# EXAMINING DRIVER BEHAVIOR IN RESPONSE TO WORK ZONE INTERVENTIONS: A DRIVING SIMULATOR STUDY

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# EXECUTIVE SUMMARY

## Objective

Construction zones pose a significant threat to both workers and drivers causing numerous injuries and deaths each year. Innovations in work zone safety could reduce these numbers. However, implementing work zone interventions before they are validated can undermine rather than enhance safety. The objective of this research is to demonstrate how driving simulators can be used to evaluate the effect of various work zone interventions on driver performance.

## Methods

This research was conducted in two phases. The first phase consisted of reviewing current work zone interventions, identifying gaps in the literature, evaluating the simulator requirements to implement each intervention, and obtaining feedback from subject matter experts. In the second phase, a study was designed to evaluate the effect of work zone barrier type (concrete barrier, drums, or 42-inch channelizers), presence or absence of a 4-ft lateral buffer, and work zone activity level (high or low) on measures of speed and lane position. Twelve middle aged (35-50 years old) and twelve senior (65-80 years old) participants completed six 12-minute drives in a National Advanced Driving Simulator (NADS) MiniSim. Their average speed, speed variability, average lane position, and lane position variability were measured.

## Major Findings

- The participants drove the fastest and with less variability in work zones with concrete barriers. Drums and channelizers affected driving performance differently depending on the work zone conditions. On-road evaluations are warranted to learn whether performance differences exist for drum and channelizers and how they might impact safety in actual work zones.

- For some combinations of conditions, the 4-ft lateral buffer provided the expected benefit of reduced speed variability.  However, average speed across all four combinations of age and gender were more similar to one another without the buffer, particularly for the drum and channelizer work zones.
- Areas of high work zone activity led to slower average speed and increased speed variability compared to low activity areas.
- These results suggest that work zones with lengthy longitudinal buffers or intermittent areas of work activity have the potential to increase crash risk by creating more opportunities for large speed differentials to develop.
- Though the results of this study do correspond to findings from *in situ* work zone studies, the generalizability of these results to actual work zone design is limited due to a need for simulator validation.  These results do suggest important research questions that can be evaluated with future *in situ* and/or simulator studies.
- Overall this project has demonstrated the feasibility and benefit of using driving simulators to investigate work zone interventions and their effect on individual driver performance.

# INTRODUCTION

Construction zones pose a significant threat to both workers and drivers. In 2008, more than 720 fatalities and over 40,000 injuries occurred within designated work zones (Federal Highway Administration, 2011). In Iowa alone, work zone crashes led to 91 fatalities from 1997 to 2006 (The National Work Zone Safety Information Clearinghouse). The total cost of crashes occurring within work zones exceeded $5.74 billion in 1997 and will undoubtedly grow as roadways become more heavily traveled (Mohan, Satish B. & Gautam, Padma, 2002). Innovations in work zone safety could reduce these numbers. These innovations include making temporary lane delineation more clear, improving the placement of signage, avoiding conflicts with permanent signage, and increasing the transition length for lane closures. However, implementing these and other work zone safety interventions on actual roadways before they are validated can undermine rather than enhance safety and could even have potentially fatal consequences. Evaluating work zone interventions on a test track is one solution, but this approach is costly, difficult to modify, subject to environmental changes, and can pose significant risks for both test participants and researchers. Driving simulators offer a safe, virtual environment that can be used to evaluate a wide range of interventions and how they may affect driver behavior in a cost-effective and safe manner before they are implemented on actual roadways.

Driving simulators have been used to evaluate driver performance for decades. A common application is the evaluation of relative driver impairment due to fatigue, drugs, or distraction. Driving simulators have been used to provide input for a variety of roadway design issues in Europe for some time (Keith et al., 2005) and the U.S. has begun to use simulators more widely for this purpose. Recent Federal Highway Administration (FHWA) projects have used simulators to investigate traffic calming in small towns (Molino, Katz, Hermosillo, Dagnall, & Kennedy, 2010), enhancement of visibility of curves on rural roads (Molino et al, 2010), driver response to a diverging diamond interchange (Federal Highway Administration, 2007), and driver response to warning of an approaching red-light violator (Inman, Davis, El-Shawarby, & Rakha, 2008). In addition, FHWA is currently funding a large project about making simulators more useful for human factors research (Federal Highway Adminstration, 2010). However, driving simulators have been used very little for work zone research. One notable exception is a study by Bella (2005) that found that speed measurements collected in a virtual work zone in a driving simulator were not significantly different from the speed measurements in the actual work zone that was replicated in the simulator.

Driving simulators offer a number of benefits over *in situ* work zone research. Investigating the response of individual drivers in actual work zones requires data collection and data reduction efforts that are quite labor intensive compared to using automatic vehicle counters to record data about the traffic stream as a whole. Even when these intense efforts are made, data are typically only collected in a few locations and measurements are usually imprecise (e.g., estimating speed to 1 mph increments from frame-by-frame analysis of video). In addition, drivers' behavior in actual work zones is likely influenced by the behavior of other drivers nearby. Driving simulators allow continuous measurement of driver performance in isolation or in the presence of simulated traffic.

A significant obstacle for *in situ* work zone research is selecting equivalent areas or timeframes to serve as controls for comparison. Even if data from enough comparable work zones could be obtained to investigate the factors of interest, it would be nearly impossible to account for the factors not under investigation, like changes in weather, lighting, work zone activity, and traffic conditions. Driving simulators offer a precise, convenient, and cost-effective way to evaluate a wide range of work zone treatments. Factorial, within-subject experimental designs allow the same cohort of drivers to experience each of the work zone variations so relative differences can be measured. Traffic, weather, and light levels can be systematically adjusted or set to remain constant.

When work zones are evaluated on actual roadways, it is nearly impossible to identify driver populations and gather subjective data about drivers' perceptions of the work zone. When evaluation takes place in a driving simulator, participants can be recruited from different populations of drivers, and additional data can be obtained from questionnaires, tests of performance, or surveys of driving style and history. In actual work zones it is impossible to control for or measure conditions like driver inattention, distraction, or fatigue. With driving simulators it is possible to see how performance is affected when the driver is not fully engaged in the driving task.

Despite its many benefits, driving simulator research is not a panacea. The term "driving simulator" has been used to describe a very wide array of devices, from auto racing video games presented on a computer monitor and driven with a gaming steering wheel all the way up to simulators with 360 degrees of visual field and a full motion base capable of producing extremely realistic motion cues. Each of these devices approximates driving to a certain degree and the level of fidelity required depends on the research question being evaluated. Each simulator must be validated by comparing driving performance in the simulator to that on the road. According to Blaauw (1982),

> “All methods [of simulator validation] give parameters describing validity by comparing conditions of driving in the simulator in relation to driving under the same road conditions. A modification of this approach is to compare performance differences between experimental conditions in the simulator with performance differences between similar conditions in the car. When these differences are of the same order and direction in both systems, then the simulator is defined to have *relative validity*. If, in addition, the numerical values are about equal in both systems, the simulator can be said to have *absolute validity* as well.”

In other words, even without an exact match in performance, driving simulators can provide useful information about on-road driver performance.

