005; ODOT, 2005). A 1996 study by Sorock, Ranney, and Lehto found that 50 percent to 75 percent of work zone crashes involved multiple vehicles and the most frequent type of incident was a daytime, rear-end crash. In addition, stopping or slowing in the work zone was the primary pre-crash activity. A 2005 study of work zone accidents at NYSDOT construction projects found that vehicle intrusion into the work area caused the highest percentage of fatal work zone accidents involving construction workers (Mohan and Zech, 2005). However, most of the work zone crash data simply describes the type of crash or pre-crash activity, but does not answer the question “what factors (driver, vehicle, organization, environment or otherwise) increase crashes on roadways where a work zone is present?”

The National Highway Transportation Safety Administration (NHTSA) found that speeding is a contributing factor in 30 percent of all accidents and fatalities (Fors, 2000). In response to this finding and other similar findings that emphasize the negative effects of speeding in work zones, there has been a significant emphasis on reducing speed and enforcing compliance with posted speed limits in work zones. Police presence or increased law enforcement in the work zone area is considered as one of most effective countermeasures to speed-related crashes in work zones. A 2002 study in Alabama pointed out police presence in work zones was the most effective method to reducing vehicle speeds. Data collected from a total of 254,841 vehicles revealed that the mean speed dropped approximately 17 percent compared to without police presence. Based on a literature review, survey responses, and interviews, Kamyab et al. (2003) concluded that use of extra law enforcement or police presence in work zones was a common practice in many states and was a significant benefit to work zone safety. A similar survey was conducted in Virginia (Arnold, 2003) and comparable results supported this argument. In 2006, Ohio announced, although the official study has not been conducted yet, they had a 17.7 percent lower crash rate in work zones with increased law enforcement than those without increased law enforcement.

Despite significant emphasis on reducing speed by many state DOTs, there are several problems with this approach. Ha and Nemeth (1995) point out that there is often an overemphasis on speed, when, in fact, driver maneuver is the primary cause of work zone crashes. Law enforcement and researchers often incorrectly conclude that speed was a factor simply because it is included in traditional crash reports (Wang et al., 1996). In support of this assertion, Raub et al. (2001) found that only 5 percent of work zone crashes are due to excessive speed. An ongoing research project by Cleveland State University found similar results. CSU's results indicated that 43 percent of all near crashes and crash relevant conflicts involved sudden braking or stopping. Only 2 percent involved excessive speed.

Furthermore, there is often an unforeseen consequence of reduced speed limits in work zones—increased speed differentials among vehicles. Many studies have concluded that drivers select their own safe speed based on road conditions, regardless of the posted speed. Thus, if the speed is reduced unnecessarily, some drivers will continue at their own perceived safe speed while other drivers will obey the reduced speed limit, thereby creating an unintentional (and dangerous) speed differential. Moreover, typical enforcement of the posted speed in work zones relies on law enforcement presence in a work zone. This often results in a "halo effect" in which drivers slow down in the vicinity of the police, but resume their former speed after a certain distance. It also produces a potentially significant speed differential when a vehicle slows down suddenly at the sight of a police car.

Therefore, the MUTCD and other guidelines suggest NOT reducing speeds in work zones unless it's absolutely necessary to avoid creating large speed differentials.

Lastly, studies that emphasize the safety improvements from reduced speeds in work zones typically use metrics such as average reduced speed rather than reduced number of crashes. In fact, a review of the literature found no studies that showed a reduction in crashes as a result of enforced reduced speed in work zones. Therefore, the evidence to support reduced speed in work zones and increased law enforcement of speed in work zones is anecdotal at best.

Future research needs to move beyond speed reduction and focus on ways to reduce other potential causes of work zone crashes (i.e., sudden stopping or slowing, driver inattention, inability to perceive stopped vehicles ahead, etc.).

Interestingly, an in depth analysis of fatal work zone crash sites throughout Texas from February 2003 through April 2004 found that only 8 percent of the crashes classified as occurring in a work zone had a direct influence from the work zone and only 39 percent of were indirectly influenced by the presence of a work zone. Perhaps most importantly, the study concluded that 45 percent of the investigated crashes appeared to have no influence from the work zone. Furthermore, 16 percent of the crashes occurred in work zones in name only (e.g., work zones with only project limit signing) (Schrock, Ullman, Cothron, Kraus, and Voigt, 2004)

In summary, there is still no consensus on the cause of work zone crashes. Moving beyond traditional data collection methods using police crash reports may provide more insight into the causes of work zone crashes.

1.4.4. Data Collection Methods and Limitations

Driver behaviors prior to the crash have historically been analyzed based on subjective information from drivers and observers. Surveys have been conducted and narratives from police reports and insurance claims have been studied. However, the usefulness of this information is limited by several factors. First, subjective data is unreliable. Drivers are often unwilling to reveal the true cause of the accident or admit fault to avoid further personal liability. In addition, eyewitness testimony is notoriously inaccurate. Therefore, a critical proportion of work zone crash data is largely unavailable for analysis. Second, databases and police forms often contain incomplete data. For example, some questions that might provide valuable information about the true cause of the accident are simply not asked. Furthermore, the actual driver speed is not usually known or recorded because it can only be estimated after the crash. And finally, data is collected for crashes only. Data on near crashes and incidents is not available in databases simply because the data is never reported to police or insurance companies and thus, is not available for analysis. Historically, work zone safety countermeasures have also been developed based on post-crash data collection (e.g., estimates of driver speed prior to crash).

Although multiple sources of work zone crash data exist, the completeness of these databases is questionable. As Chambless et al. (2002) points out, there is no nationally recognized definition of work zones or work zone-related crashes. Therefore, it is possible that the current work zone crashes are substantially underreported. For example, crasehes that occur in the warning area may not be recognized as part of a work zone. They also found that many states disagreed the FARS database because the actual numbers of work zone crashes were greater than those appeared in the FARS database. According to the study performed by Raub, et al. (2001), 65 percent of crashes may have been miscoded in Illinois' crash severity database. As a result, the miscoded data would lead to the conclusion that the work zone crashes were more severe than non-work zone crashes. The more important evidence in their study showed that only the 56 reports which carried the "construction zone" code would have showed up in the state database as work zone crashes when, in fact, there were over 103 crashes related to work zones.

In addition, Qi, et al. (2005) identified the fact that many federal databases provide very little additional information about the work zone area in which a crash occurred as a disadvantage of using crash databases to determine causation.

1.4.5. Alternative Methods to Studying Work Zone Crash Causation

Due to limitations of existing methods on investigation of crash causation, alternative methods have been introduced to address the knowledge gaps resulting from using existing methods. Several new approaches, such as a macroergonomic approach, naturalistic driving approach and a driving simulator, are described in the following sections.

1.4.5.1.Macroergonomic Approach

Macroergonomics is a sociotechnical systems approach to the analysis and design of systems and the application of overall systems design to human factors issues (Hendrick and Kleiner, 2002). Macroergonomics considers a system's personnel, technological, organizational, and environmental subsystems and their interactions with each other as part of a larger system framework to analyze human factors problems and develop human factors design solutions. Macroergonomics emphasizes congruency between subsystems and the joint optimization of those subsystems. For example, to understand work zone crashes, we must understand that causal factors such as driver behavior and work zone infrastructure are interrelated and cannot be studied in isolation from vehicle technology, roadway conditions, and the driving environment. We must study all aspects of the driving system and the interaction between subsystems (i.e., people, technology, organization, and environment) so that we can understand how their interaction causes unsafe driving. This is referred to as joint causation. Furthermore, we must take all the subsystems into account when designing a solution so that a positive effect on one subsystem does not result in a negative effect on another. This is called joint optimization. It is the understanding of these interactions and the prescription of appropriate interventions based on that understanding that will ultimately lead to a safer and more efficient driving system. Thus, both work zone safety research and the resultant engineering solutions should take a macroergonomic approach. Figure 2 shows how a work zone safety analysis will fit within the macroergonomic framework.

Driver factors can be characterized by psychosocial attributes (e.g., risk-taking propensity, age, driving experience, etc.) as well as behaviors (e.g., wireless device use, changing lanes, etc.). Vehicle factors might include vehicle size or type, instrumentation (e.g., ABS brakes, "smart technologies"). The organizational subsystem for driving includes federal and state agencies such as USDOT and ODOT as well as law enforcement agencies. The driving environment includes such factors as road conditions, weather, traffic density, speed limits, etc. A work zone safety system is centered at the intersection of drivers, vehicle and roadway technology, and organizational agencies with all operate in the driving environment. Thus, a macroergonomic approach to driving research will take all aspects of the sociotechnical system into account to develop more effective work zone safety countermeasures.

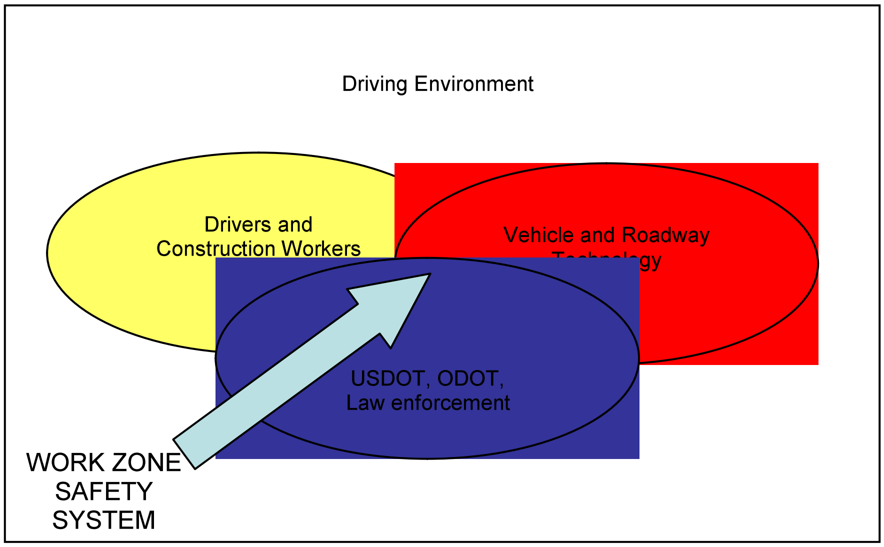

Figure 2. Macroergonomic framework for work zone safety research

1.4.5.2.Naturalistic Driving Approach

"Naturalistic" driving data includes both vehicular and behavioral data that is collected while driving in an instrumented vehicle under various driving conditions and while performing various daily routines. Data is collected from multiple vehicle sensors and video cameras placed unobtrusively in the vehicle. Drivers are not given driving instructions and experimenters are not present in the vehicle so as to illicit "natural" driving behaviors.

Naturalistic driving studies provide more external validity than laboratory studies and thus, are more generalizable to the driving population and driving conditions at large. Because naturalistic studies can provide data on near-crashes and incidents in addition to crashes, it fills a large gap in the existing driving safety literature. In fact, in a 100-car naturalistic driving study by Virginia Tech Transportation Institute (VTTI), near-crashes occurred 15 times more frequently than crashes (Drive and Stay Alive, 2005). By relying solely on data from crashes, we are neglecting a significant amount of critical safety data including, for example, what factors played a role in the driver's ability to successfully perform an evasive maneuver rather than crash.

Because current data sources (e.g., crash databases) cannot provide objective data on driver behaviors prior to a crash (for reasons cited above), this research will utilize naturalistic driving data from the VTTI 100-car study obtained during work zone driving to determine what driver behaviors as well as technological, organizational, and environmental factors may cause crashes, near crashes, and incidents. The naturalistic driving data provides videotaped data on driver behaviors, driver distractions, secondary tasks performed while driving, vehicle dynamics, environmental factors, as well as many other factors present at the time of a crash, near-crash, or incident in a work zone. In addition, data is available on near-crashes and incidents that would otherwise have gone unreported and unanalyzed. The naturalistic data is a critical piece of work zone safety data that has not previously been available nor analyzed for work zones specifically.

Data on vehicle technology and environmental conditions is available in the naturalistic data and is available to a limited extent in the ODOT crash database. The naturalistic data provides information on vehicle type, some technological information (e.g., ABS present on vehicle), and vehicle dynamics information prior to and during a crash, near crash or incident. In addition, the weather conditions, time of day, and other environmental factors present during a crash, near crash, or incident are available. The ODOT crash database can provide the information typically available on a police report (e.g., vehicle make and model, weather, time of day, etc.).

Organizational data is available from a variety of sources. This research will consolidate multiple sources of information in an attempt to determine the major causal factors of crashes, near crashes and incidents in work zones using a macroergonomic approach. Once the relevant aspects of the driver, vehicle, organization, and environment have been identified, these factors and their interactions will be considered jointly.

1.4.5.3.Driving Simulator Approach

Using a driving simulator to study work zone driving behaviors is a proactive (rather than historically reactive) approach to understanding the driver-related causes of work zone crashes and can provide information about the driver's actions prior to crashes and near-crashes that would be otherwise unavailable . In addition, driving simulators can be utilized to test the effectiveness of recommended safety countermeasures (both infrastructure and driver-related) without putting any drivers at physical risk. Therefore, the simulator provides the ability to perform both basic behavioral driving research as well as applied research to test the effectiveness of safety initiatives. This can include analyzing current work zone jobs in progress to determine if there are potentially dangerous causal factors present that may increase the frequency and/or severity of work zone incidents.

As the prevalence of driving simulators in safety research increases, it is importatnt to understand the differences in driving experience and experimental results between simulators and on-the-road driving. The differences can be dexcribed in terms of fidelity and validity. Fidelity is the physical correspondence of the simulator's components, layout, and dynamics with its real world counterpart. The closer a simulator is to real driving in terms of vehicle handling, layout of controls, and realism of graphics, the higher the fidelity of the simulator.

There are two types of validity—relative and absolute. Relative validity is the comparison of the performance differences between experimental condition in the driving simulator and a real car (Blaauw, 1982). Absolute validity is defined as similar numerical values in two similar environments between the simulator and a real car. In general, two aspects of simulator validity were assessed in previous research: absolute validity and relative validity (Tornros, 1998; Reed, et al., 1999; Godley, et al., 2002). The absolute validity is established if the numerical values between simulator and real car are the same, whereas the relative validity is claimed when the differences between experimental conditions are in the same direction.

In Lee et al. study (2003), driving performance of older drivers was assessed both on-road driving and simulated driving. They revealed that 65.7 percent of variability in the on-road driving assessment could be explained by simulated driving assessment. If the simulator sickness participates were removed from analysis, the explainable variability from on-road driving by simulator was 67.1 percent. Validation studies regarding to drivers' distractions have been conducted in various research. The research about telephone dialing task while driving revealed that generally the variables values were larger in the simulator than on the road even though the same effects were significant both in two methods. Furthermore, the relative validity was established in speed control when the secondary task was performed while driving between the simulator and the on road driving. Other research to compare results of performing in-vehicle information systems while driving among simulators and real word data was conducted by Santos, et al. (2005). However, many inconsistent experimental results were obtained such as mean speed and lateral position.