A number of validation studies comparing on-road and simulator performance have demonstrated relative validity (see Bella (2009) for a recent review). However, not all simulators have the fidelity required to investigate all issues—there are some research questions that can only be evaluated in actual driving conditions. For example, even state-of-the-art projectors cannot provide the contrast ratio needed to render nighttime scenes so simulators are not well suited for evaluating visibility of retroreflective technologies. A low fidelity virtual environment maybe be suitable for evaluating some work zone treatments, perhaps sequential warning lights (Finley, Ullman, & Dudek, 2001), merge timing (Beacher, Fontaine, & Garber, 2005), or variable message signs. Other interventions, such as rumble strips, require higher levels of fidelity. Consequently, the first phase of this project consisted of identifying a range of possible interventions and considering the specific simulator requirements needed to implement each of them. After determining the simulator characteristics and development necessary to effectively model the various work zone interventions, a subset of inventions was selected based on gaps in the body of research and feasibility of implementation in the various driving simulators on the University of Iowa (UI) campus. The subset of interventions was presented to a group of work zone experts who offered feedback via phone, email, and face to face conversations. Based on the feedback, an experiment was designed to investigate the effect of work zone barrier type, lateral buffer presence, work zone activity level, and driver age and gender on speed, speed variability, lane position, and variability in the lane in a National Advanced Driving Simulator (NADS) MiniSim fixed-base simulator.

## REVIEW OF WORK ZONE INTERVENTIONS

The review of standard and emerging work zone interventions began with a literature search. Once the body of work zone interventions was gathered, it was organized into four broad categories or functional areas: speed regulation, path regulation, visibility and conspicuity, and a final category of general work zone interventions. The description of the interventions that follows is the summary that was compiled for the work zone experts' consideration.

### Speed regulation

Interventions to enhance speed regulation aim to inform motorists of the posted speed limit and/or influence their choice of driving speed. These interventions influence motorists in two ways – directly or indirectly.

Direct methods, such as changeable message signs (CMSs), have been the subject of considerable research and have been shown to be effective in warning motorists of special roadway conditions, and if equipped with radar, telling the motorists their driving speed compared to the posted speed limit. The additional reduction in speed for CMSs compared to static message signs ranges from 3 to 8 mph. Similarly, the main role of variable speed limits (VSLs), additional police enforcement, photo-enforcement, rumble strips, and flaggers is to attempt to directly influence motorists to reduce their driving speed to match the posted speed limit. However, mixed results in terms of their ability to reduce speeds have been observed in different studies.

Indirect methods, such as perceptual countermeasures, have been estimated to have a calming effect on motorists with reductions in mean speeds of about 2 to 6 mph. Perceptual countermeasures are a class of non-obtrusive and indirect measures that have the purpose of manipulating the driver's perceived speed. They can take the form of pavement markings of various patterns (horizontal stripes, herring bone pattern, chevrons, etc.), rumble strips, or sequentially-lit flashing warning lights (see Table 1). These are spaced such that the motorists perceive they are driving faster (or slower) than they actually are as they traverse an increasing (or decreasing) number of markings or lights along the roadway and consequently reduce (or increase) their speed. Though few in number, studies on perceptual countermeasures help address a notable gap in the research on counteracting erratic acceleration and deceleration behavior.

Table 1 shows selected research for speed regulation. Interventions that can be studied in driving simulators and have received insufficient attention by researchers are highlighted in bold text.

**Table 1 - Speed regulation interventions, with those that merit simulator-based assessment shown in bold**

| Intervention | Description | Empirical Studies |
|---|---|---|
| Changeable message signs (CMSs) | Message boards with light bulbs or light emitting diodes (LEDs) post warning messages such as lane closures, speed limit, fines for speeding, etc. Also known as variable message signs (VMSs) | Brewer et al. (2006),<br>Benekohal et al. (1992) |
| Vehicle triggered CMSs | Speeding vehicle triggers a CMS equipped with radar that shows specific warning such as “You are speeding” or “Slow down now” or current speed against posted speed limit. The CMS may be placed on a mobile trailer. | Pesti and McCoy (2007),<br>Wang et al. (2007),<br>Brewer et al. (2006),<br>Fontaine et al. (2000),<br>Garber and Patel (1995) |
| Variable Speed limit (VSL) | The normal posted maximum speed limit is typically reduced by 10 mph around work zones. Based on work zone conditions, posted speed limits are changed dynamically using a CMS | Riffkin et al., (2008),<br>Michigan DOT (2003) |
| Presence of uniformed law enforcement officials and/or police vehicle | Uniformed law enforcement officials provide assistance in regulating traffic and their presence heightens motorists’ alertness. | Medina et al. (2009),<br>Kamyab et al. (2003),<br>Noel et al. (1987) |
| Photo-enforcement | An automated system that takes a photo of a vehicle that violates traffic rules such as speeding, running through red lights or stop signs, etc. | Medina, Juan C. et al. (2009) |

| Intervention | Description | Empirical Studies |
|---|---|---|
| Flaggers | Highway workers by the work zone who direct traffic using hand-signaling devices such as paddles, lights and flags. | Noel et al. (1989) |
| Rumble strips | Temporary rumble strips can be set up in critical zones to lower speed. | Meyer, E. (2005),<br>Fontaine et al. (2000),<br>Noel et al. (1989) |
| **Perceptual counter-measures** | **Pavement markings used to give a perception of driving at higher speeds while approaching a critical area which causes motorists to decelerate** | Katz (2004),<br>Voigt and Kuchangi, (2008) |
| | **Synchronized flashing warning lights used to generate a wave of lights moving towards or away from the driver generating a perception of driving at a higher or lower speed.** | Vercuryssen et al. (1995) |
| Radar drone | A drone that emits a radio frequency that triggers commercially available radar detectors giving motorist the impression that police enforcement is in effect in the work zone. | Fontaine et al. (2000) |

## Path regulation

The objective of these interventions is to demarcate the work zone and prevent motorist incursions into the work area. Temporary traffic control (TTC) devices, pavement markings, and signage are used to delineate open lanes. Their configurations at the taper and tangential sections of the work zone are generally implemented using standards from the Manual on Uniform Traffic Control Devices (MUTCD) published by the Federal Highway Administration (FHWA). However, empirical studies looking at their effect on driving behavior are sparse. Another area of interest concerns the vehicle conflicts that can arise in a lane closure scenario. Encouraging the traffic in the closing lane to merge shortly before the closure is called late merge strategy (LMS) and emphasizes traffic flow and management. Early merge strategy (EMS) emphasizes safety. Both strategies aim to reduce erratic lane change behavior. LMS tries to do this by using signals at the merge point allowing vehicles in open and closing lanes to merge into the work zone alternately. EMS tries to reduce erratic lane change behavior by giving motorists, especially truck drivers, greater leeway in settling into the open lane much before the latest merge point. Both strategies act on the motorists before they enter into the work zone. One can research individual drivers' motivations to adopt a particular strategy under various traffic conditions to investigate how a particular strategy can be better enforced. Also, gaps in research are evident in areas such as taper and lateral buffer zone design. Table 2 shows selected research for path regulation. Interventions that can be studied in driving simulators and have received insufficient attention by researchers are highlighted in bold text.

**Table 2 - Path regulation interventions with those that merit simulator-based assessment shown in bold**

| Intervention | Description | Empirical Studies |
|---|---|---|
| Road closures, lane closure and narrowing lanes | Traffic is diverted away from the work zone. This typically involves lane closures and/or narrowing of lanes. Entire roads may be closed if necessary. | Chitturi et al. (2008) |
| Disambiguation between permanent and temporary signs and pavement markings | Typically permanent signs and pavement markings are removed around work zones and new temporary ones are put in to demarcate open lanes and new regulations on the roadway. Better alignment of markings with open roadways improves drivers' ability to identify open paths. | Ullman et al. (2008a) |
| Design of pavement markings | Geometric design modifications to conventional pavement markings improve recognition, warn motorists and/or perceptually affect motorists' driving behavior. | Voigt, and Kuchangi, (2008), Ullman et al. (2008a), Zwahlen and Schnell (1999), Lessner (2005) |
| **Length of taper at transition and termination area** | **Transition area precedes the work zone where traffic moves out of the closed lanes and the termination area allows traffic to move into normal roadway. The taper facilitates merging into common road space.** | |
| **Transition strategy** | **Strategy implemented for adjusting the distance before the beginning of the work zone where traffic merges in or out of a lane to accommodate lane closure** | Minnesota DOT (2004), Scriba and Luttrell (2004), Beacher et al. (2004) |
| **Channelizing devices** | **Channelizing devices include cones, drums, tubular markers, vertical panels, barricades, etc that demarcate the work zone and separate the traffic from the work area.** | Fontaine et al. (2000), Bligh et al. (1998), Ross et al. (1993) |

| Intervention | Description | Empirical Studies |
|---|---|---|
| **Design of lateral buffer zone** | **Lateral distance between the traffic stream and the active work zone are hypothesized to affect driver behavior. Drivers may be inclined to travel faster than the posted speed limit if the lateral buffer is large or bounded by semi-permanent barriers. Drivers might reduce their speed if the lateral buffer is small and bounded by temporary barriers like cones or drums.** | |
| Shadow vehicle | A vehicle equipped with appropriate light and warning signs that trails close to mobile and constantly moving operations such as pothole repair, striping, etc. | |

### Visibility and conspicuity

The objective of these interventions is to make work zones, work zone personnel and equipment, and approach areas more visible and conspicuous. Drivers can thus anticipate events and use appropriate judgment while driving through the work zone, particularly in nighttime and low visibility conditions. Considerable literature is available in this area concerning illumination and use of reflectivity and fluorescence in work zones. The general trend in this area is in improving existing technology, research tools, and protocols for using devices like retroreflective signs, vests, flashing lights, etc. An issue that needs further investigation is the effect of different arrangements of retroreflective TTC devices and flashing lights on driver perception and behavior. However, even state-of-the-art driving simulators are not well-equipped to investigate retroreflectivity and visibility. Table 3 shows selected research in the area of improving work zone visibility and conspicuity.

**Table 3 - Visibility and conspicuity interventions**

| Intervention | Description | Empirical Studies |
|---|---|---|
| General work zone illumination | General work zone conspicuity during day and nighttime | Ullman et al. (2008b), Aktan et al. (2006), Barton et al. (2002) |
| Steady burn or flashing warning lights or beacons | Warning lights or beacons draw additional attention to critical areas, warning signs and channelizing devices. They are used under steady burn or flashing mode. | Gibbons et al. (2008), Finley et. al (2001) |
| Retroreflectivity and fluorescence | Materials and colors that make road signs, equipment, vehicles, TTC devices and clothing worn by highway workers highly reflective and/or contrasting from the surroundings, hence making them more conspicuous. | Fontaine et al. (2000), Zwahlen and Schnell (1997) |

### General work zone interventions

The objective of these measures is to provide systemic regulations and guidance to improve overall work zone management and safety. These measures can reach beyond the active work zone and aim to affect the society in general to instill a safety culture among drivers. A number of states have adopted a public awareness and education campaigns to achieve this. Research in this area is focused on providing a basis for standardization of technology, methods and traffic rules in order to help motorists easily recognize work zones and work zone elements. Cost of implementing various interventions versus their effectiveness is a research area that needs to be expanded. Another possible research avenue in this area is the effectiveness of different symbolism and verbiage such as “My Mom/Dad Works Here” that elicit emotional response from the drivers compared to “XX[ number of] citations issued to date” that aim to deter speeding by reaffirming the notion of being penalized. Table 4 shows selected research under general work zone interventions that can be studied in driving simulators and have received insufficient attention by researchers are highlighted in bold text.

**Table 4 - General interventions with those that merit simulator-based assessment shown in bold**

| Intervention | Description | Empirical Studies |
|---|---|---|
| Public awareness and education | Promotional campaigns aimed at building a safety culture among commuters. | The National Work Zone Safety Information Clearinghouse<br>Fylan et al. (2006) |
| Work zone planning and worker training | Guidelines for planning project duration and traffic control plans as well as worker training provide systemic regulation of safety and traffic throughput around work zones. | Washington et al. (2006), Antonucci et al (2005), |
| Information technology | Use of sensors, relays, CMS, radio stations, etc. to inform motorists of impending roadway conditions. | Huebschman et al. (2003) |
| Fines | Fines for moving vehicle violations within work zones typically double and hitting a worker also entails imprisonment | Huebschman et al. (2003) |
| **Advance warnings** | **Static sign boards or CMSs inform motorists of what to expect ahead in distance and/or time. The distance of the signage from the work zone and date/time mentioned on signage is a control variable** | Benekohal et al. (1995), Huebschman et al. (2003) |
| Verbiage and symbolism used on sign boards and their design | The wording and symbols used on signboards must convey the appropriate message. The sign boards must be visible and legible in a variety of lighting and weather conditions. | Wang et al. (2007), Ullman et al. (2005), Dudek and Ullman (2002), Durkop and Dudek (2001), US DOT - FHWA (1996) |
| **Screens** | **Screens are used to block the road users' view of potentially distracting work zone activities** | |

## Conclusion

The literature survey identified many different work zone interventions. Some of these have been well-studied and many are commonly implemented. Other interventions that show promise for making work zones safer or that have not been considered at all merit additional research attention. Some of these are suitable for investigation in a driving simulator.

- Pavement markings, flashing beacons, or other objects (e.g., cones or drums) can be spaced in specific patterns to influence motorists’ perception of their own speed. What kinds of markings or objects are most effective and how they might be placed upstream from or within a work zone to calm or stabilize motorist speed are unknowns that can be investigated in a simulator.

- Characteristics of lateral buffer and work zone boundaries affect motorist speed through a work zone, yet the MUTCD does not contain guidelines for considering these characteristics when determining speed limits for work zones. If drivers are uncomfortable driving at the posted work zone speed limit, they will drive slower. The consequence is large deceleration rates and increased crash risk for upstream motorists who expect to travel through the work zone at the posted speed limit. Driver response to a variety of different lateral buffer dimensions and boundaries can be measured in a driving simulator.
- Whether a motorist decides to merge early or late as they approach a work zone with the lane closure might depend on how the drivers around them respond to the lane closure. If most other motorists are waiting to merge, an individual driver might wait to merge as well. The effect of other motorists' behaviors can be difficult or impossible to measure in actual work zones, but in a simulator the behavior and density of the ambient traffic can be manipulated and driver response measured.