General speaking, absolute validity was not easy to get in previous research, while relative validity was common been proven. Good relative validity of driving behaviors to drive through the tunnel between simulated road and real road was confirmed (Tornros, 1998). In addition, relative validity was also established for the stop sign approaching speed in a speeding countermeasures study (Godley, et al., 2002). Though the absolute validity is difficult to establish between simulators and real cars, however, relative validity is sufficient for a simulator to be a useful research tool because related research usually aimed to investigate the similar driving behavior patterns, rather than aim to determine numerical measurements (Godley, etl al., 2002).

Compared to enormous simulator-based research as above, applying simulators in work zone safety is rare. Muttart, et al. applied simulator to investigate driver behaviors approaching work zone. They revealed that using cell phone when driving may increase the possibilities of rear-end and sidewipe crashes which are usually seen in work zones. It was attributed to the finding that 30 percent less to check rear view mirror of drivers using cell phone when driving compared to those without using cell phone. Validation of simulators applied in work zone safety studies is also important as mentioned above. Bella (2004) investigated vehicle speed through work zones by conducting experiments both on real highway work zones and on simulated virtual work zones in simulator. Inconsistently, the mean vehicle speeds through work zones were the same between on real highway work zones and on simulated virtual work zones, while most studies concluded that the mean speed was higher in the simulator compared to the real car on road (Godley, et al., 2002; Totnros, 1998; Reed, et al., 1999). Finally, the negative results of absolute validity and relative validity were obtained in the research for nighttime work zone devices (McAvoy, et al., 2007).

In sum, applying simulators have some aforementioned advantages, while there are some disadvantages including simulator sickness, physical sensations, and validity (Godley, et al, 2006).

1.5. Research Objectives

The objectives of this research are 1) to use a macroergonomic approach to study the causes of work zone crashes, near crashes, and incidents to determine the primary causal factors and 2) to validate a high-fidelity driving simulator (DriveSafety's DS-600c) based on the findings of the naturalistic data. For purposes of this proposal, the definitions of crashes, near-crashes, and incidents are provided in Table 1 below.

Table 1. Definitions of crashes, near-crashes, and incidents

Event	Definition
Crashes	Any contact between the subject vehicle and another vehicle, fixed object, pedestrian, pedacyclist, animal
Near Crashes	A conflict situation requiring a rapid, severe evasive maneuver to avoid a crash
Incidents	Conflict requiring an evasive maneuver, but of lesser magnitude than a near crash

2. GENERAL DESCRIPTION OF THE RESEARCH

To address the crash causation portion of the research, CSU will use a macroergonomic approach to analyze naturalistic work zone driving data collected from 100 cars over a one-year period and ODOT historical crash data to identify the subsystem factors (driver, vehicle, organizational, and environmental) that influence work zone safety. In addition, CSU will determine what subsystem interactions play a critical role in work zone safety. To accomplish the second research objective, the pre-crash, near-crash and incident conditions will be replicated in a high-fidelity, fully-immersive simulator and then drivers will be tested under these conditions to determine whether the naturalistic data analysis results can be replicated using the simulator.

This research project fulfills one of the main tenets of the OPREP program—to demonstrate the viability of innovative concepts and their potential to address long-range transportation needs. This research is innovative in terms of its macroergonomic approach to analyzing work zone safety and because data from a large-scale naturalistic driving study has not yet been used to investigate work zone driving behavior. A simulator validated with naturalistic data has significant potential to address long-range transportation needs. These include but are not limited to: configuring potentially dangerous work zones prior to construction to identify unknown dangers and testing the effectiveness of safety countermeasures for any driving domain.

3. MACROERGONOMIC ANALYSIS OF NATURALISTIC DRIVING DATA

Naturalistic driving data of this scope and magnitude has not previously been analyzed to determine what factors influence crashes, near crashes and incidents in work zones specifically. Furthermore, a macroergonomic analysis has not been performed. This project analyzed the naturalistic data (and ODOT crash database data where appropriate) from a macroergonomic perspective to determine what, if any, joint causation exists among driving subsystems.

4. PILOT STUDY ON WORK ZONE SAFETY

An experimental pilot study was conducted using Cleveland State University's driving simulator to evaluate the effects of experimental factors on driver behavior in work zones. The simulator was used to conduct an experiment of driver performance through various work zones to determine what factors impact driver behavior and their performance. Cleveland State University's driving simulator was manufactured by DriveSafety, Inc. of Salt Lake City, Utah. The specific simulator was the DS-600C Research Simulator. The simulator allows for creation of custom virtual reality scenarios based upon various roadway types (urban, rural, highway, intersections), stop controls (stop sign or traffic signal), different levels of interactive ambient traffic, variable weather conditions, and varying levels of roadway friction. The simulator included a vehicle cab which included all the entities associated with the front portion of a vehicle such as windshield, front seats and doors, roof, safety belts, all standard dashboard instrumentation and driver controls, a rear view mirror, two side mirrors, an audio system, a steering wheel, gas and brake pedals, starting ignition, a motion platform and a 180 degree screen for the graphics display. The motion platform provides real time motion simulation based upon inertial cues from the vehicle cab including $\pm$ 2.5 degree pitch and five-inch longitudinal motion. The driving simulator is pictorially shown in Figures 3 and 4.

Figures 3 and 4. Cleveland State University's Driving Simulator

4.1. Simulator Development

While it was originally considered to design the simulator scenarios based upon the macroergonomic analysis of the 100-car naturalistic driving study, the work zone configurations were not documented in this study which eliminated the possibility of replicating the work zones in the simulator. Therefore, the simulator validation study, which would have been developed and conducted based on the findings obtained from the naturalistic data analysis in comparison to data obtained from the driving simulator, was not conducted. In addition, due to the lack of knowledge of the work zone configurations in the naturalistic driving study, the scope, content and experimental design of the pilot study was determined in cooperation with ODOT. After the scenarios were developed, ODOT then conducted a site visit to discuss the elements implemented in the scenarios.

Simulator development began in January of 2008 with the creation of virtual work zones in driving simulator scenarios. The work zones included traffic control devices and signs placed on the roadway in accordance with the Ohio Manual on Uniform Traffic Control Devices. Various factors were utilized in the development of the scenarios including work zone traffic density, roadway type, work zone type and precipitating elements. The precipitating factors can be described as an element that causes driver behavior or the state of the environment to change which initiates a crash, near-crash, or incident and the subsequent sequence of actions that result in a crash relevant conflict, near-crash or crash. For each of the factors, several levels were introduced into the scenario development. For the work zone traffic density, there were three levels including free flow conditions with no restrictions on traffic flow, free flow conditions with some maneuverability issues and speed restrictions, and stable flow with increased maneuverability issues and even further speed restrictions. The free flow conditions with no restrictions can be defined as low density or occupancy along the roadway and through the work zone. The second level of the work zone traffic density introduced some maneuverability issues through the increased density of ambient traffic along the roadway and through the work zone while the aped restrictions generally required a ten mile per hour reduction in speed. The further reduction in maneuverability can be described as an increased density of ambient traffic with more than a ten mile per hour reduction in the traveling speed. In terms of roadway type, two levels were included in the scenarios, a divided highway and an undivided roadway. There were also two levels of work zone type introduced in the scenarios including a lane closure and shoulder work with minor encroachments into the travel lane. The precipitating elements were quite extensive in the scenarios, but can be described in two levels. The first level was a stopped or slow vehicle in the travel lane while the second level was an object in the roadway.

A total of four scenarios were presented to study participants. Each scenario contained six treatment combinations (three on divided roads, three on undivided roads) or work zone configurations. The order in which treatment combinations or work zone appeared in the scenario was counterbalanced to prevent confounding. The order in which scenarios were presented was also randomized. Figures 5 and 6 pictorially show various scenes from the simulator scenarios.

Figure 5. Work Zone 6 (worker in lane)

Figure 6. Work Zone 9 (slow moving truck)

Table 2 outlines the details of each of the four scenarios resulting in 24 different treatment combinations or work zones. Table 3 indicates the order in which the treatment combinations were presented in each scenario to the participants.

Table 2. Developed Scenario Treatment Combinations

Work Zone Number	Road Type Level	Traffic Flow Level	Work Zone Type Level	Precipitating Factor
1	Divided	Free Flow	Lane Closure	Stopped Truck in Work Zone
2	Divided	Free Flow	Lane Closure	Cone Knocked Over in Travel Lane
3	Divided	Free Flow	Shoulder Work	Slow Moving Car in Work Zone
4	Divided	Free Flow	Shoulder Work	Barrel Encroaching on Travel Lane
5	Divided	Free Flow, Some Restrictions	Lane Closure	Braking Truck
6	Divided	Free Flow, Some Restrictions	Lane Closure	Worker in Roadway
7	Divided	Free Flow, Some Restrictions	Shoulder Work	Stopped Car in Work Zone
8	Divided	Free Flow, Some Restrictions	Shoulder Work	Sign Encroaching on Travel Lane
9	Divided	Stable, More Restrictions	Lane Closure	Slow Moving Truck
10	Divided	Stable, More Restrictions	Lane Closure	Cone Encroaching on Travel Lane
11	Divided	Stable, More Restrictions	Shoulder Work	Braking Car
12	Divided	Stable, More Restrictions	Shoulder Work	Barrel Knocked Over in Travel Lane
13	Undivided	Free Flow	Lane Closure	Braking Car
14	Undivided	Free Flow	Lane Closure	Cone Encroaching on Travel Lane
15	Undivided	Free Flow	Shoulder Work	Braking Truck
16	Undivided	Free Flow	Shoulder Work	Barrel Knocked Over in Travel Lane
17	Undivided	Free Flow, Some Restrictions	Lane Closure	Slow Moving Car in Work Zone
18	Undivided	Free Flow, Some Restrictions	Lane Closure	Cone Knocked Over in Travel Lane
19	Undivided	Free Flow, Some Restrictions	Shoulder Work	Stopped Truck in Work Zone
20	Undivided	Free Flow, Some Restrictions	Shoulder Work	Barrel Encroaching on Travel Lane
21	Undivided	Stable, More Restrictions	Lane Closure	Stopped Car in Work Zone
22	Undivided	Stable, More Restrictions	Lane Closure	Sign Encroaching on Travel Lane
23	Undivided	Stable, More Restrictions	Shoulder Work	Slow Moving Truck
24	Undivided	Stable, More Restrictions	Shoulder Work	Worker in Roadway

Table 3. Order of Treatment Combinations or Work Zone Configuration

Work Zone Number by Scenario			
Scenario 1	Scenario 2	Scenario 3	Scenario 4
6	17	5	22
3	20	8	13
9	16	11	15
18	1	23	2
19	7	24	12
21	4	14	10

4.2. Focus Group

The focus group of drivers was comprised of a sample from the general driver population of Ohio, selected from residents of metropolitan Cleveland, and with experience driving on the region's freeway system on their commute to work or school. Due to the participation of human subjects in this research, federal regulations required a review and approval for the proposed research methodology by an Institutional Review Board (IRB) for Human Subjects. At Cleveland State University, application for expedited approval for the simulator experiment was submitted to the IRB for Human Subjects Committee on April 8, 2008 and the expedited approval was received on September 10, 2008. During this time period, the researchers were not allowed to discuss the project, recruit participants or introduce participants to the driving simulator. The driving simulator experiment began in October of 2008 as soon as participants responded to the recruitment application. Included in the approved documents was the methodology detailing the procedures for the simulator experiment, the research informed consent form, and the driver participant pre-experiment and post-experiment questionnaires. The approved documents are provided in Appendix A.

Random sampling methods were not reasonable approaches for recruitment due to the relationship between the location of the driving simulator and the residence of randomly sampled individuals, time constraints and available resources. Convenience sampling measures were utilized to organize the focus group for the simulator experiment. For the majority of the individuals selected for the research, convenience sampling allowed the researchers to select individuals who were available to participate in the study. The participants were solicited on a voluntary basis by the researchers through direct person to person contact on Cleveland State University's campus or by email. Each individual was informed that their participation was voluntary, they could withdraw from the experiment at any time and they would be compensated ten dollars per hour once they started the experiment. Although the advantages of utilizing convenience sampling procedures are obvious, the disadvantages of the procedure may have resulted in a biased sample. In order to reduce the potential for biased results, each participant completed a questionnaire which documented various demographic data and driving habits or patterns.

In the pre-experiment questionnaire, the participants were asked to comment on their driving experiences both in work zones and in normal driving conditions, their involvement in crashes and violations, as well as their driving habits such as cell phone use or sending text messages. The pre-experiment questionnaire was also used to obtain demographic information in order for correlations to be made with their performance in the driving simulator and to determine if the focus group consisted of a representative sample of motorists from the State of Ohio. The post-experiment questionnaire was utilized to assess the reasonableness of the driving simulator to represent field conditions and to compare the subjects driving habits in the simulator to those stated during the pre-experiment questionnaire. The pre and post-experiment questionnaires are provided in Appendix B.

In order to generalize the data and results of the simulator experiment, comparisons were made between the sample population used in the simulator experiment and the population in Ohio. When comparing an observed frequency distribution or percentage with the corresponding values of an expected distribution, the intent was to test whether the discrepancies between the observed and expected frequencies or percentages could be attributed to chance. If the discrepancies were attributed to chance, then the differences between the two percentages would be deemed insignificant. The statistical equation used to determine if the gender and age distribution in the sample population were significantly different than the population in Ohio was the test for goodness-of-fit, or the chi-square test. The chi-square goodness-of-fit test was used to examine the null hypothesis that the participant profiles were similar to the population in Ohio in terms of age and gender. The null hypothesis for the chi-square or goodness of fit test was as follows:

H_o (null hypothesis): There was not a difference between the age or gender of the focus group sample and the population in Ohio.

The following equation was used to test the chi-square or goodness of fit (Hinkle, et al., 2003).

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

Where:
o_i = value of the observed frequency, the simulator experiment sample
e_i = value of the expected frequency, Ohio's population
k = number of categories

The result of this calculation yields the calculated chi-square value which was compared with the critical chi-square value obtained from available statistical tables. If the calculated chi-square value was greater than the critical chi-square value then the differences in the demographic data were significant and the null hypothesis was rejected. The chi-square test has underlying assumptions including discrete or categorical data of non-overlapping categories and nominal data, where the categories are described by name only, such as female and male, and not by levels of the variable (Hinkle, et al., 2003). The chi-square test can be a very powerful test for large samples; however, becomes quite weak when dealing with small samples.

The participants obtained from the convenience sampling procedures for the driving simulator experiment totaled 45 individuals. The 45 individuals comprised a sample from the general driver population, selected from the Cleveland State University community and residents of the metropolitan Cleveland area, with experience driving on the region's freeway system to commute to work or school. Participants were not allowed to partake in the research unless they possessed a valid driver's license and had corrected/uncorrected vision of 20/20. The gender breakdown of the participants was 75.6 percent male and 24.4 percent female, with varied ages. One participant did not desire to indicate her age, therefore, the age frequencies total 44 participants. In order to generalize the data and the results of the driving simulator experiment to Ohio drivers, comparisons were made between the participants of the simulator experiment and the population demographics of Ohio. The gender totals for Ohio included those individuals Table 4 summarizes the various demographics obtained from the 45 participants alongside similar data from Ohio residents. The data for the State of Ohio include those individuals 15 years of age and older, in other words, those that have a learner's permit or a driver's license. The State of Ohio data was obtained from the United States Census Bureau. The expected values were obtained by multiplying the number of participants in the simulator study by the State of Ohio percentages.

Table 4. Participant and Ohio Population Profile

Demographic Data		Simulator Sample		Ohio (2008)		Expected Value
		Frequency	Percent	Frequency	Percent	Frequency
Gender	Male	34	75.6	4,458,835*	48.2	22
	Female	11	24.4	4,786,687	51.8	23
Age	15-19	5	11.4	809,174	14.8	7
	20-24	21	47.7	762,549	13.9	6
	25-29	9	20.4	774,535	14.1	6
	30-34	4	9.1	688,933	12.6	5
	35-39	1	2.3	759,216	13.9	6
	40-44	3	6.8	796,463	14.5	7
	45-49	1	2.3	886,417	16.2	7

The observed frequency distribution or percentage of simulator demographics was compared with the corresponding values of the expected distribution of Ohio's demographics. The intent of the comparison was 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 from the simulator experiment was significantly different than the population from the State of Ohio was the test of goodness-of-fit, or the chi-square test as previously described. A standardized residual value was also calculated to determine if an observed value was a major contributor to the statistically significant result of the chi-square test (Field, 2005). The standardized residual was calculated by subtracting the expected value from the observed value and dividing that quantity by the square root of the expected value. If the standardized residual value was greater than a positive or negative value of two, it was concluded that the particular category was a major contributor to the significant difference in the demographic data (Hinkle et al., 2003). The chi-square test was conducted at an alpha level equal to 0.05 and a beta level equal to 0.20 or a level of confidence of 95 percent and a power of 80 percent. Table 5 summarizes the results of the chi-square test for the hypotheses regarding the gender and age of the driving simulator participants as compared to the driving population in Ohio.

Table 5. Results of the Chi-Square Test for Goodness of Fit

Demographic		Standardized Residual	χ^2_{calc}	Degrees of Freedom	χ^2_{cr}	Test Result
Gender	Male	2.56	12.81	1	3.84	Reject Null; $O_G \neq E_G$
	Female	-2.50				
Age	15-19	-0.76	51.37	6	12.59	Reject Null; $O_A \neq E_A$
	20-24	6.12				
	25-29	1.22				
	30-34	-0.45				
	35-39	-2.04				
	40-44	-1.51				
	45-49	-2.27				

The results of the chi-square test indicated that the gender of the 45 simulator experiment participants was statistically different to that of Ohio residents. A significant difference was also found for the comparison of the age between the simulator experiment participants and Ohio residents. Based upon the standardized residual calculations, the age brackets of 15 through 19, 25 through 29, 30 through 34 and 40-44 were not significantly over or under-represented in the sample for the simulator experiment. As expected, the age bracket of 20 through 24 was significantly over-represented and the age bracket of 45 through 49 was under-represented.

As differences were found between the simulator experiment participants and Ohio's population, discussions were required regarding the capability of generalizing the results of this research to Ohio's driving population. Since Ohio's population was not represented in the simulator experiment in terms of gender and age, crash involvement was considered. If the statistical analysis of the simulator data were conclusive for drivers that exhibit extreme variations for any measure of performance, then that data should also be conclusive for drivers exhibiting moderate or average performance measures. Table 6 summarizes the crash rates by age bracket based upon the 2007 Ohio Traffic Crash Facts and the 2007 Federal Highway Administration Highway Statistics on Licensed Drivers. It is important to note that the age brackets utilized in the Census are slightly different than those utilized for the crash frequency. The crash frequency and driver license totals age brackets are also different; however, the difference is only one year. Therefore, the age brackets utilized in crash frequencies have been utilized for the following analysis.

The age bracket with the highest crash rate in 2007 was those between the ages of 16 and 20. The simulator experiment sample reasonably represented Ohio's population age bracket of 16 through 20 years of age based upon the standardized residual value. However, the sample over-represented Ohio's population age bracket of 21 through 25 years of age, which has the second highest crash rate in 2007. As the research was conducted at a university, it was expected that this age bracket would include a higher proportion of individuals than the other age brackets. Since drivers that record higher crash rates based upon Ohio crash data were over-represented in the simulator experiment sample, the sample was considered to contain a higher percentage of high risk drivers than Ohio's driving population. Preliminary results from the crash analyses indicate that there were 84 crashes out of a possible 833 work zones driven in the simulator experiment which indicated a crash rate 0.101 crashes per work zone. The crash rate in the simulator is nearly identical to the crash rate for the age bracket of 21 through 25 of 0.103. This verified the high risk nature of the simulator experiment participants.

Table 6. Crash Rates for Ohio Motorists by Gender and Age Group

Demographic		Involvement in Severe Crashes (Fatal and Injury)	Involvement in Total Crashes	Number of Licensed Drivers	Severe Crash Rate*	Overall Crash Rate*
Gender	Male	77,152	293,957	3,864,340	0.020	0.076
	Female	63,709	227,518	4,111,434	0.015	0.055
Age	15-19	21,848	79,140	522,790	0.042	0.151
	20-24	18,152	66,171	644,032	0.028	0.103
	25-29	14,555	52,925	623,730	0.023	0.085
	30-34	12,391	45,637	602,200	0.021	0.076
	35-39	12,654	47,027	691,848	0.018	0.068
	40-44	12,405	46,936	737,221	0.017	0.064
	45-49	12,225	46,440	816,257	0.015	0.057

*Crashes per Licensed Driver

4.3. Data Collection

The purpose of the simulator experiment was to observe and quantify participant performance while driving through work zones representing various traffic densities, roadway types, work zone types and precipitating factors. The performance of the participants was recorded on the simulator control station as well as with a video camera for data validation, if necessary. The performance measures included the following:

- Crash frequency,
- Speed characteristics,
- Lateral lane placement,
- Acceleration, and
- Braking (Deceleration).

Comparisons were made of the driving performances of the focus group between the various work zones to determine the impact of the factors introduced in each work zone.

4.3.1. Crash Data

Traffic crash data was collected by the simulator control station to determine, for each work zone, if the participant crashed, at what time they crashed and the object into which they crashed. The simulator video was then reviewed to verify the object into which participant crashed. Based upon this information, the crash frequency was determined for all participants. A traffic crash occurred when the participant veered from the travel lane and hit an object. Upon hitting a object, the simulator experiment for that participant did not end, they were allowed to continue traveling through the scenario. In reality, based upon the severity of the crash, the driver may not have been able to continue driving. Unfortunately, severity of the crash was not able to be collected for this particular experiment.

4.3.2. Speed Data

The speed for each participant was recorded at a rate of 60 Hertz, or approximately every 0.034 seconds along the entire length of the four simulation scenarios. Each work zone was separated by normal, non-work zone driving intervals. The speed data that was collected during those intervals were not included in the calculations or data analysis since these roadway segments did not alter the participant's performance. The average speed for all the participants was calculated for each work zone. The average maximum speed attained through each work zone was also determined. Both the mean and maximum speeds collected through the work zone were in meters per second.

4.3.3. Lateral Lane Position and Lane Deviation Data

The lateral placement for each participant of the simulator experiment was quantified for each work zone. The lane offset for each participant was recorded similar to that of the speed, approximately every 0.034 seconds along the length of the simulation scenarios. The lane offset is recorded in meters within the current travel lane in which the participant is driving based upon the centerline of the vehicle. The lane offset is recorded as a positive number if the participant is traveling to the right of the center of the lane and a negative number if they are left of the center of the lane. As each lane was 3.6 meters in width, or 12 feet, the lane offset could be recorded as a $\pm$ 1.8 meters, or six feet. The average lateral position for each participant was calculated for each work zone based upon the lane offset. In addition, the lane deviation was calculated by subtracting the minimum lane position from the maximum lane position for each work zone.

4.3.4. Acceleration and Deceleration Data

The acceleration and braking for each participant was recorded at a rate of 60 Hertz, or approximately every 0.034 seconds along the entire length of each work zone. The acceleration was recorded as a normalized accelerator value with a range between 0.00 and 1.00. A value of 0.00 indicated that the accelerator pedal was not being depressed and a value of 1.00 indicated that the accelerator pedal was at maximum depression. Similarly, the braking data was recorded as a normalized braking value with a range from 0.00 to 1.00. The same descriptions apply for the braking data; expect the pedal evaluated is the braking pedal. The average acceleration and deceleration for all the participants were calculated for each work zone.

4.3.5. Statistical Analysis Methodology for the Crash Data

Crash data is typically analyzed based upon a Comparative Parallel Evaluation Plan or a Before and After Study Type Evaluation Plan. The Comparative Parallel Evaluation Plan utilizes test and control sites where a test site has been improved with a safety countermeasure and a control site has not been improved. The Before and After Study Type Evaluation Plan examines crash frequencies at the same site before and after the installation of the safety countermeasure. Both evaluations utilize the Poisson Test to determine if the safety countermeasure provided statistically significant reductions in traffic crashes. While the Evaluation Plans are different in this simulator study, the Poisson Test can be utilized for some of the analyses where the frequency in crashes is greater than five. The Poisson Test is not valid for crash frequencies below five. In addition, the Poisson Test cannot indicate which level of each factor contributed to the difference. Therefore, for both of these reasons, the chi-square test, as described in the Focus Group Section of this report, will be utilized to determine the statistical significance.

The chi-square test utilizes an expected crash frequency and an observed crash frequency. The expected crash frequency for each factor analysis was based upon the crash frequency data for the State of Ohio, as explained in the following statements. As described earlier, the total number of licensed drivers for similar age groups utilized in the simulator experiment equaled 4,638,078 individuals. The number of work zone crashes in Ohio, as stated earlier, was 5854 crashes. This equates to a crash rate of 0.0013 crashes per licensed driver. Therefore, the expected crash rate for each factor analysis was calculated by multiplying this crash rate by the number of participants for that particular factor.

4.3.6. Statistical Analysis Methodology for Mean Data

The mean data analysis involved the speed, lane placement, acceleration and deceleration data. In order to compare several means simultaneously, a one-way analysis of variance (ANOVA) was utilized to determine if the means were similar. Although a Student's t-test could have been conducted on the same data, several iterations of the t-test would be required in order to compare all possible scenarios. However, the Type I error rate is greater when multiple t-tests are conducted and can be calculated as follows (Hinkle, et al., 2003):

$$\text{Type I Error Rate} = 1 - (1 - \alpha)^{C}$$

Where:

α= the level of confidence for each t-test
C = the number of independent t-tests

The ANOVA determines the level of confidence based upon the number of dependent variable categories that are being compared. For instance, if the mean speed for each level of traffic density was compared, there would be three individual t-tests that would be conducted; free flow with restricted free flow, free flow with stable flow, and restricted free flow with stable flow. Although a desired Type I error of 0.05 was selected, the calculated Type I error rate was equal to 0.14. However, the ANOVA would utilize a level of confidence of 31.7 percent or alpha equal to 0.017 for each of the comparisons which would yield an alpha of 0.05 for the entire analysis.

The one-way ANOVA required the comparison of one independent variable, for example, traffic density, with several categories of the dependent variable, such as mean speed, lane deviation or acceleration. The assumptions for the ANOVA are similar to those for the Student's t-test. The data must be continuous, independent, follow the normal distribution and have equal variances (Hinkle, et al., 2003). Violations of these assumptions impact the results of the test; however, the robustness of the ANOVA varies from the Student's t-test. For instance, the ANOVA is considered a very robust test even with the violation of normality, unless the variances and sample sizes are unequal (Hinkle, et al., 2003). To perform the ANOVA, an F-statistic is calculated which is equal to the mean squares between the groups divided by the mean squares within the groups. If F- calculated was greater than the F-critical obtained in available statistical tables, the difference in the means was statistically significant. When conducting the ANOVA test, the Levene's test for equal variances was performed simultaneously. When the Levene's test indicated that the variances were equal, the ANOVA calculated F-statistic was reported. If the variances were determined not to be equal, the Welch's modification to the ANOVA was conducted and the calculated F value based upon an asymptotically distribution was reported. The equations used to perform this test are as follows (Hinkle, et al., 2003):

$$SS_T = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \frac{T^2}{N}$$

Where:

SS_T = Total sum of squares

$\sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2$ = squared scores summed across all individuals and groups

K = Number of groups

n = Number of observations

T = sum of scores summed across all observations and groups

N = total number of scores

$$SS_B = \sum_{k=1}^{K} \frac{T_k^2}{n_k} - \frac{T^2}{N}$$

Where:

SS_B = Sum of squares between-groups

T_k= sum of observations for k^{th} group

$$SS_W = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \sum_{k=1}^{k} \frac{T_k^2}{n_k}$$

Where:

SS_W = Sum of squares within-groups

$$MS_B = \frac{SS_B}{K - 1}$$

$$MS_W = \frac{SS_W}{N - K}$$

$$F_{calc} = \frac{MS_B}{MS_W}$$

Where:

MS_B = Mean sum of squares between-groups

MS_W = Mean sum of squares within-groups

When statistically significant results are obtained in the ANOVA, the only conclusion that can be drawn from the test is that differences exist between the means. However, the determination of which two means are in fact not equal cannot be concluded. Therefore, in order to solve this issue, post-hoc tests can be utilized to assist in specific comparisons among groups. There are numerous post-hoc tests that have been established for various assumptions or violation of assumptions. Most of the post-hoc tests have been shown in past statistical research to withstand small deviations from normality. The determination of the *post hoc* tests conducted during this research was based upon summaries of past research (Hinkle, et al., 2003). When the samples sizes were not equal but the variances were equal, the Gabriel test was conducted. If the variances were not assumed equal and the sample sizes were not equal, the Games-Howell test was conducted.