The literature survey points out an important gap in the research concerning regulating erratic acceleration and deceleration which is a worthwhile avenue for research given that erratic speeding behavior is a leading cause of rear-end collisions. The interventions above all aim to encourage motorist to drive more calmly with more consistent and appropriate speeds as they approach and travel through work zones.

**Simulator requirements**

The various driving simulators on the University of Iowa (UI) campus vary widely in fidelity, from desktop driving simulator with gaming style controls to fixed-base simulators with full vehicle cabs to the National Advanced Driving Simulator's NADS-1 with 360 degrees of visual scene and a full motion base. In order to identify which of the compiled work zone interventions would be feasible to evaluate in this project, the identified interventions were compared to five UI driving simulators. The first is a fixed-based DriveSafety simulator with full vehicle cab. The remaining four simulators are various versions of the NADS, starting with a desktop version; the NADS MiniSim with a single seat cab and wide field of view; the NADS-2 with a fixed-base full vehicle cab, wide field of view, and rear view visuals; and the NADS-1.

**Table 5. Legend for Table 6. Estimated level of enhancement to simulator capabilities required to implement the work zone interventions in the simulator.**

| | |
|---|---|
| ○ | Little to no enhancement required |
| ⊙ | Moderate enhancement required |
| ● | Substantial enhancement required |
| X | Impossible or infeasible to implement |

**Table 6. Simulator enhancements required to implement the work zone interventions in driving simulators on the University of Iowa campus.**

| Control Measure | Required Simulator Capabilities | Drive-Safety | NADS Desk-top | NADS Mini-Sim | NADS -2 | NADS -1 |
|---|---|---|---|---|---|---|
| Changeable message sign (CMS) and CMS related countermeasures such as variable speed limit (VSL) and vehicle triggered CMS. | Geometric model of a trailer or message board<br>Ability to control display parameters of dynamically changing text using speed and other data from virtual vehicles | ● | ⊙ | ⊙ | ⊙ | ⊙ |
| Rumble strips | Motion based simulator or haptic feedback in a fixed-base simulator | X | X | ● | ● | ● |

| Control Measure | Required Simulator Capabilities | Drive-Safety | NADS Desktop | NADS Mini-Sim | NADS-2 | NADS-1 |
|---|---|---|---|---|---|---|
| Perceptual countermeasures | Ability to position and orient the geometric models of TTC devices or pavement markings within the virtual world | ○ | ○ | ○ | ○ | ○ |
| Road closures, lane closure and narrowing lanes | Ability to modify the visual appearance and geography of the road network of the virtual world. | X | ⊙ | ⊙ | ⊙ | ⊙ |
| Disambiguation between permanent and temporary signs and pavement markings | Ability to modify the visual appearance of the road network | X | ⊙ | ⊙ | ⊙ | ⊙ |
| Length of taper at transition and termination area | Geometric models or instances of traffic control devices such as cones, drums, etc. | ○ | ○ | ○ | ○ | ○ |
| Transition strategy | Ability to simulate dynamic CMSs that can be dynamically changed within the virtual world or appropriate signage | ● | ⊙ | ⊙ | ⊙ | ⊙ |
| Channelizing devices | Geometric models or instances of temporary traffic control (TTC) devices such as cones, drums, etc. | ○ | ○ | ○ | ○ | ○ |
| Shadow vehicle | Lead vehicle model capable of being programmed | ○ | ○ | ○ | ○ | ○ |
| General work zone illumination | Advanced lighting models with control over global and local spread of light within the virtual world | X | X | X | X | X |
| Steady burn or flashing warning lights or beacons | Geometric models or instances of the warning light<br>Ability to control the on and off duration | ● | ⊙ | ⊙ | ⊙ | ⊙ |
| Retroreflective martial and fluorescent colored signs, objects, clothing | Advanced lighting models with ability to control reflectivity of different textures under different simulated lighting conditions.<br>Realistic dynamic models of human motion | X | ● | ● | ● | ● |
| Presence of uniformed law enforcement officials and/or police vehicle | Geometric models or instances of a uniformed policeman and/or police vehicle | X | X | X | X | X |
| Photo-enforcement | | X | X | X | X | X |

| Control Measure | Required Simulator Capabilities | Drive-Safety | NADS Desk-top | NADS Mini-Sim | NADS -2 | NADS -1 |
|---|---|---|---|---|---|---|
| Flaggers | Geometric models or instances of a flagger | X | X | X | X | X |
| Advance warnings | Ability to position geometric instances of message signs at the desired coordinates within the virtual world. | ● | ⊙ | ⊙ | ⊙ | ⊙ |
| Verbiage and symbolism used on sign boards and their design | Ability to create and load new sign models | ● | ○ | ○ | ○ | ○ |
| Screens | Geometric model of the screen that can be positioned at the desired coordinates and orientation within the virtual world | ○ | ⊙ | ⊙ | ⊙ | ⊙ |

### Expert feedback

Eight work zone experts, identified by the study team, IDOT personnel, and the SWZDI administrator, were contacted via email (see Appendix A for the letter) and asked to kindly offer their feedback about the various work zone interventions and which (if any) they were most interested in seeing evaluated in a driving simulator. Four of the eight experts contacted replied. Two offered their feedback via email and two agreed to phone conversations with the study team. A fifth expert and several other DOT professionals offered feedback during a group discussion held during a visit to the Iowa DOT headquarters in Ames.

On the whole, the work zone experts were very doubtful about the ability of perceptual countermeasures to evoke a change in driver behavior with only one expert expressing a high level of interest in learning more about the issue using a driving simulator. The early vs. late merge strategies generated a lot of discussion about how these might be implemented in a driving simulator; however, a number of complicated issues were raised, including that traffic density needs to be high enough to warrant the use of a late merge strategy and implementation of this kind of scenario in a simulator would require 360 degree visual field of view (only available on the National Advanced Driving Simulator's NADS-1) and complex traffic control.

All of the experts we spoke with expressed a high level of interested in issues associated with use of lateral buffers in work zones and agreed that this was an area underrepresented in the body of work zone research. Several also noted that there was a lack of knowledge about the effect of different kind of barriers (e.g., drums or channelizers) on driver behavior. Nearly all of the experts expressed concern about driver characteristics, including senior drivers, distracted and inattentive drivers, and road rage. Finally, the experts shared the general opinion that the safest way for drivers to pass through work zones is for all drivers to go the same speed. When one or more drivers in the traffic stream travel more slowly than others, the potential for large speed differentials between vehicles in the advance warning area increases and accordingly so does the crash risk.

## Research questions

Based on the expert feedback, the availability of driving simulators and financial resources, and feasibility of implementing the work zone interventions in the driving simulator, a research study was designed. The three main research questions to be addressed were:

- What effect do different barrier types have on driver performance?
- What effect does including a lateral buffer within the work zone boundaries have on driver performance?
- What effect does the level of activity in the work zone have on driver performance?