5. RESULTS

5.1. Crash Data Analysis

The analysis of crash data was used as an indication of the risk associated with a particular work zone. The crash frequency data was analyzed with the crash target, or object into which the participant crashed, identified. Statistical tests, the chi-square test in particular, were used to determine if the crash frequencies were statistically significant for several levels, including the following:

- Work Zone Comparisons
- Road Type Comparisons
- Work Zone Type Comparisons
- Traffic Flow Comparisons
- Precipitating Factor Comparisons

The following sections detail the statistical analysis for each comparison.

5.1.1. Work Zone Comparisons

The observed crash frequencies for each work zone, the number of participants completing the simulator experiment for that particular work zone, and the expected crash frequency, based upon a crash rate of 0.0013 crashes per participant, are shown in Table 7. The crash rate calculation was described in the Statistical Analysis Methodology for Crash Frequency previously in this report.

Table 7. Work Zone Crash Data Summary

Work Zone Number	Observed Crash Frequency	Number of Participants	Expected Crash Frequency
1	31	40	0.052
2	0	23	0.0299
3	0	42	0.0546
4	0	37	0.0481
5	1	34	0.0442
6	3	45	0.0585
7	1	37	0.0481
8	0	34	0.0442
9	5	43	0.0559
10	0	22	0.0286
11	8	34	0.0442
12	6	22	0.0286
13	7	23	0.0299
14	6	33	0.0429
15	2	23	0.0299
16	1	40	0.052
17	3	40	0.052
18	1	43	0.0559
19	3	42	0.0546
20	0	40	0.052
21	1	41	0.0533
22	5	27	0.0351
23	0	34	0.0442
24	0	34	0.0442

The chi-square test was conducted at an alpha level equal to 0.05 and a beta level equal to 0.20 or a level of confidence of 95 percent and a power of 80 percent. The results of the chi-square test are summarized in Table 8. The test indicated that the crash frequency among the work zones was statistically different. Based upon the standardized residual calculations, work zone one crashes were substantially over-represented in the sample. Other work zones that were also over-represented include work zones 5, 6, 7, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21 and 22.

Table 8. Results of the Work Zone Crash Frequency Chi-Square Test

Work Zone	Standardized Residual	χ^2_{calc}	Degrees of Freedom	χ^2_{cr}	Test Result
1	135.716	25382.83	23	35.17	Reject Null; $O \neq E$
2	-0.17292				
3	-0.23367				
4	-0.21932				
5	4.546277				
6	12.16161				
7	4.34029				
8	-0.21024				
9	20.91131				
10	-0.16912				
11	37.84188				
12	35.30963				
13	40.30913				
14	28.76115				
15	11.39338				
16	4.157255				
17	12.92784				
18	3.993118				
19	12.60515				
20	-0.22804				
21	4.100613				
22	26.50068				
23	-0.21024				
24	-0.21024				

5.1.2. Road Type Comparisons

The observed crash frequencies for each road type, the number of participants completing the simulator experiment for that particular road type, and the expected crash frequency, based upon a crash rate of 0.0013 crashes per participant, are shown in Table 9.

Table 9. Road Type Crash Data Summary

Road Type	Observed Crash Frequency	Number of Participants	Expected Crash Frequency
Divided	55	413	0.5369
Undivided	29	420	0.546

The chi-square test was conducted at an alpha level equal to 0.05 and a beta level equal to 0.20 or a level of confidence of 95 percent and a power of 80 percent. The results of the chi-square test are summarized in Table 10. The test indicated that the crash frequency among the road types was statistically different. Based upon the standardized residual calculations, crashes occurring in the divided roadway type were substantially more over-represented in the sample than the undivided roadway type crashes.

Table 10. Results of the Road Type Crash Frequency Chi-Square Test

Road Type	Standardized Residual	χ^2_{calc}	Degrees of Freedom	χ^2_{cr}	Test Result
Divided	74.32855	7007.57	1	3.84	Reject Null; O ≠ E
Undivided	38.50765				

5.1.3. Traffic Flow Comparisons

The observed crash frequencies for each traffic flow level, the number of participants completing the simulator experiment for that particular level, and the expected crash frequency, based upon a crash rate of 0.0013 crashes per participant, are shown in Table 11.

Table 11. Traffic Flow Crash Data Summary

Traffic Flow	Observed Crash Frequency	Number of Participants	Expected Crash Frequency
Free Flow	47	261	0.3393
Some Restrictions	12	315	0.4095
Stable Flow	25	257	0.3341

The chi-square test was conducted at an alpha level equal to 0.05 and a beta level equal to 0.20 or a level of confidence of 95 percent and a power of 80 percent. The results of the chi-square test are summarized in Table 12. The test indicated that the crash frequency among the traffic flow levels was statistically different. Based upon the standardized residual calculations, crashes primarily occurred more frequently when traffic flow was free and secondarily when traffic flow was stable. However, all traffic flow levels were over-represented in the sample.

Table 12. Results of the Traffic Flow Crash Frequency Chi-Square Test

Traffic Flow	Standardized Residual	χ^2_{calc}	Degrees of Freedom	χ^2_{cr}	Test Result
Free Flow	80.10494	8565.89	2	5.99	Reject Null; O ≠ E
Some Restrictions	18.11237				
Stable Flow	42.67355				

5.1.4. Work Zone Type Comparisons

The observed crash frequencies for each work zone type, the number of participants completing the simulator experiment for that particular work zone type, and the expected crash frequency, based upon a crash rate of 0.0013 crashes per participant, are shown in Table 13.

Table 13. Work Zone Type Crash Data Summary

Work Zone Type	Observed Crash Frequency	Number of Participants	Expected Crash Frequency

Lane Closure	63	414	0.5382
Shoulder Work	21	419	0.5447

The chi-square test was conducted at an alpha level equal to 0.05 and a beta level equal to 0.20 or a level of confidence of 95 percent and a power of 80 percent. The results of the chi-square test are summarized in Table 14. The test indicated that the crash frequency among the work zone types was statistically different. Based upon the standardized residual calculations, crashes occurring in lane closures were substantially more over-represented in the sample than the shoulder work crashes.

Table 14. Results of the Work Zone Type Crash Frequency Chi-Square Test

Work Zone Type	Standardized Residual	χ^2_{calc}	Degrees of Freedom	χ^2_{cr}	Test Result
Lane Closure	85.14176	8017.29	1	3.84	Reject Null; $O \neq E$
Shoulder Work	27.71578				

5.1.5. Precipitating Factor Comparisons

The observed crash frequencies for each precipitating factor, the number of participants completing the simulator experiment for that particular factor, and the expected crash frequency, based upon a crash rate of 0.0013 crashes per participant, are shown in Table 15.

Table 15. Precipitating Factor Crash Data Summary

Precipitating Factor	Observed Crash Frequency	Number of Participants	Expected Crash Frequency
Stopped Truck	34	82	0.1066
Cone Knocked Over	1	66	0.0858
Slow Moving Car	3	82	0.1066
Barrel Encroaching	0	77	0.1001
Braking Truck	3	57	0.0741
Worker	3	79	0.1027
Stopped Car	2	78	0.1014
Sign Encroaching	5	61	0.0793
Slow Moving Truck	5	77	0.1001
Cone Encroaching	6	55	0.0715
Braking Car	15	57	0.0741
Barrel Knocked Over	7	62	0.0806

The chi-square test was conducted at an alpha level equal to 0.05 and a beta level equal to 0.20 or a level of confidence of 95 percent and a power of 80 percent. The results of the chi-square test are summarized in Table 16. The test indicated that the crash frequency among the various precipitating factors was statistically different. Based upon the standardized residual calculations, work zone crashes involving a stopped truck or car, a cone or barrel knocked over, a slow moving truck or car, a braking truck or car, a worker, an encroaching sign or cone were substantially over-represented in the sample. The only precipitating factor that was not over-represented in the sample was an encroaching barrel. In terms of impact, the stopped truck caused the most crashes in work zones. Other precipitating factors that substantially played a role in work zone crashes were a braking truck or car, a knocked over barrel, and a cone or sign encroaching in to the travel lane.

Table 16. Results of the Precipitating Factor Crash Frequency Chi-Square Test

Precipitating Factor	Standardized Residual	χ^2_{calc}	Degrees of Freedom	χ^2_{cr}	Test Result
Stopped Truck	103.8094	15734.87	11	19.68	Reject Null; O ≠ E
Cone Knocked Over	3.121027				
Slow Moving Car	8.861962				
Barrel Encroaching	-0.31639				
Braking Truck	10.74856				
Worker	9.040829				
Stopped Car	5.962309				
Sign Encroaching	17.47392				
Slow Moving Truck	15.4871				
Cone Encroaching	22.17133				
Braking Car	54.83166				
Barrel Knocked Over	24.37255				

5.2. Speed Data Analysis

The analysis of speed data was used as an indication of the participant's perceived risk of traveling through a particular work zone. The speed data was analyzed with the mean speed by work zone calculated and the maximum speed identified. Statistical tests were used to determine if the mean speed or average maximum speed were statistically significant for several levels, including the following:

- Work Zone Comparisons
- Road Type Comparisons
- Work Zone Type Comparisons
- Traffic Flow Comparisons
- Precipitating Factor Comparisons

The following sections detail the statistical analysis for each comparison.

5.2.1. Work Zone Comparisons

The mean speed, maximum speed and the corresponding standard deviations for each work zone are summarized in Table 17.

Table 17. Work Zone Speed Data Summary

Work Zone Number	Mean Speed (mps)	Mean Speed Standard Deviation	Maximum Speed (mps)	Maximum Speed Standard Deviation
1	9.98	2.80	22.98	2.92
2	24.67	4.56	27.88	2.96
3	24.43	3.05	26.57	2.58
4	25.07	2.92	26.87	2.72
5	14.92	2.54	24.27	3.78
6	21.01	3.49	27.58	2.67
7	27.22	2.51	32.73	2.93
8	25.72	4.07	27.74	3.32
9	20.92	5.00	27.18	2.90
10	25.26	3.78	27.90	3.04
11	21.83	5.43	31.62	3.72
12	22.15	9.94	28.80	3.77
13	4.47	1.07	10.77	1.51
14	15.10	3.05	21.54	3.19
15	7.69	2.04	14.15	3.12
16	18.42	3.26	21.38	2.83
17	12.84	3.47	20.44	3.26
18	11.22	6.27	17.52	3.82
19	12.29	3.01	17.01	3.33
20	15.45	2.01	22.00	3.97
21	8.21	3.95	17.49	5.40
22	16.10	5.24	17.64	5.52
23	15.30	3.50	17.57	2.92
24	7.39	1.94	13.00	1.86

To determine the appropriate statistical test for comparison of the speed data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean speed and maximum speed data for the work zones. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean speeds between the work zones was rejected as shown in Table 18. Therefore, there were differences between the mean speeds of the various work zones.

Table 18. Work Zone Mean Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	34300.92	23	1491.34	237.80	1.54	Reject Null; WZ_i Mean Speed ≠ WZ_i Mean Speed
Within Groups	12708.544	276.42	15.71			
Total	47009.46	299.42				

The post hoc test provided numerous results indicating which work zones were statistically similar to each other in terms of mean speed. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 19 by indicating which work zones are statistically similar by groups.

Table 19. Work Zone Mean Speed *Post hoc* Results by Homogeneous Subsets

Group Number	Work Zone Number	Work Zone Similar Qualities	Significance Value (p-value)
1	13, 24, 15	Undivided Roadway	0.242
2	24, 15, 21, 1	Undivided Roadway	0.884
3	15, 21, 1, 18	Undivided Roadway	0.086
4	1, 18, 19, 17	Undivided Roadway	0.626
5	19, 17, 5, 14, 23, 20	Undivided Roadway	0.294
6	17, 5, 14, 23, 20, 22	Undivided Roadway	0.212
7	5, 14, 23, 20, 22, 16	Undivided Roadway	0.098
8	16, 9, 6. 11	Element in Roadway	0.130
9	9, 6, 11, 12, 3	Element in Roadway	0.092
10	6, 11, 12, 3, 2	Element in Roadway	0.052
11	11, 12, 3, 2, 4, 10	Element in Roadway	0.122
12	12. 3, 2, 4, 10, 8	Element in Roadway	0.074
13	3, 2, 4, 10, 8, 7	Element in Roadway	0.689

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the maximum speeds between the work zones was rejected as shown in Table 20. Therefore, there were differences between the maximum speeds of the various work zones.

Table 20. Work Zone Maximum Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	26322.77	23	1144.47	171.64	1.54	Reject Null; WZ_i Max Speed ≠ WZ_i Max Speed
Within Groups	9177.75	275.64	11.35			
Total	35500.53	298.64				

The post hoc test provided numerous results indicating which work zones were statistically similar to each other in terms of maximum speed. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 21 by indicating which work zones are statistically similar by groups.

Table 21. Work Zone Maximum Speed *Post hoc* Results by Homogeneous Subsets

Group Number	Work Zone Number	Work Zone Similar Qualities	Significance Value (p-value)
1	13, 24	Undivided Roadway	0.860
2	24, 15	Undivided, Shoulder	1.000
3	15, 19	Undivided, Shoulder	0.151
4	19, 21, 18, 23, 22	Undivided	1.000
5	21, 18, 23, 22, 17	Undivided	0.106
6	17, 16, 14, 20, 1	Undivided	0.460
7	16, 14, 20, 1, 5	Undivided	0.139
8	5, 3, 4, 9	Divided	0.125
9	3, 4, 9, 6, 8, 2, 10, 12	Divided	0.867
10	12, 11	Divided, Shoulder	0.175
11	11, 7	Divided, Shoulder	1.000

5.2.2. Road Type Comparisons

The mean speed, maximum speed and the corresponding standard deviations for each roadway types are summarized in Table 22.

Table 22. Road Type Speed Data Summary

Road Type	Mean Speed	Mean Speed Standard	Maximum Speed	Maximum Speed Standard

	(mps)	Deviation	(mps)	Deviation
Divided	21.65	6.49	27.56	4.03
Undivided	12.35	5.27	17.95	4.78

To determine the appropriate statistical test for comparison of the speed data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean speed and maximum speed data for the two roadway types. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean speeds between the roadway types was rejected. Therefore, there were differences between the mean speeds of undivided and divided roadways. The results of the one-way ANOVA are shown in Table 23. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of road type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that mean speeds were higher on divided roadways than along undivided roadways.

Table 23. Road Type Mean Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	17991.2	1	17991.282	513.449	1.52	Reject Null; Mean Speed ≠ Mean Speed
Within Groups	29018.18	792.25	34.92			
Total	47009.46	793.25				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the maximum speeds between the two roadway types was rejected. Therefore, there were differences between the maximum speeds of the two roadway types. The results of the one-way ANOVA are shown in Table 24. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of road type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that maximum speeds were higher on divided roadways than along undivided roadways.

Table 24. Road Type Maximum Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	19247.31	1	19247.31	986.89	1.52	Reject Null; Max Speed

Within Groups	13253.21	812.09	19.56			≠ Max Speed
Total		813.09				

5.2.3. Work Zone Type Comparisons

The mean speed, maximum speed and the corresponding standard deviations for each work zone type are summarized in Table 25.

Table 25. Work Zone Type Speed Data Summary

Work Zone Type	Mean Speed (mps)	Mean Speed Standard Deviation	Maximum Speed (mps)	Maximum Speed Standard Deviation
Lane Closure	15.08	7.05	22.06	5.98
Shoulder Work	18.82	7.51	23.36	6.98

To determine the appropriate statistical test for comparison of the speed data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean speed and maximum speed data for the two work zone types. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean speeds between the work zone types was rejected. Therefore, there were differences between the mean speeds of the two work zone types. The results of the one-way ANOVA are shown in Table 26. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of work zone type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that mean speeds were higher when only the shoulder was closed for construction than when a lane closure was in effect.

Table 26. Work Zone Type Mean Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	2908.64	1	2908.64	54.85	1.52	Reject Null; Mean Speed ≠ Mean Speed
Within Groups	44100.82	828.79	53.07			
Total	47009.46	829.79				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the maximum speed between the work zone types was rejected. Therefore, there were differences between the maximum speeds of the two work zone types. The results of the one-way ANOVA are shown in Table 27. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of work zone type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that maximum speeds were higher when only the shoulder was closed for construction than when a lane closure was in effect.

Table 27. Work Zone Type Maximum Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	353.34	1	353.34	8.37	1.52	Reject Null; Max Speed ≠ Max Speed
Within Groups	35147.19	814.42	42.30			
Total	35500.53	815.42				

5.2.4. Traffic Flow Comparisons

The mean speed, maximum speed and the corresponding standard deviations for each traffic flow level are summarized in Table 28.

Table 28. Traffic Flow Speed Data Summary

Traffic Flow Level	Mean Speed (mps)	Mean Speed Standard Deviation	Maximum Speed (mps)	Maximum Speed Standard Deviation
Free Flow	16.99	7.88	22.26	5.84
Some Restricted Flow	17.35	6.82	23.45	6.15
Stable Flow	16.45	7.94	22.27	7.52

To determine the appropriate statistical test for comparison of the speed data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean speed and maximum speed data for the traffic flow levels. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean speeds between the traffic flow levels was accepted. Therefore, traffic flow did not impact the mean speeds of vehicles through work zones. The results of the one-way ANOVA are shown in Table 29.

Table 29. Traffic Flow Mean Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	114.84	2	57.42	1.03	1.53	Accept Null; Mean Speed = Mean Speed
Within Groups	46894.63	529.30	56.50			
Total	47009.46	531.30				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the maximum speeds between the traffic flow levels was rejected. Therefore, there were differences between the maximum speeds of the various work zones. The results of the one-way ANOVA are shown in Table 30.

Table 30. Traffic Flow Maximum Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	272.93	2	136.47	3.46	1.53	Reject Null; Max Speed ≠Max Speed
Within Groups	35227.59	532.66	42.44			
Total	35500.53	534.66				

The post hoc test indicated which traffic flow levels were statistically similar to each other in terms of maximum speed. The post hoc analysis indicates that the free flow condition and stable flow condition as well as the slightly restricted traffic flow and the stable flow condition are similar. The free flow condition and the slightly restricted traffic flow condition are not statistically similar. The detailed post hoc analysis has been summarized in Table 31.

Table 31. Traffic Flow Maximum Speed *Post hoc* Results

Comparison	Mean Difference	Standard Error of the Difference	95% Lower Bound Confidence Interval	95% Upper Bound Confidence Interval	Test Result
Free Flow: Some Restrictions	-1.19	0.50	-2.36	-0.010	FF ≠ SR
Free Flow: Stable Flow	-0.14	0.59	-1.41	1.38	FF = SF
Some Restrictions: Stable Flow	1.17	0.58	-0.20	2.54	SR = SF

5.2.5. Precipitating Factor Comparisons

The mean speed, maximum speed and the corresponding standard deviations for each precipitating factor are summarized in Table 32.

Table 32. Precipitating Factor Speed Data Summary

Precipitating Factor	Mean Speed (mps)	Mean Speed Standard Deviation	Maximum Speed (mps)	Maximum Speed Standard Deviation
Stopped Truck	11.17	3.12	19.92	4.33
Cone Knocked Over	15.91	8.61	21.13	6.09
Slow Moving Car	18.77	6.67	23.58	4.24
Barrel Encroaching	20.07	5.44	24.34	4.19
Braking Truck	12.01	4.27	20.18	6.11
Worker	15.15	7.38	21.30	7.63
Stopped Car	17.23	10.12	24.72	8.83
Sign Encroaching	21.46	6.65	23.27	6.70
Slow Moving Truck	18.44	5.20	22.94	5.60
Cone Encroaching	19.16	6.02	24.08	4.42
Braking Car	14.82	9.57	23.21	10.75
Barrel Knocked Over	19.74	6.64	24.01	4.77

To determine the appropriate statistical test for comparison of the speed data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean speed and maximum speed data for the various precipitating factors. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean speeds between the precipitating factors was rejected. Therefore, there were differences between the mean speeds of the various precipitating factors. The results of the one-way ANOVA are shown in Table 33.

Table 33. Precipitating Factor Mean Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	7919.81	11	719.98	35.009	1.54	Reject Null; Mean Speed ≠Mean Speed
Within Groups	39089.65	311.36	47.61			
Total	47009.46	322.36				

The post hoc test provided numerous results indicating which precipitating factors were statistically similar to each other in terms of mean speed. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 34 by indicating which work precipitating factors are statistically similar by groups.

Table 34. Precipitating Factor Mean Speed *Post hoc* Results by Homogeneous Subsets

Group Number	Precipitating Factor	Significance Value (p-value)
1	Stopped Truck, Braking Truck, Braking Car, Worker	0.052
2	Braking Truck, Braking Car, Worker, Cone Knocked Over	0.066
3	Braking Car, Worker, Cone Knocked Over, Stopped Car, Slow Moving Truck, Slow Moving Car	0.057
4	Cone Knocked Over, Stopped Car, Slow Moving Truck, Slow Moving Car, Cone Encroaching, Barrel Knocked Over	0.079
5	Stopped Car, Slow Moving Truck, Slow Moving Car, Cone Encroaching, Barrel Knocked Over Barrel Encroaching	0.662
6	Slow Moving Truck, Slow Moving Car, Cone Encroaching, Barrel Knocked Over, Barrel Encroaching, Sign Encroaching	0.505

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the maximum speeds between the precipitating factors was rejected. Therefore, there were differences between the maximum speeds of the various precipitating factors. The results of the one-way ANOVA are shown in Table 35.

Table 35. Precipitating Factor Maximum Speed Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	2150.04	11	195.46	7.17	1.54	Reject Null; Max Speed ≠Max Speed
Within Groups	33350.49	312.96	40.62			
Total	35500.53	323.97				

The post hoc test provided numerous results indicating which precipitating factors were statistically similar to each other in terms of maximum speed. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 36 by indicating which work zones are statistically similar by groups.

Table 36. Precipitating Factor Maximum Speed *Post hoc* Results by Homogeneous Subsets

Group Number	Precipitating Factor	Significance Value (p-value)
1	Stopped Truck, Braking Truck, Cone Knocked Over, Worker, Slow Moving Truck, Braking Car, Sign Encroaching, Slow Moving Car	0.056
2	Cone Knocked Over, Worker, Slow Moving Truck, Braking Car, Sign Encroaching, Slow Moving Car, Barrel Knocked Over, Cone Encroaching, Barrel Encroaching, Stopped Car	0.068

5.3. Lane Position and Lane Deviation Data Analysis

The lateral placement of vehicles through the work zone was quantified in order to assess the ability of the driver in terms of guidance through the work zone. The lane position data was analyzed with the mean lane position and lane deviation by work zone calculated. Statistical tests were used to determine if the mean lane position or mean lane deviation were statistically significant for several levels, including the following:

- Work Zone Comparisons
- Road Type Comparisons
- Work Zone Type Comparisons
- Traffic Flow Comparisons
- Precipitating Factor Comparisons

The following sections detail the statistical analysis for each comparison.

5.3.1. Work Zone Comparisons

The mean lane position, lane deviation and the corresponding standard deviations for each work zone are summarized in Table 37.

Table 37. Work Zone Lane Position Data Summary

Work Zone Number	Mean Lane Position (m)	Mean Lane Position Standard Deviation	Lane Deviation (m)	Lane Deviation Standard Deviation
1	-0.58	0.36	-1.46	0.86
2	-0.52	0.28	-2.24	1.17
3	-0.43	0.30	-1.39	1.20
4	-0.34	0.34	-1.69	1.22
5	-0.68	0.25	-1.49	0.97
6	-0.56	0.25	-2.62	1.17
7	-0.14	0.26	-3.04	0.82
8	-0.25	0.35	-1.49	1.31
9	-0.50	0.39	-2.57	1.07
10	-0.53	0.30	-1.55	0.60
11	-0.20	0.21	-2.48	1.27
12	-0.24	0.30	-2.26	1.36
13	-0.09	0.27	-2.20	0.42
14	0.09	0.22	-2.95	0.34
15	-0.15	0.23	-0.97	0.66
16	-0.36	0.32	-1.65	0.50
17	-0.63	0.33	-2.26	1.36
18	-0.66	0.50	-2.10	1.13
19	-0.60	0.32	-2.26	1.43
20	-0.49	0.33	-2.78	1.19
21	-0.60	0.37	-2.19	0.96
22	-0.24	0.32	-1.25	1.08
23	-0.52	0.25	-1.81	0.39
24	-0.13	0.25	-0.92	0.55

To determine the appropriate statistical test for comparison of the lane position data, the data was examined for homogeneity of variances. The Levene’s test determined that there were not any differences in the variance among the mean lane position data for the work zones. Therefore, the Gabriel post hoc test was selected.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane positions between the work zones was rejected. Therefore, there were differences between the mean lane positions of the various work zones. The results of the one-way ANOVA are shown in Table 38.

Table 38. Work Zone Mean Lane Position Statistical Results (ANOVA)

<table>
<tr><th>Source of Variation</th><th>Sum of Squares (SS)</th><th>Degrees of Freedom (df)</th><th>Mean Squares (MS)</th><th>F-Calculated</th><th>F-Critical</th><th>Test Result</th></tr>
<tr><td>Between Groups</td><td>35.62</td><td>23</td><td>1.55</td><td rowspan="3">15.38</td><td rowspan="3">1.52</td><td rowspan="3">Reject Null; WZ_i Mean LP $\neq$ WZ_i Mean LP</td></tr>
<tr><td>Within Groups</td><td>81.47</td><td>809</td><td>0.10</td></tr>
<tr><td>Total</td><td>117.09</td><td>832</td><td></td></tr>
</table>

The post hoc test provided numerous results indicating which work zones were statistically similar to each other in terms of mean lane position. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 39 by indicating which work zones are statistically similar by groups.

Table 39. Work Zone Mean Lane Position *Post hoc* Results by Homogeneous Subsets

Group Number	Work Zone Number	Significance Value (p-value)
1	5, 18, 17, 19, 21, 1, 6, 10, 2, 23, 9, 20, 3	0.238
2	17, 19, 21, 1, 6, 10, 2, 23, 9, 20, 3, 16, 4	0.055
3	10, 2, 23, 9, 20, 3, 16, 4, 8, 22, 12	0.055
4	20, 3, 16, 4, 8, 22, 12, 11	0.063
5	3, 16, 4, 8, 22, 12, 11, 15, 7	0.074
6	16, 4, 8, 22, 12, 11, 15, 7, 24, 13	0.134
7	11, 15, 7, 24, 13, 14	0.064

To determine the appropriate statistical test for comparison of the lane position data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the lane deviation data for the work zones. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane positions between the work zones was rejected. Therefore, there were differences between the mean lane positions of the various work zones. The results of the one-way ANOVA are shown in Table 40.

Table 40. Work Zone Lane Deviation Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	283.03	23	12.31	26.64	1.54	Reject Null; WZ_i LD ≠ WZ_i LD
Within Groups	924.74	276.06	1.14			
Total	1207.773	299.06				

The post hoc test provided numerous results indicating which work zones were statistically similar to each other in terms of mean lane deviation. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 41 by indicating which work zones are statistically similar by groups.

Table 41. Work Zone Lane Deviation *Post hoc* Results by Homogeneous Subsets

Group Number	Work Zone Number	Significance Value (p-value)
1	7, 14, 20, 6, 9, 11, 12, 17, 19, 2, 13, 21, 18	0.098
2	20, 6, 9, 11, 12, 17, 19, 2, 13, 21, 18, 23	0.060
3	6, 9, 11, 12, 17, 19, 2, 13, 21, 18, 23, 4, 16	0.067
4	11, 12, 17, 19, 2, 13, 21, 18, 23, 4, 16, 10, 8, 5	0.050
5	12, 17, 19, 2, 13, 21, 18, 23, 4, 16, 10, 8, 5, 1, 3	0.233
6	2, 13, 21, 18, 23, 4, 16, 10, 8, 5, 1, 3, 22	0.055
7	23, 4, 16, 10, 8, 5, 1, 3, 22, 15, 24	0.198

5.3.2. Road Type Comparisons

The mean lane position, lane deviation and the corresponding standard deviations for each road type are summarized in Table 42.

Table 42. Road Type Lane Position Data Summary

Road Type	Mean Lane Position (m)	Mean Lane Position Standard Deviation	Lane Deviation (m)	Lane Deviation Standard Deviation
Divided	-0.42	0.35	-2.03	1.23
Undivided	-0.40	0.40	-2.00	1.18

To determine the appropriate statistical test for comparison of the lane position data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean lane position and lane deviation data for the road types. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane positions between the road types was accepted. Therefore, there were not any differences between the mean lane positions of the two road types indicating that a divided or undivided roadway did not impact the ability of motorists to guide themselves through a work zone. The results of the one-way ANOVA are shown in Table 43.

Table 43. Road Type Mean Lane Position Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.063	1	0.063	0.448	1.52	Accept Null; Mean LP = Mean LP
Within Groups	117.03	816.78	0.141			
Total		817.78				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane deviation between the road types was accepted. Therefore, there were not any differences between the mean lane deviation of the two road types indicating that a divided or undivided roadway did not impact the ability of motorists to guide themselves through a work zone. The results of the one-way ANOVA are shown in Table 44.