In addition to these three main research questions, the analyses also investigated how any observed effects varied by gender and age groups.

# METHODS

## Study design

This study was a mixed design with three within-subjects factors and two between-subjects factors. The first within-subjects factor was work zone barrier type and contained three treatments: drum, channelizer, and concrete barrier. A second factor was the presence or absence of a 4-ft lateral buffer between the work zone workers and vehicles and the buffer. Both work zone barrier type and lateral buffer were consistent within each experimental drive and the crossing of these two factors resulted in 6 experimental drives. The third factor was work zone activity level transition type. There were two levels of activity (low and high) arranged in three different ways: a work zone that initially had low activity but then became high activity (LH transition), a work zone that initially had high activity but then became low activity (HL transition), and a work zone that had a low activity level throughout (LL transition). Each of the three work zone transitions appeared once in each of the six drives and the order of appearance was randomized across the drives. Thus each participant experienced a total of 18 different work zones during the study. The order in which the six drives were presented to the participants was counterbalanced using a 6 x 6 Latin square resulting in six different drive orders. The Latin square was carefully selected such that the three drives with the lateral buffer or the three drives without the lateral buffer would not driven in a block. Tables detailing the counterbalancing of the experimental conditions over the drives, the drives over the orders, and the orders over the between-subjects groups can be found in Appendix B.

## Participants

Twenty-five participants took part in the study. One participant who completed the study had to be replaced because the sound system for the simulator was not turned on before her session.  No participants experienced simulator sickness during the study.  The twenty-four participants whose data was included in the analysis were evenly divided between both genders and two age groups, 35-50 (mean = 45, SD = 4.6 years) and 65-80 (mean = 71, SD = 3.3 years), for 6 participants in each between-subjects group.  Each participant in a group was randomly assigned to one of the six drive orders.  Each participant had at least 19 years of driving experience and drove at least 3 times per week.  Eight of the middle age participants and 10 of the senior participants reported that they drive every day.

### Simulator description

The simulator selected for this study was the National Advanced Driving Simulator (NADS) MiniSim (see Figure 1).  The NADS MiniSim utilizes the same state-of-the-art driving simulation technology, visual database design, and vehicle dynamics modeling of the NADS-1 driving simulator, but the MiniSim is powered by two PCs.  It utilizes the steering column, brake, and accelerator pedal from an actual vehicle.  The visual scene is displayed on three flat panel screens, each with 1024 by 768 resolution.  The view is adjusted to accommodate for the approximately 4-degree portion of the visual scene that is not visible between adjacent displays. At a viewing distance of 48”, the display offers a field of view that is 132 by 24 degrees.  The dynamics of the simulated vehicle were based on a Chevy Malibu.  The dynamics model, visual scene, and data stream were all updated at 60 Hz.

### Scenario design

Six unique experimental drives were developed using the NADS Interactive Scenario Authoring Tool (ISAT).  The drives took place on a rural interstate highway with two 12-ft lanes of traffic in each direction divided by an 80-ft grass median.  The highway did not include any exits to or on-ramps from other roadways.  The scenery consisted of distant tree lines, hills, and bill boards. Approximately 200 ft from the simulated vehicle's starting position on the left shoulder of the road was a 70 mph speed limit sign.

**Figure 1. The NADS MiniSim (scenario pictured was not used in this study)**

### *Work zone layout*

Each of the work zones (three in each drive) were laid out the same way. Three pairs of signs (see Figure 2) were placed in the advance warning area of each work zone, one sign on each side of the roadway. The distance from the simulated vehicle's starting position to the first sign for the first work zone was 7000 ft. The first pair of signs read "Road Construction Ahead." The next pair of signs, located 2640 ft after the first pair, read "One Lane Road Ahead." The third pair of signs signified that the right lane was closing, included a 55 mph advisory speed sign posted directly below each main sign, and was located 1500 ft after the second pair. Approximately 900 ft after the third pair of signs, a taper formed of drums closed the right lane over a length of 760 ft.

**Figure 2.  Signs in the advance warning area of the work zone.**

Following the taper of the drums, the right lane was closed for a total of 9000 ft.  While the right lane was closed, the work zone barrier was formed of channelizers, drums, or concrete barriers (see Figure 3).  Only one type of barrier was used in each of the six drives.  Each channelizer was 1 ft wide by 1 ft long by 3.5 ft high, and the channelizers were placed approximately 30 ft apart with small random offsets in both the longitudinal and lateral direction selected from a normal distribution with a mean of 0 and standard deviation of 0.3 ft.  Each drum was 2.7 ft wide by 2.7 ft long by 4.15 ft tall, and the drums were placed approximately 20 ft apart with small random offsets like the channelizers.  The concrete barrier was 2.5 ft wide by 3.75 ft high and each section was 100 ft long.  The concrete barriers were centered on the center line of the two-lane interstate highway.  A pair of signs (one on each side of the road) that read “End Construction Zone” was located at the end of the work zone barrier.  The first pair of signs for the next work zone was located 5000 ft after the end of the work zone.  The end of the drive was indicated by a pair of “stop ahead” warning signs located 2000 ft after the third and final work zone, followed by a pair of stop signs 400 ft ahead.

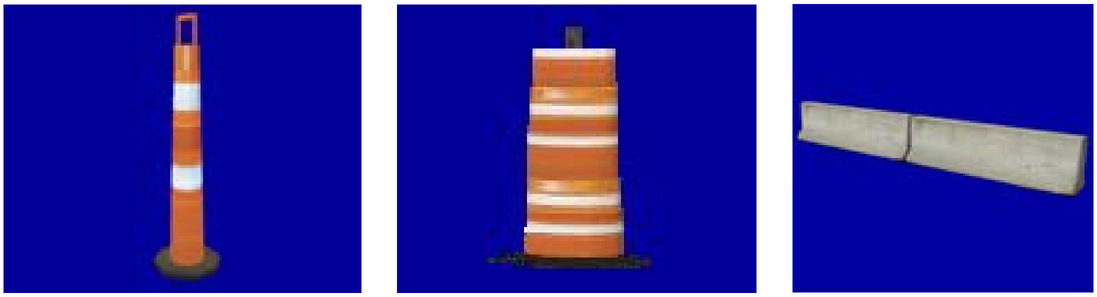


**Figure 3. Three different barrier types evaluated in this study: 42" channelizer, drum, and concrete barrier.**

### *Work zone vehicles and workers*

In order to give the virtual work zones the appearance of activity, a variety of pedestrian and vehicle models were placed within the work zones. Images of all the work zone object models can be found in Appendix C. The pedestrians (herein called “workers”) wore high visibility attire and hard hats. Three of the worker models were dynamic and were programmed to begin walking one of three different types of paths as the participant’s vehicle approached (see Appendix C for path diagrams). The other worker models were static and did not move.

There were five different work zone vehicles and each of these could be set to either dynamic (i.e., moving) or static (i.e., parked). The dynamic vehicles followed one of four different types of paths and were programmed to start moving as the participant approached. Images of the work zone vehicles and diagrams of the dynamic vehicle paths can be found in Appendix C. The work zones also included some passenger vehicles (presumably driven to the job site by the workers) parked on the shoulder of the closed lane.