Table 44. Road Type Lane Deviation Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.289	1	0.289	0.199	1.52	Accept Null; LD = LD
Within Groups	1207.48	827.81	1.453			
Total	1207.77	828.81				

5.3.3. Work Zone Type Comparisons

The mean lane position, lane deviation and the corresponding standard deviations for each work zone type are summarized in Table 45.

Table 45. Work Zone Type Lane Position Data Summary

Work Zone Type	Mean Lane Position (m)	Mean Lane Position Standard Deviation	Lane Deviation (m)	Lane Deviation Standard Deviation
Lane Closure	-0.49	0.40	-2.11	1.11
Shoulder Work	-0.34	0.33	-1.92	1.29

To determine the appropriate statistical test for comparison of the lane position data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean lane position and lane deviation data for the work zones. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane positions between the work zone types was rejected. Therefore, there were differences between the mean lane positions of the two work zone types. The results of the one-way ANOVA are shown in Table 46. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of work zone type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that there was a greater mean lane position when a lane was closed as opposed to a shoulder closure. This indicates that in a lane closure, the drivers were traveling further away from the channelizing devices than when the shoulder was closed.

Table 46. Work Zone Type Mean Lane Position Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	4.61	1	4.61	33.98	1.52	Reject Null; Mean LP ≠ Mean LP
Within Groups	112.48	798.18	0.14			
Total	117.09	799.18				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane deviation between the work zone types was rejected. Therefore, there were differences between the mean lane deviations of the two work zone types. The results of the one-way ANOVA are shown in Table 47. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of work zone type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that there was a greater mean lane deviation when a lane was closed as opposed to a shoulder closure. This indicates that in a lane closure, the drivers were traveling further away from the channelizing devices than when the shoulder was closed.

Table 47. Work Zone Type Lane Deviation Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	7.73	1	7.738	5.368	1.52	Reject Null; LD ≠ LD
Within Groups	1200.04	816.52	1.444			
Total	1207.77	817.52				

5.3.4. Traffic Flow Comparisons

The mean lane position, lane deviation and the corresponding standard deviations for each traffic flow level are summarized in Table 48.

Table 48. Traffic Flow Lane Position Data Summary

Traffic Flow Level	Mean Lane Position (m)	Mean Lane Position Standard Deviation	Lane Deviation (m)	Lane Deviation Standard Deviation
Free Flow	-0.32	0.36	-1.79	1.04
Some Restricted Flow	-0.51	0.38	-2.28	1.28
Stable Flow	-0.38	0.35	-1.93	1.21

To determine the appropriate statistical test for comparison of the lane position data, the data was examined for homogeneity of variances. The Levene's test determined that there were not any differences in the variance among the mean lane position for the traffic flow levels. Therefore, the Gabriel post hoc test was selected.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane positions between the traffic flow levels was rejected. Therefore, there were differences between the mean lane positions of the three levels of traffic flow. The results of the one-way ANOVA are shown in Table 49.

Table 49. Traffic Flow Mean Lane Position Statistical Results (ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	5.54	2	2.771	20.621	1.52	Reject Null; Mean LP ≠Mean LP
Within Groups	111.55	830	0.134			
Total	117.09	832				

The post hoc test indicated which traffic flow levels were statistically similar to each other in terms of mean lane position. The post hoc analysis indicates that the free flow condition and stable flow condition are similar. The free flow condition and the slightly restricted traffic flow condition as well as the stable flow condition and the slightly restricted traffic flow condition are not statistically similar. The detailed post hoc analysis has been summarized in Table 50.

Table 50. Traffic Flow Mean Lane Position *Post hoc* Results

Comparison	Mean Difference	Standard Error of the Difference	95% Lower Bound Confidence Interval	95% Upper Bound Confidence Interval	Test Result
Free Flow: Some Restrictions	0.19	0.03	0.119	0.264	FF ≠ SR
Free Flow: Stable Flow	0.07	0.03	-0.011	0.143	FF = SF
Some Restrictions: Stable Flow	-0.13	0.03	-0.200	-0.053	SR ≠ SF

To determine the appropriate statistical test for comparison of the lane deviation data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean lane deviation data for the work zones. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane deviations between the three traffic flow levels was rejected. Therefore, there were differences between the mean lane deviations of the traffic flow levels. The results of the one-way ANOVA are shown in Table 51.

Table 51. Traffic Flow Lane Deviation Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	37.70	2	18.85	13.348	1.53	Reject Null; LD ≠LD
Within Groups	1170.07	547.44	1.41			
Total	1207.77					

The post hoc test indicated which traffic flow levels were statistically similar to each other in terms of mean lane deviation. The post hoc analysis indicates that the free flow condition and stable flow condition are similar. The free flow condition and the slightly restricted traffic flow condition as well as the stable flow condition and the slightly restricted traffic flow condition are not statistically similar. The detailed post hoc analysis has been summarized in Table 52.

Table 52. Traffic Flow Lane Deviation *Post hoc* Results

Comparison	Mean Difference	Standard Error of the Difference	95% Lower Bound Confidence Interval	95% Upper Bound Confidence Interval	Test Result
Free Flow: Some Restrictions	0.493	0.097	0.2657	0.7203	FF ≠ SR
Free Flow: Stable Flow	0.139	0.099	-0.0930	0.3719	FF = SF
Some Restrictions: Stable Flow	-0.354	0.104	-0.599	-0.1082	SR ≠ SF

5.3.5. Precipitating Factor Comparisons

The mean lane position, lane deviation and the corresponding standard deviations for each precipitating factor are summarized in Table 53.

Table 53. Precipitating Factor Lane Position Data Summary

Precipitating Factor	Mean Lane Position (m)	Mean Lane Position Standard Deviation	Lane Deviation (m)	Lane Deviation Standard Deviation
Stopped Truck	-0.59	0.34	-1.87	1.24
Cone Knocked Over	-0.61	0.44	-2.14	1.14
Slow Moving Car	-0.53	0.33	-1.81	1.35
Barrel Encroaching	-0.42	0.34	-2.25	1.32
Braking Truck	-0.47	0.36	-1.28	0.89
Worker	-0.38	0.33	-1.89	1.27
Stopped Car	-0.38	0.40	-2.59	0.99
Sign Encroaching	-0.25	0.34	-1.39	1.21
Slow Moving Truck	-0.51	0.33	-2.24	1.27
Cone Encroaching	-0.16	0.40	-2.39	0.83
Braking Car	-0.15	0.24	-2.36	1.02
Barrel Knocked Over	-0.32	0.32	-1.87	0.94

To determine the appropriate statistical test for comparison of the lane position data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean lane position and lane deviation data for the various precipitating factors. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane positions between the precipitating factors was rejected. Therefore, there were differences between the mean lane positions of the various precipitating factors. The results of the one-way ANOVA are shown in Table 54.

Table 54. Precipitating Factor Mean Lane Position Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	17.00	11	1.545	14.207	1.54	Reject Null; Mean LP ≠Mean LP
Within Groups	100.09	315	0.122			
Total	117.09	326				

The post hoc test provided numerous results indicating which precipitating factors were statistically similar to each other in terms of mean lane position. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 55 by indicating which work zones are statistically similar by groups.

Table 55. Precipitating Factor Mean Lane Position *Post hoc* Results by Homogeneous Subsets

Group Number	Precipitating Factor	Significance Value (p-value)
1	Cone Knocked Over, Stopped Truck, Slow Moving Car, Slow Moving Truck, Braking Truck, Barrel Encroaching	0.078
2	Slow Moving Car, Slow Moving Truck, Braking Truck, Barrel Encroaching, Stopped Car, Worker	0.545
3	Slow Moving Truck, Braking Truck, Barrel Encroaching, Stopped Car, Worker, Barrel Knocked Over	0.096
4	Barrel Encroaching, Stopped Car, Worker, Barrel Knocked Over, Sign Encroaching	0.255
5	Barrel Knocked Over, Sign Encroaching, Cone Encroaching, Braking Car	0.338

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean lane deviations between the precipitating factors was rejected. Therefore, there were differences between the mean lane deviations of the various precipitating factors. The results of the one-way ANOVA are shown in Table 56.

Table 56. Precipitating Factor Lane Deviation Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	112.94	11	10.27	9.89	1.54	Reject Null; LD ≠LD
Within Groups	1094.83	316.82	1.33			
Total	1207.77	327.82				

The post hoc test provided numerous results indicating which precipitating factors were statistically similar to each other in terms of mean lane deviation. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 57 by indicating which precipitating factors are statistically similar by groups.

Table 57. Precipitating Factor Lane Deviation *Post hoc* Results by Homogeneous Subsets

Group Number	Precipitating Factor	Significance Value (p-value)
1	Stopped Car, Cone Encroaching, Braking Car, Barrel Encroaching, Slow Moving Truck, Cone Knocked Over	0.803
2	Cone Encroaching, Braking Car, Barrel Encroaching, Slow Moving Truck, Cone Knocked Over, Worker, Stopped Truck, Barrel Knocked Over, Slow Moving Car	0.207
3	Worker, Stopped Truck, Barrel Knocked Over, Slow Moving Car, Sign Encroaching, Braking Truck	0.134

5.4. Acceleration and Deceleration Data Analysis

The analysis of acceleration and deceleration data was used as an indication of the participant's reaction time and attention span while traveling through a particular work zone. The data was analyzed with the mean acceleration or deceleration by work zone calculated. Statistical tests were used to determine if the mean acceleration or mean deceleration were statistically significant for several levels, including the following:

- Work Zone Comparisons
- Road Type Comparisons
- Work Zone Type Comparisons
- Traffic Flow Comparisons
- Precipitating Factor Comparisons

The following sections detail the statistical analysis for each comparison.

5.4.1. Work Zone Comparisons

The mean acceleration, mean deceleration and the corresponding standard deviations for each work zone are summarized in Table 58.

Table 58. Work Zone Acceleration and Deceleration Data Summary

Work Zone Number	Mean Accel.	Mean Accel. Standard Deviation	Mean Decel.	Mean Decel. Standard Deviation
1	0.08	0.028	0.05	0.034
2	0.14	0.067	.01	0.169
3	0.16	0.047	0.01	0.125
4	0.17	0.038	0.00	0.003
5	0.32	0.036	0.04	0.029
6	0.14	0.030	0.02	0.018
7	0.17	0.030	0.00	0.003
8	0.16	0.054	0.00	0.011
9	0.13	0.034	0.01	0.015
10	0.16	0.053	0.01	0.013
11	0.20	0.055	0.07	0.035
12	0.12	0.053	0.05	0.064
13	0.04	0.022	0.06	0.057
14	0.09	0.039	0.03	0.028
15	0.08	0.013	0.05	0.026
16	0.09	0.036	0.01	0.012
17	0.07	0.029	0.03	0.056
18	0.07	0.035	0.05	0.090
19	0.09	0.022	0.02	0.018
20	0.06	0.029	0.01	0.011
21	0.07	0.036	0.06	0.065
22	0.09	0.063	0.01	0.010
23	0.07	0.037	0.01	0.013
24	0.06	0.020	0.02	0.017

To determine the appropriate statistical test for comparison of the acceleration and deceleration data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the means for the work zones. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean acceleration between the work zones was rejected. Therefore, there were differences between the mean accelerations of the various work zones. The results of the one-way ANOVA are shown in Table 59.

Table 59. Work Zone Mean Acceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	1.659	23	0.072	56.107	1.54	Reject Null; WZ_i Mean Accel $\neq$ WZ_i Mean Accel
Within Groups	1.209	275.62	0.001			
Total	2.868	298.62				

The post hoc test provided numerous results indicating which work zones were statistically similar to each other in terms of mean acceleration. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 60 by indicating which work zones are statistically similar by groups.

Table 60. Work Zone Mean Acceleration *Post hoc* Results by Homogeneous Subsets

Group Number	Work Zone Number	Significance Value (p-value)
1	13, 20, 24, 21, 17, 18, 23	0.303
2	20, 24, 21, 17, 18, 23, 1, 15, 22, 16, 19, 14	0.411
3	15, 22, 16, 19, 14, 12	0.075
4	12, 9, 5, 6, 2	0.812
5	9, 5, 6, 2, 10, 3	0.068
6	5, 6, 2, 10, 3, 8	0.240
7	6, 2, 10, 3, 8, 7, 4	0.178
8	7, 4, 11	0.228

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean deceleration between the work zones was rejected. Therefore, there were differences between the mean deceleration of the various work zones. The results of the one-way ANOVA are shown in Table 61.

Table 61. Work Zone Mean Deceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.390	23	0.017	28.342	1.54	Reject Null; WZ_i Mean Decel ≠ WZ_i Mean Decel
Within Groups	1.024	271.16	0.001			
Total	1.414	294.16				

The post hoc test provided numerous results indicating which work zones were statistically similar to each other in terms of mean deceleration. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 62 by indicating which work zones are statistically similar by groups.

Table 62. Work Zone Mean Deceleration *Post hoc* Results by Homogeneous Subsets

Group Number	Work Zone Number	Significance Value (p-value)
1	4, 7, 8, 3, 22, 10, 2, 23, 9, 16, 20, 19, 6, 24, 17, 14	0.071
2	23, 9, 16, 20, 19, 6, 24, 17, 14, 5	0.058
3	20, 19, 6, 24, 17, 14, 5, 12	0.066
4	6, 24, 17, 14, 5, 12, 1, 15, 18	0.161
5	17, 14, 5, 12, 1, 15, 18, 21	0.240
6	14, 5, 12, 1, 15, 18, 21, 13	0.137
7	5, 12, 1, 15, 18, 21, 13, 11	0.131

5.4.2. Road Type Comparisons

The mean acceleration, mean deceleration and the corresponding standard deviations for each road type are summarized in Table 63.

Table 63. Road Type Acceleration and Deceleration Data Summary

Road Type	Mean Accel.	Mean Accel. Standard Deviation	Mean Decel.	Mean Decel. Standard Deviation
Divided	0.15	0.05	0.02	0.033
Undivided	0.07	0.04	0.03	0.047

To determine the appropriate statistical test for comparison of the acceleration data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the mean acceleration for the road types. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean acceleration between the road types was rejected. Therefore, there were differences between the mean accelerations of the two road types. The results of the one-way ANOVA are shown in Table 64. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of road type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that mean acceleration data was higher on divided roadways than along undivided roadways.