The first 500 ft of the 9000 ft where the right lane was closed did not contain any vehicles or workers in order to create a longitudinal buffer in the work zone. The next 8000 ft of the work zone consisted of two 4000-ft areas. Work zone objects were placed in each area according to work zone activity level. High activity areas had the following number of objects *in each 500-ft segment* of the 4000-ft work zone area:

- 1 dynamic work zone vehicle or 1 dynamic worker
- 4 static work zone vehicles
- 3 static workers in the closed lane of the work zone
- 2 static workers on the shoulder of the closed lane
- 2 passenger vehicles parked on the shoulder of the closed lane.

Low activity work zones included the following number of objects *in each 4000 ft work zone area*:

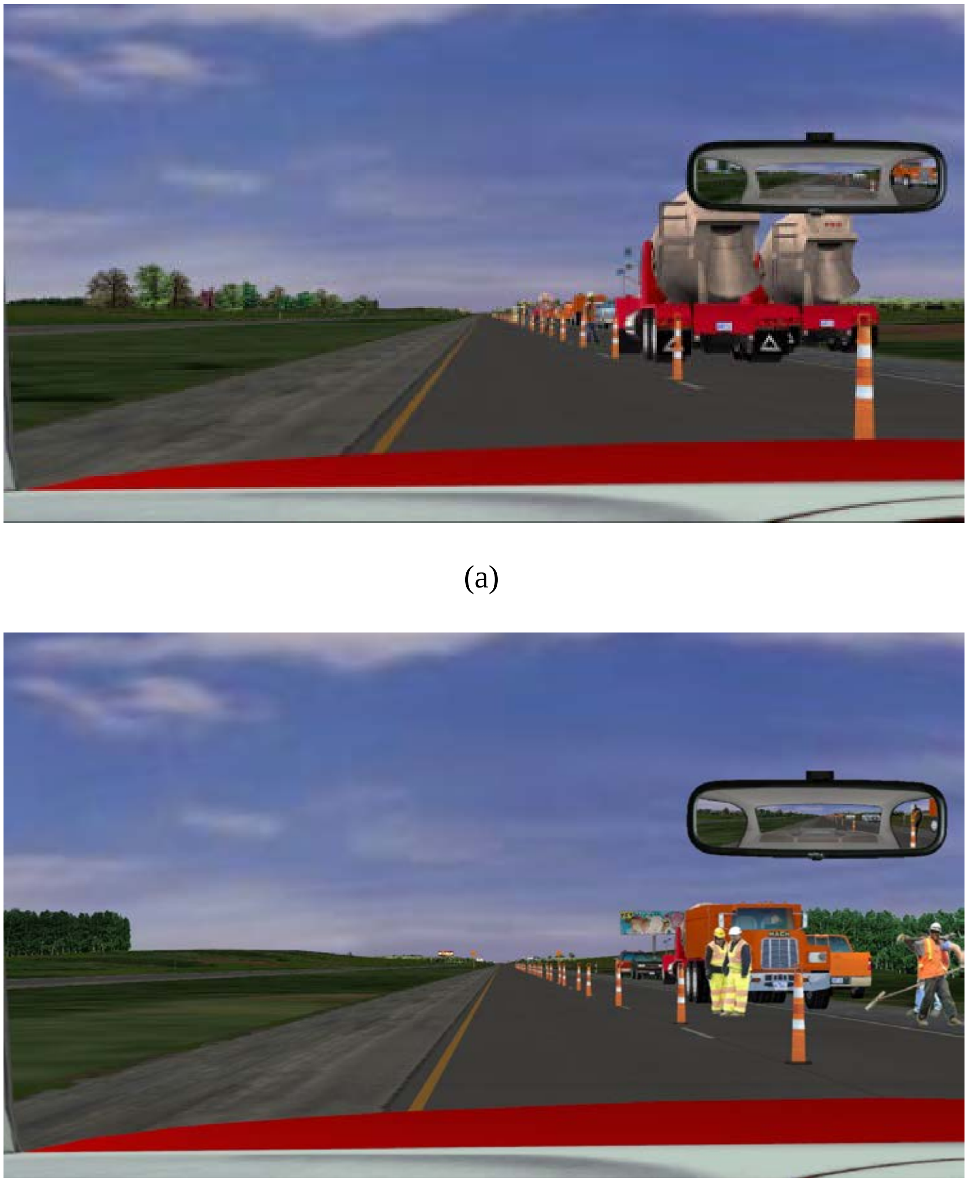
- 4 static work zone vehicles in the closed lane of the work zone
- 2 static work zone vehicles on the shoulder of the closed lane
- 4 static workers in the closed lane of the work zone
- 4 static workers on the shoulder of the closed lane
- 2 passenger vehicles parked on the shoulder of the closed lane.

The high activity area had approximately six times the number of objects as the low activity area. The dynamic vehicles and workers were located only the high activity areas.

### *Lateral buffer*

In order to evaluate the effect of a lateral buffer between the work zone objects and the barriers, for three of the six drives the position of all of the vehicles and workers in the work zone (but not the barriers) were shifted four feet away from the open driving lane. Since the

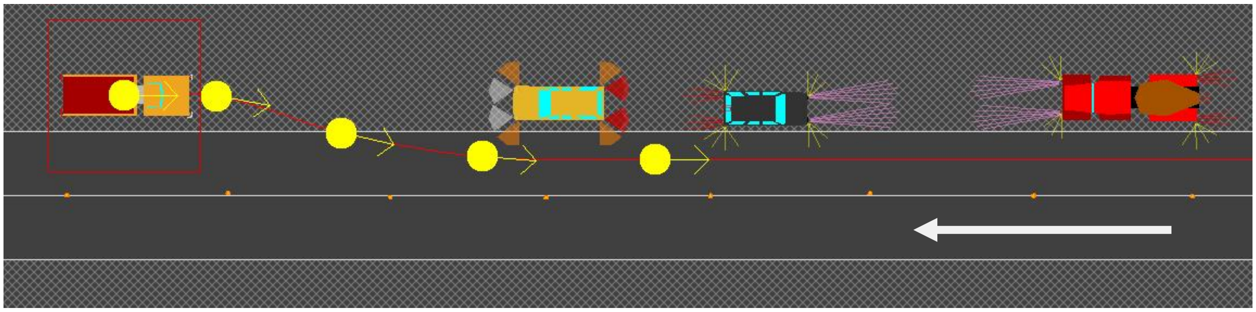
MUTCD states that “the width of a lateral buffer should be determined by engineering judgment” (p. 555 of 2009 Ed.), we selected the width by considering what lateral buffer would be realistic for this type of roadway in the real world and how the buffer appeared in the simulator.  Figures 4 and 5 show the lateral buffer from the driver’s and bird’s eye perspectives, respectively.



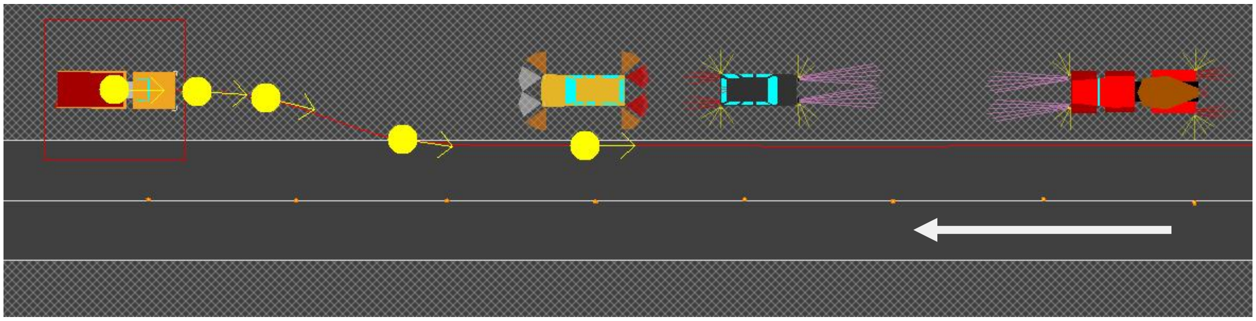
(a)

(b)

**Figure 4.  Driver's view of a work zone without (a) and with (b) a 4-ft lateral buffer.**



(a)



(b)

**Figure 5. Bird's eye view of the simulated driving environment in the Interactive Scenario Authoring Tool (ISAT). The arrows and nodes indicate the pullout path of a dynamic work zone vehicle. The white arrows indicate direction of travel of the simulated vehicle. Figure 5a shows the set up without the lateral buffer. Figure 5b shows how the vehicles and pullout path were shifted to created the 4-ft lateral buffer.**

## Protocol

When the participants arrived in the lab they were presented with the informed consent document. After they read the document, received answers to any questions that they had, and gave their consent, they were seated in the driving simulator. Verbal instructions (see Appendix D) about how to operate the simulator were given. Then the participant drove a practice scenario that contained one work zone and took about 7 minutes to drive. The approach to the work zone was identical to the approach for the work zones in the experimental scenarios. Following the taper of drums to close the right lane, the work zone barrier consisted of channelizers for approximately 4500 ft. Then the barrier changed and consisted of drums for another 4500 ft.

The final 4500 ft of the work zone was demarcated by the concrete barrier. The scenario also contained one instance of each of the work zone vehicles and workers that were present in the experiment scenarios. Before and after the work zone in the practice drive were several different speed zones (either 50 or 70 mph). The participants were instructed to drive as close to the posted speed limit as possible. The end of the drive was indicated with two “Stop Ahead” signs (one on each side of the roadway) followed a short distance later by two stop signs. The participants were instructed to brake to a stop when they saw these signs. The instructions also describe the symptoms of simulator sickness and the participants were instructed to stop driving immediately if they started to feel ill or uncomfortable.

After the practice drive had been completed, the participants were asked how they were feeling physically and the experimenter verified they had no symptoms of simulator sickness. Then the participants were asked if they felt comfortable driving the simulator and if they would like to complete the practice drive a second time. All of the participants reported that they were comfortable with the driving simulator and were ready to proceed with the experimental drives after completing the practice drive once.

The six experimental drives were completed in two blocks of three drives with a 5-minute break between blocks. The experimental drives each took about twelve minutes to complete and were presented in the order the participant had been randomly assigned to. Instructions were read aloud to the participant before each drive (see Appendix D for the instructions read to the participants). After the sixth experimental drive, the participant completed a survey and a payment form. The entire experimental session took 2 to 2.5 hours to complete.

## Analysis plan

Four primary dependent measures were considered: average speed, variability of speed (calculated by taking the standard deviation), average lane position in the driving lane, and variability of lane position (again calculated by taking standard deviation). Distance at which the participant merged for the closed lane in the work zone was also calculated. Analyses were completed for three sets of summarized data. One set summarized driver performance in the approach to each work zone. Another set summarized driver performance over each 4000-ft area of the work zone. A final data set summarized the change in driver performance in the 2000 ft after the transition relative to performance in the 2000 ft feet before the transition in order to investigate the effects of changing the activity level in the work zone. All statistical analyses were completed in SAS 9.2 using the mixed linear model (PROC MIXED) with participant as a repeated measure. The significance level (α) was set to 0.05.

## Hypotheses

There are a number of models of driver behavior that consider how drivers respond to changes in the driving environment in order to maintain the *status quo*. For example, Risk Homeostasis Theory, proposed by Wilde, posits that each driver seeks to maintain a target level of risk (Fuller, 2005). The Safety Margin Model posed by Summala, suggest that drivers respond in order to maintain a desired margin of safety (Lewis-Evans & Rothengatter, 2009). Fuller's Task-Capacity interface model (2005) claims that drivers act to achieve task difficulty homeostasis. Both Fuller (2005) and Lewis-Evans & Rothengatter (2009) found that ratings of task difficulty were very similar to ratings of the experience (i.e., feelings) of risk. When drivers experience an increase in task difficulty or feelings of risk, they tend to reduce their speed and navigate their vehicle around or away from the source of the risk.

For this study, it was hypothesized that the presence of a lateral buffer would reduce driver perception of risk and increase driver comfort in the work zone, and this would be associated with a higher average speed and less speed variability. If driver perception of risk in the work zone decreased, it was expected that the average lane position would move closer to the work zone and that lane position would be less variable. Women and seniors were expected to be more risk adverse and thus drive more slowly and with greater variability in both speed and lane position than men and those in the middle age group.

An increase in work zone activity level was hypothesized to increase the drivers' perception of risk and lead to a decrease in average speed and a shift in average lane position away from the work zone. A decrease in activity level was expected to increase average speed and shift lane position toward the work zone as the driver accepts a smaller safety margin between them and the work zone due to the reduction in perceived risk.

No predictions about barrier type were made. One could hypothesize that drivers would be more comfortable driving near the concrete barriers because they provided a solid barricade around the work zone. On the other hand, some drivers might be very uncomfortable driving near a solid concrete barrier. Similarly opposing hypotheses could be drawn for the other two barrier types.

## RESULTS

### Approach to the work zone

There were no significant differences in the distance at which the participants changed lanes to merge for the work zone for age group, gender, drive number, or work zone number or any interactions of the conditions. On average, participants merged 953.9 ft before the first drum in the taper that closed the right lane.

Speed in the approach to the work zone was evaluated by dividing the approach into several segments as described in Table 7 and calculating the average speed in each segment. An effect of drive number was found to be significant, with speed in entry segment 1 being significantly slower in the first drive compared to same segment in all subsequent drives. A similar pattern was seen for the other six approach segments with average speed generally increasing with subsequent drives. There was also an interaction of age group and drive number for the first two approach segments, with seniors driving nearly 5 mph slower in the first approach segment and about 4 mph slower in the second approach segment than the middle age group. By the third segment for all drives and by the third drive for all segments, there was no longer a significant difference between the two age groups. As the participants gained more experience with the work zones and how they were laid out, they seemed to be comfortable waiting to slow down until they got closer to the taper.