Table 64. Road Type Mean Acceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	1.163	1	1.163	563.568	1.52	Reject Null; Mean Accel ≠ Mean Accel
Within Groups	1.704	722.27	0.002			
Total	2.868	723.27				

To determine the appropriate statistical test for comparison of the deceleration data, the data was examined for homogeneity of variances. The Levene's test determined that there were not any differences in the variance among the mean deceleration for the two road types. Therefore, the Gabriel post hoc test was selected.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean deceleration between the two road types was rejected. Therefore, there were differences between the mean deceleration of the road types. The results of the one-way ANOVA are shown in Table 65. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of road type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that mean deceleration was slightly higher on undivided roadways than along divided roadways.

Table 65. Road Type Mean Deceleration Statistical Results (ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.012	1	0.012	7.324	1.52	Reject Null; Mean Decel ≠ Mean Decel
Within Groups	1.402	831	0.002			
Total	1.414	832				

5.4.3. Work Zone Type Comparisons

The mean acceleration, mean deceleration and the corresponding standard deviations for each work zone type are summarized in Table 66.

Table 66. Work Zone Type Acceleration and Deceleration Data Summary

Work Zone Type	Mean Accel.	Mean Accel. Standard Deviation	Mean Decel.	Mean Decel. Standard Deviation
Lane Closure	0.10	0.05	0.03	0.049
Shoulder Work	0.12	0.06	0.02	0.030

To determine the appropriate statistical test for comparison of the acceleration and deceleration data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the means for the work zone types. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean acceleration between the work zone types was rejected. Therefore, there were differences between the mean accelerations of the various work zone types. The results of the one-way ANOVA are shown in Table 67. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of work zone type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that mean acceleration was higher when a shoulder closure was in effect as compared to a lane closure.

Table 67. Work Zone Type Mean Acceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.11	1	0.111	33.503	1.52	Reject Null; Mean Accel ≠ Mean Accel
Within Groups	2.76	809.69	0.003			
Total	2.87	810.69				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean deceleration between the work zone typess was rejected. Therefore, there were differences between the mean deceleration of the various work zone types. The results of the one-way ANOVA are shown in Table 68. Post hoc tests can only be conducted where there are three or more levels of a variable. Therefore, for the analysis of work zone type, a post hoc test was not conducted. However, based upon the results of the data, it can be observed that mean deceleration was higher when a lane closure was in effect as compared to a shoulder closure.

Table 68. Work Zone Type Mean Deceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.046	1	0.046	27.903	1.53	Reject Null; Mean Decel ≠ Mean Decel
Within Groups	1.368	683.87	0.002			
Total	1.414	684.87				

5.4.4. Traffic Flow Comparisons

The mean acceleration, mean deceleration and the corresponding standard deviations for each traffic flow level are summarized in Table 69.

Table 69. Traffic Flow Acceleration and Deceleration Data Summary

Traffic Flow Level	Mean Accel.	Mean Accel. Standard Deviation	Mean Decel.	Mean Decel. Standard Deviation
Free Flow	0.11	0.06	0.03	0.034
Some Restricted Flow	0.11	0.05	0.02	0.044

Stable Flow	0.11	0.06	0.03	0.044

To determine the appropriate statistical test for comparison of the acceleration and deceleration data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the means for the traffic flow levels. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean acceleration between the traffic flows was accepted. Therefore, there were not any differences between the mean accelerations of the various work zones. The results of the one-way ANOVA are shown in Table 70.

Table 70. Traffic Flow Mean Acceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.001	2	0.000			Accept Null; Mean Accel = Mean Accel ES = 0.42
Within Groups	2.87	531.54	0.003	0.087	1.53	
Total	2.868	533.54				

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean deceleration between the traffic flows was accepted. Therefore, there were not any differences between the mean deceleration of the three traffic flow levels. The results of the one-way ANOVA are shown in Table 71.

Table 71. Traffic Flow Mean Deceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.007	2	0.003			Accept Null; Mean Decel =Mean Decel
Within Groups	1.407	543.63	0.002	1.841	1.53	
Total	1.414	545.63				

5.4.5. Precipitating Factor Comparisons

The mean acceleration, mean deceleration and the corresponding standard deviations for each precipitating factors are summarized in Table 72.

Table 72. Precipitating Factor Acceleration and Deceleration Data Summary

Precipitating Factor	Mean Accel.	Mean Accel. Standard Deviation	Mean Decel.	Mean Decel. Standard Deviation
Stopped Truck	0.08	0.03	0.03	0.032
Cone Knocked Over	0.09	0.06	0.04	0.076
Slow Moving Car	0.11	0.06	0.02	0.042
Barrel Encroaching	0.12	0.07	0.01	0.010
Braking Truck	0.11	0.04	0.05	0.280
Worker	0.11	0.05	0.02	0.017
Stopped Car	0.12	0.06	0.03	0.055
Sign Encroaching	0.13	0.07	0.00	0.010
Slow Moving Truck	0.10	0.04	0.01	0.014
Cone Encroaching	0.12	0.06	0.02	0.026
Braking Car	0.14	0.09	0.07	0.045
Barrel Knocked Over	0.10	0.04	0.02	0.042

To determine the appropriate statistical test for comparison of the acceleration and deceleration data, the data was examined for homogeneity of variances. The Levene's test determined that there were differences in the variance among the means for the precipitating factors. Therefore, the Welch's modification to the ANOVA was selected as was the Games-Howell post hoc test.

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean acceleration between the precipitating factors was rejected. Therefore, there were differences between the mean accelerations of the various factors. The results of the one-way ANOVA are shown in Table 73.

Table 73. Precipitating Factor Mean Acceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.16	11	0.015	7.088	1.54	Reject Null; Mean Accel ≠ Mean Accel
Within Groups	2.70	310.92	0.003			
Total	2.86	321.92				

The post hoc test provided numerous results indicating which precipitating factors were statistically similar to each other in terms of mean acceleration. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 74 by indicating which precipitating factors are statistically similar by groups.

Table 74. Precipitating Factor Mean Acceleration *Post hoc* Results by Homogeneous Subsets

Group Number	Precipitating Factor	Significance Value (p-value)
1	Stopped Truck, Cone Knocked Over, Barrel Knocked Over, Slow Moving Truck, Worker, Braking Truck, Slow Moving Car, Barrel Encroaching, Stopped Car	0.069
2	Cone Knocked Over, Barrel Knocked Over, Slow Moving Truck, Worker, Braking Truck, Slow Moving Car, Barrel Encroaching, Stopped Car, Cone Encroaching	0.633
3	Barrel Knocked Over, Slow Moving Truck, Worker, Braking Truck, Slow Moving Car, Barrel Encroaching, Stopped Car, Cone Encroaching, Sign Encroaching	0.126
4	Worker, Braking Truck, Slow Moving Car, Barrel Encroaching, Stopped Car, Cone Encroaching, Sign Encroaching, Braking Car	0.151

Based upon the statistical analyses, the null hypothesis stating that there were no differences in the mean deceleration between the precipitating factors was rejected. Therefore, there were differences between the mean deceleration of the various precipitating factors. The results of the one-way ANOVA are shown in Table 75.

Table 75. Precipitating Factor Mean Deceleration Statistical Results (Welch's ANOVA)

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calculated	F-Critical	Test Result
Between Groups	0.225	11	0.02	28.334	1.54	Reject Null; Mean Decel ≠Mean Decel
Within Groups	1.189	310.35	0.001			
Total	1.414	311.35				

The post hoc test provided numerous results indicating which precipitating factors were statistically similar to each other in terms of mean deceleration. Instead of providing the detailed post hoc analysis, the results of the data have been summarized in Table 76 by indicating which precipitating factors are statistically similar by groups.

Table 76. Precipitating Factor Mean Deceleration Post hoc Results by Homogeneous Subsets

Group Number	Precipitating Factor	Significance Value (p-value)
1	Sign Encroaching, Barrel Encroaching, Slow Moving Truck, Slow Moving Car, Cone Encroaching, Barrel Knocked Over, Worker	0.198
2	Slow Moving Car, Cone Encroaching, Barrel Knocked Over, Worker, Stopped Truck, Stopped Car, Cone Knocked Over	0.120
3	Worker, Stopped Truck, Stopped Car, Cone Knocked Over, Braking Truck	0.051
4	Braking Car	1.00

6. CONCLUSIONS

After reviewing the results of the statistical analysis, the conclusions outlined as follows by measure of effectiveness are summarized.

- Crash Data Analysis
  - More crashes occurred in the simulator than occur on Ohio roadways. This was somewhat expected since the participants in the simulator were shown to include age groups that exhibit greater risk along roadways.
  - Significantly more crashes occurred in the work zone scenario including a divided roadway with free flow traffic conditions and a lane closure when a work zone truck stopped in the work zone. This was substantiated with the analysis that more crashes occur on divided roadways than undivided roadways. More crashes also occur in a lane closure situation than during a shoulder closure. In addition, a stopped truck in the work zone caused substantially more crashes than any other precipitating event.
  - The crash occurrences in traffic flow levels indicated that more crashes occur in free flow conditions followed by stable flow conditions.
- Speed Data Analysis
  - Mean and maximum speeds were higher along divided roadways in comparison to undivided roadways.
  - Mean and maximum speeds were slightly lower when there was a lane closure as compared to a shoulder closure.
  - Regardless of the traffic flow levels, the mean speeds were similar. However, the maximum speeds were different when comparing the free flow conditions to the slightly restricted flow conditions. The other conditions were found to be similar. The speed data from the simulator indicated that the mean and maximum speeds were greatest during the slightly restricted flow, which may not be representative of actual travel speeds through work zones in the real world.
  - Speeds were similar when there was a stopped truck, braking car or truck and a worker in the work zone. Speeds were also similar when there was a slow moving car or truck in the work zone as well as if there was an element encroaching onto the travel lane or knocked over into the travel lane, such as a cone or barrel.
- Lane Position Data Analysis
  - Regardless of roadway type, the participants were able to guide themselves through the work zone in a similar manner.
  - In a lane closure situation, the participants moved further away from the channelizing devices than in a shoulder closure situation.
  - When faced with a stopped car, braking car, slow moving truck, a knocked over cone, and a barrel or cone encroaching into the travel lane, participants were more likely to swerve to avoid the element.
- Acceleration and Deceleration Data Analysis
  - Participants accelerated more frequently along divided roadways as compared to undivided roadways; however their deceleration, although statistically different, were nearly similar.

- As expected, participants accelerated more frequently when a shoulder closure was present as compared to a lane closure and decelerated more frequently when a lane closure was present as compared to a shoulder closure.
- Traffic flow did not have an impact on acceleration or deceleration.
- Participants depressed their brake pedal more frequently when faced with a braking car or truck, a knocked over cone or a stopped truck in the work zone.

6.1. Recommendations

Based upon the results of the simulator data analysis, additional future research can be identified to validate the driving simulator in terms of similarities with Ohio work zones. For instance, the speeds observed in the simulator were greater for divided roadways than undivided roadways. Absolute, relative and interactive validity could be analyzed to determine what differences, if any, exist between the simulator and the data collected in Ohio. Since the naturalistic study conducted by Virginia Tech did not identify or document the work zone configurations, the simulator validity portion of this project could not be completed. However, additional data collection in Ohio could validate the simulator using other data and methods.

Due to the sample collected in the simulator, additional research could be conducted to obtain a more representative sample, particularly for individuals 35 years of age and older. If a sample could be obtained that included the more conservative drivers, it would be anticipated that the crash frequency in the simulator would decrease. However, the crash frequency may not be reduced substantially enough to equal similarities with the State of Ohio crash frequencies in work zones. Ultimately, the simulator could be utilized to test various work zone traffic control devices, configurations or innovative traffic control measures with fair amount of assurances that more crashes would occur in the simulator than in the field. In this circumstance, the simulator is a more conservative evaluation device than what would be found in the field if the same circumstances were implemented.

The simulator traffic flow scenarios should be thoroughly examined to determine the rationale behind the confounding results in the comparisons of free flow, slight restrictions in the traffic flow and stable flow. This would involve extensive evaluations of the driving simulator video data for each participant.

6.2. Implementation

An additional research study should be considered to fully validate the simulator for work zone research in the State of Ohio comparing the existing simulator data to Ohio work zone data.

While the simulator has not been validated for Ohio work zones, research can begin using the simulator for innovative work zone devices in a variety of situations. Impacts on traffic flow should not be considered at this time, until the simulator is proven to handle specific speed reductions seen in work zones.

7. REFERENCES

Andrew, L.B. and Bryden, J.E. (2001): A work zone intrusion Initiative to Reduce Highway Construction Accidents, *Transportation Research Board 2001 Annual Meeting*. Washington D. C..

Arditi, D., Ayrancioglu, M., and Shi, J. J. (2005), Worker safety issues in night-time highway construction. *Engineering, Construction and Architectural Management*, 12 (5), 487-501.

Bai, Y. and Li, Y. F. (2006). Determining the major causes of highway work zone accidents in Kansas. Kansas Department of Transportation Report No. K-TRAN: KU-05-1.

Bella F. (2004). Driving simulation in virtual reality for work zone design on highway: a validation study. *The Second SIIV International Congress*, Florence, Italy.

Benekohal, R. F., Shim, E., and Resende, T. V. (1995). Truck drivers' concerns in work zones: travel characteristics and accident experiences. *Transportation Research Record 1509*, 55 – 64.

Broughton, K. L., Switzer, F., and Scott, D. (2007). Car following decisions under three visibility conditions and two speeds tested with a driving simulator. *Accident Analysis and prevention*, 39, 106-116.

Caccamise, D. J. (1995). Implementation of a team approach to nuclear criticality safety: The use of participatory methods in macroergonomics, *International Journal of Industrial Ergonomics*, 15, 397-409.

Carayon, P. (2006). Human factors of complex sociotechnical systems. *Applied Ergonomics*, 37, 525-535.

Carayon, P., Hundt, A. S., Karsh, B. T., Gurses, A. P., Alvarado, C. J., Smith, M., and Brennan, P. F. (2006). Work system design for patient safety: the SEIPS model, *Quality Safety Health Care*, 15(Supplement I), i50-i58.

Chambless, J., Belou, L., Lindly, J. K., and Mcfadden, J. (2001). Identification of over-represented parameters for work zone crashes in Alabama, Michigan, and Tennessee. *Transportation Research Board 2001 Annual Meeting,* Washington D. C..

Chambless, J., Ghadiali, A. M., Lindly, J. K., and Mcfadden, J. (2002). Multistate work-zone crash characteristics. *ITE Journal*, 72 (5), 46-50.

Charlton, S. G. (2004). Perceptual and attentional effects on drivers' speed selection at curves. *Accident Analysis and Prevention*, 36, 877-884.