**Table 7. Definition of segments to analyze driver performance in the approach to each work zone**

| Segment number | Beginning | End | Distance |
|---|---|---|---|
| 1 | 1000 ft before Road Work 1 Mile sign | Road Work 1 Mile sign | 1000 ft |
| 2 | Road Work 1 Mile sign | Right Lane Closed sign | 2640 ft |
| 3 | Right Lane Closed sign | Right Lane Merge sign | 1500 ft |
| 4 | Right Lane Merge sign | Start shoulder taper | 900 ft |
| 5 | Start shoulder taper | End of transition area | 760 ft |
| 6 | End of transition area | End of longitudinal buffer | Not less than 500 ft* |

*Actual distance depended on location of first vehicle or worker in the work zone

## First area of the work zone compared to the second area

Driver performance was evaluated for each area of the work zone (i.e., the 4000 ft immediately following the longitudinal buffer or the subsequent 4000 ft). The mixed linear model included age group, gender, work zone activity level, work zone area (first or second), buffer, and work zone barrier type as well as all 2- and 3-way interactions.

### *Average speed*

The main effect of work zone activity level was significant (F(1,20) = 19.62, $p = 0.0003$) with average speed being 1.0 mph faster in the low activity zones (54.0 mph) than in the high activity zones (53.0 mph). The main effect of work zone half was also significant (F(1,20) = 17.41, $p = 0.0005$) with average speed being 1.0 mph faster in the second half of the work zone (54.0 mph) than in the first half of the work zone (53.0 mph).

Work zone barrier type had a significant effect on average speed (F(2,40) = 50.85, $p < 0.0001$). Participants drove significantly faster with the concrete barriers (55.1 mph) than with the channelizers (52.4 mph) or the drums (52.9 mph). There was also a significant three-way interaction of age group, gender and barrier type (F(2,40) = 10.17, $p =0.0003$; see Figure 6). All participants drove significantly faster with the concrete barrier type than with the drum barrier type. All participants with the exception of middle age males drove significantly faster with the concrete barrier type than with the channelizer barrier. Middle age females drove significantly faster with the drum barrier type than with the channelizer barrier. These results suggest that the participants were more comfortable driving in work zones with the concrete barriers in place.

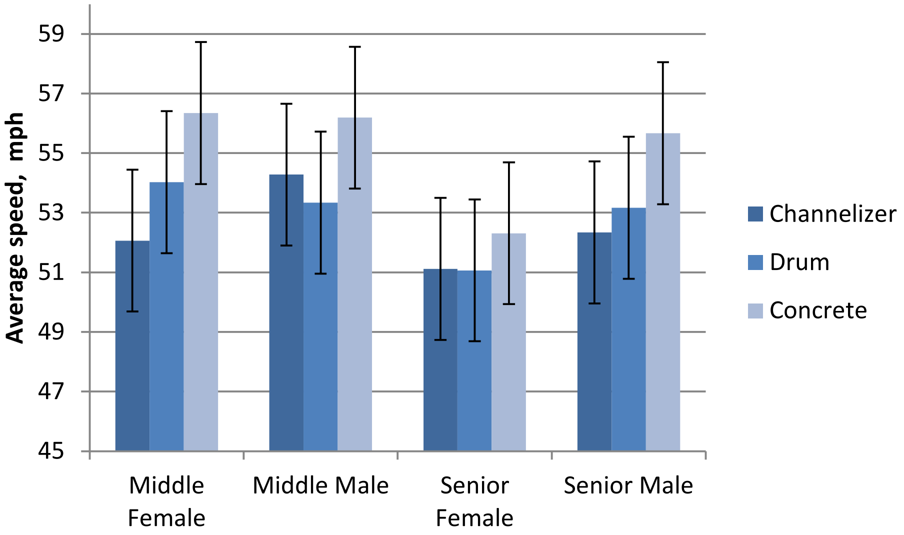


**Figure 6. Three-way interaction of age group, gender, and barrier type on average speed.**

The three-way interaction of age, barrier, and buffer was significant (F(2,42) = 3.97, p = 0.0263; see Figure 7). It was expected that the presence of a buffer would be associated with an increase in average speed regardless of barrier type or age group. Although the expected increase in speed was seen for the middle age group, the seniors' average speed depended on barrier type. Average speed for seniors in work zones with drums was not significantly affected by the presence of a lateral buffer, and in the work zones with the channelizer barrier type, the effect was in the opposite direction as expected. The average speed for the senior participants was 1.6 mph lower with the lateral buffer than without it. The average speeds for each age group were similar without the buffer for both the channelizer and drum barrier types.

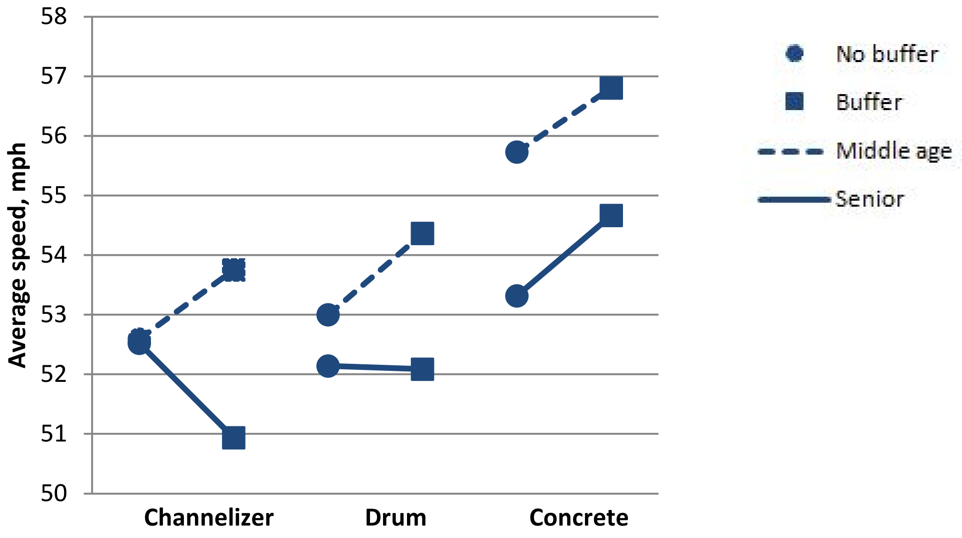


**Figure 7. Three-way interaction of barrier type, buffer presence, and age group on average speed.**

### *Variability of speed*

Variability of speed was evaluated by calculating the standard deviation of speed for each half of the work zone. As expected, there was a main effect of age group (F(1,20) = 6.89, p =0.0162) with the senior participants being more variable in their speed (2.3 mph) than the middle age participants (1.6 mph). Age did not interact with any other factors. There was a main effect of work zone half (F(1,20) = 16.81, p = 0.0006) with speed being more variable in the first half of the work zone (2.1 mph) compared to the second half (1.7 mph).

The work zone activity level and interaction of buffer presence was found to significantly affect speed variability (F(1, 21) = 4.94, p = 0.0373). As shown in Figure 8, speed in high activity zones was more variable without the buffer (2.2 mph) compared to with the buffer (1.8 mph) and compared to low activity zone both with and without the buffer (both 1.8 mph).

**Figure 