Dingus, T. A., Neale, V. L., Klauer, S. G., Petersen, A. D., and Carroll, R. J. (2006). The development of a naturalistic data collection system to perform critical incident analysis: An investigation of safety and fatigue issues in long-haul trucking. *Accident Analysis and Prevention*, 38, 1127-1136.

Dingus, T., McGehee, D., Hulse, M., Jahns, S., Manakkal, N., Mollenhauer, M, and Fleishman, R. (1995). *Travtek Evaluation Task C_3-Camera Car Study*. FHWA Publication No. FHWA-RD- 94-076, Washington, D.C..

Drive and Stay Alive, Inc. (2005). 100-car naturalistic driving study tracks drivers for a year. www.driveandstayalive.com

Federal Highway Administration. (2005). *Facts and Statistics*.

Federal Highway Administration. (2000). *Manual on Uniform Traffic Control Devices* (MUTCD). Washington D. C..

http://ops.fhwa.dot.gov/wz/resources/facts_stats.htm.

Fatality Analysis Reporting System. (2006). Retrieved January 19, 2006. http://www-fars.nhtsa.dot.gov/.

Fontaine, M. D., Carlson, P. J., and Hawkins, H. G., Jr.. (2000) *Evaluation of traffic control devices for rural high-speed maintenance work zones: second year activities and final recommend actions*. FHWA, Publication No. FHWA-TX- 01-1879-2

Fors, C. (2000). Slowing Them Down in Deadly Work Zones. *Better Roads*, 70 (6), 35-37.

Garber, N. J. and Woo, T. H. (1990). Accident characteristics at construction and maintenance zones in urban areas. Virginia Transportation Research Council Report No. VTRC 90 – R12, Charlottesville, Virginia.

Garber, N. J., and Zhao, M. (2002). Crash characteristics at work zones. Virginia Transportation Research Council Report No. VTRC 02-R12, Charlottesville, Virginia.

Godley, S. T., Triggs, T. J., and Fildes, B. N. (2002). Driving simulator validation for speed research, *Accident Analysis and Prevention*, 34, 589-600.

Ha, T-J, and Nemeth, Z.A. (1995). *Detailed Study of Accident Experience in Construction and Maintenance Zones.* Transportation Research Record: Journal of the Transportation Research Board, No. 1509, TRB, National Research Council, Washington, D.C., pp. 38-45.

Hall, J. W. and Lorenz, V. M. (1989). Characteristics of construction zone crashes. *Transportation Research Record 1230*, 20 – 27.

Hanowski, R. J., Wierwille, W. W., Garness, S. A., and Dingus, T. A. (1995). *Impact of Local/Short haul operations on driver fatigue*. Report No. DOC-MC- 00-203, Federal Motor Carrier Safety Administration, Washington, D.C..

Hanowski, R. J., Perez, M. A., and Dingus, T. A. (2005). Driver distraction in long-haul truck drivers. *Transportation Research Part F*, 8, 441-458.

Hendrick, H.W. and Kleiner, B.M. (2002). *Macroergonomics: An Introduction to Work System Design*. Santa Monica: Human Factors and Ergonomics Society.

Holstein, D. (2006). Personal Communication.

Horberry, T., Anderson, J., Regan, M. A., Triggs, T. J., and Brown, J. (2006). Driver distraction: the effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. *Accident Analysis and Prevention*, 38, 185-191.

Ikeda, A., Katou, T., Kinoshita, M., and Aihara, M. (2002). Study of driver characteristics using driving simulator considerations on difference in accident avoidance performance due to age. *Journal of Society of Automotive Engineers of Japan*, 23, 219-222.

Kamyab, A., McDonald, T., Storm, B., and Anderson-Wilk, M. (2003). *Effectiveness of Extra Enforcement in Construction and Maintenance Work Zones*, Midwest States Smart Work Zone Deployment Initiative, Report No. MwSWZDI Year 4 Technology Evaluation #1.

Keenan, C. (2004). Work zones that work. *Public Roads* (FHWA-HRT-05-002), 68(3).

Khattack, A.J., Khattak, A.J. and Council, F.M. (2002). *Effects of work zone presence on injury and non-injury crashes*. Accident Analysis and Prevention. 34, 19-29.

Kleiner, B. M. (2006). Macroergonomics: Analysis and design of work systems. *Applied Ergonomics*, 37, 81-89.

Kraemer, S. and Carayon, P. (2007). Human errors and violations in computer and information security: The viewpoint of network administrators and security specialists. *Applied Ergonomics*, 38, 143-154.

Lee, H. C., Cameron, D., and Lee. A. H. (2003). Assessing the driving performance of older adult drivers: on road versus simulated driving. *Accident Analysis and Prevention*, 35, 797-803.

Leung, S., and Starmer, G. (2005). Gap acceptance and risk-taking by young and mature drivers, both sober and alcohol-intoxicated, in a simulated driving task. *Accident Analysis and Prevention*, 37, 1056-1065.

Lindly, J. K, Noorjahan, S., and Hill, S. (2002). *Identification of potential enhancements for work zone safety in Alabama*. University Transportation Center for Alabama, Report No. 00465.

Mattox, J. H., Sarasua, W. A., Ogle, J. H., Eckenrode, R. T., and Dunning, A. (2006). Development and evaluation of a speed-activated sign to reduce speeds in work zones. *Transportation Research Board*. Paper No. 06-0015.

McAvoy, D. S, Schattler, K. L., and Datta, T. K. (2007). Driving simulator validation for nighttime construction work zone devices. *Transportation Research Board 2007 Annual Meeting*, Washington D. C..

Mohan, S. and Zech, W.C. (2005). Characteristics of worker accidents on NYSDOT construction projects. *Journal of Safety Research*. 36, 353-60.

Mohan, S. B., and Gautam, P. (2002). Cost of highway work zone injuries. *Practice Periodical on Structural Design and Construction*, 7 (2), 68-73.

Muttart, J. W., Fisher, D. L., Knodler, M., and Pollatsek, A. (2007). Driving simulator evaluation of driving performance during hands-free cell phone operation in a work zone: driving without a clue. *Transportation Research Board 2007 Annual Meeting*, Washington D. C..

National Roadway Safety Award. (2005). Federal Highway Administration. http://safety.fhwa.dot.gov/awards.htm#a3

Neale, V.L., Dingus, T.A., Klauer, S.G., Sudweeks, J., and Goodman, M. An overview of the 100-car naturalistic study and findings. Paper number 04-400.

Nemeth Z. A., and Migletz, D. J. (1978). Accident characteristics before, during, and after safety upgrading projects on Ohio's rural interstate system. *Transportation Research Record* 672, 19-23.

Ohio Department of Public Safety. (2006). Retrieved March 5, 2007. http://www.publicsafety.ohio.gov/publicat/HSY7606/HSY7606-2005.PDF

Ohio Department of Transportation. (2006). Internet News Release. http://www.dot.state.oh.us/news/2006/04-03-06.htm

Office of Highway Policy Information. (2001). *Highway Statistics 2001*. Publication No. FHWA-PL-02-020, Washington D.C..

Ohio Transportation Safety Program Receives National Recognition. (2005). Retrieved February 15, 2006. www.governor.ohio.gov/releases/112105odot.htm

Pigman, J. G. and Agent, K. R. (1990). Highway crashes in construction and maintenance work zones. *Transportation Research Record 1270*, 12 – 21.

Qi, Y., Srinivasan, R., Teng, H., and Baker, R. F. (2005). *Frequency of work zone accidents on construction projects.* New York State Department of Transportation Report No. 55657-03-15.

Rakauskas, M. E., Gugerty, L. J., and Ward, N. J. (2004). Effects of naturalistic cell phone conversations on driving performance. *Journal of Safety Research*, 35, 453-464.

Raub, Richard A., Sawaya, Omar B., Schofer, Joseph L., Ziliaskopoulos, Athanasios. (2001). *Enhanced Crash Reporting to Explore Workzone Crash Patterns*. Northwestern University Center for Public Safety, Evanston, IL, 2001.

Reed, M. P., and Green, P. A. (1999). Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialing task, *Ergonomics*, 42 (8), 1015-1037.

Santos, J., Merat, N., Mouta, S., Brookhuis, K., and Waard, D. (2005). The interaction between driving and in-vehicle information systems: Comparison of results from laboratory, simulator and real-world studies. *Transportation Research Part F*, 8, 135-146.

Schrock, S. D., Ullman, G. L., Cothron, A. S., Krasu, E., and Voigt, A. P. (2004). An analysis of fatal work zone crashes in Texas. FHWA Report No. FHWA/TX-05/0-4028-1, Washington, D.C..

Sorock, G.S., Ranney, T.A., and Lehto, M.R. *Motor vehicle crashes in roadway construction*

workzones: an analysis using narrative text from insurance claims. Accident Analysis and Prevention, 28 (1), 131-138.
State Warns Drivers: 'Slow Down or Pay Up.' (2005). The Ohio Department of Transportation.
Strayer, D., Drews, F. A., and Crouch, D. J. (2003). Fatal distraction? a comparison of the cell-phone driver and the drunk driver. *Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 25-30.
Stutts, J., Feaganes, J., Reinfurt, D., Rodgman, E., Hamlett, C., Gish, K., and Staplin, L. (2005). Driver's exposure to distractions in their natural driving environment. *Accident Analysis and Prevention*, 37, 1093-1101.
Tornros, J. (1998). Driving behaviour in a real and a simulated road tunnel—a validation study. *Accident Analysis and Prevention*, 30, 497-503.
Ullman, G. L., and Krammes, R. A. (1991). Analysis of Accidents at Long-Term Construction Projects in Texas. FHWA Report No. FHWA/TX-90/1108-2, Washington, D. C..
Ullman, G. L., Finley, A. D., and Ullman, B. R. (2006). Analysis of crashes at active night work zones in Texas, *Transportation Research Board 2006 Annual Meeting*, Washington D. C..
U.S. Government Accountability Office. (2003). Research continues on a variety of factors that contribute to motor vehicle crashes. Report No. GAO-03-436, Washington, D. C..
United States General Accounting Office. (2003). *Research Continues on a variety of factors that contribute to motor vehicle crashes*. GAO-03-436.
Wang, Jun, Warrren E. Huges, Forrest M. Council, and Jeffery F. Paniati. (1996). *Investigation of Highway Work Zone Crashes: What We Know and What We Don't Know*. Transportation Research Record: Journal of the Transportation Research Board, No. 1529, TRB, National Research Council. Washington, D.C., pp. 54-62.
Young, K., Regan, M., and Hammer, M. (2003). *Driver distraction: a review of the literature*. Monash University, Accident Research Centre, Report No. 206.

APPENDIX A
Institutional Review Board Approved Documents

APPENDIX B

Pre and Post-Experiment Questionnaires

Pre-experiment Questionnaire

Directions: Please provide the following information about yourself to the best of your knowledge. The data collected is strictly for research purposes and will be kept confidential.

1. Gender: Male ☐ Female ☐

2. Age:_______ years

3. I have:

   perfect vision ☐ to wear corrective lenses ☐

4. Current student status:

   Undergraduate ☐

   Graduate ☐

   Doctoral ☐

   Post-doctoral ☐

5. Driving Experience: ___________ years

6. Do you own your motor vehicle (e.g., car, truck, sports utility vehicle)?

   Yes ☐ No ☐

7. How often do you drive a motor vehicle (e.g., car, truck, sports utility vehicle)?

   Very Rarely (e.g., a couple of times a year) ☐

   Rarely (e.g., a couple of times a month) ☐

   Frequently (e.g., a couple of times a week) ☐

   Very Frequently (e.g., everyday) ☐

8. Please list and provide a brief description of any accidents or traffic violations in your U.S. driving history.

____

____

____

____

____

9. Do you listen to music (e.g., radio, CD, MP3 player) while driving? Yes ☐ No ☐

9a. If yes, how often do you listen to music while driving?

Very Rarely ☐ Rarely ☐ Frequently ☐ Very Frequently ☐

10. Do you talk on your cell phone while driving? Yes ☐ No ☐

10a. If yes, how often do you use your cell phone while driving?

Very Rarely ☐ Rarely ☐ Frequently ☐ Very Frequently ☐

11. Do you send text messages while driving? Yes ☐ No ☐

11a. If yes, how often do you send text messages while driving?

Very Rarely ☐ Rarely ☐ Frequently ☐ Very Frequently ☐

12. Do you read text messages while driving? Yes ☐ No ☐

12a. If yes, how often do you read text messages while driving?

Very Rarely ☐ Rarely ☐ Frequently ☐ Very Frequently ☐

13. Do you use hands-free devices (e.g., Bluetooth) while driving? Yes ☐ No ☐

13a. If yes, how often do you use hands-free devices while driving?

Very Rarely ☐ Rarely ☐ Frequently ☐ Very Frequently ☐

14. Do you use a Global Positioning System (GPS) while driving? Yes ☐ No ☐

14a. If yes, how often do you use a GPS while driving?

Very Rarely ☐ Rarely ☐ Frequently ☐ Very Frequently ☐

Circle the answer that best indicates how much you agree or disagree with the statement.

15. I consider myself a conscientious driver.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

16. I obey speed limits when driving on roadways in non-work zones (i.e., drive no more than 5 mph over the posted speed limit).

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

17. I obey speed limits in work zones (i.e., drive no more than 5 mph over the posted speed limit).

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

18. I think that most accidents (both in work zones and non-work zones) are caused by speeding.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

19. I pay more attention to driving and the surrounding environment when I am going through a work zone.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

20. I drive more cautiously when I am going through a work zone.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

21. Using electronic devices (e.g., cell phones, PDAs, and MP3 players) while driving is distracting.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

22. I think that most accidents (both in work zones and non-work zones) are caused by using electronic devices.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

Post-experiment Questionnaire

Directions:
For each question, circle the answer that best indicates how much you agree or disagree with the statements.

1. The driving experience in the simulator was realistic.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

2. After a short time in the simulator, I fell into my typical driving habits (e.g., not attending to the forward roadway).

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

3. The weather conditions in the scenarios (e.g., snow, rain) affected my ability to drive.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

4. I was concerned about getting into an accident in a work zone.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

5. I was concerned about getting into an accident in a non-work zone.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

6. I felt I paid more attention to the speed limit, driving conditions and the surrounding environment, etc. in work zones than in non-work zones.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

7. I felt my driving ability was affected by other vehicles on the roadways.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

8. It was easy to adhere to the posted speed limits on roadways in non-work zones.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

9. It was easy to adhere to the posted speed limits in work zones.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

10. It was easy to drive with one lane closure in a work zone.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

11. It was easy to maintain my lane on roadways in non-work zones.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree

12. It was easy to maintain my lane in work zones.

1	2	3	4	5
Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree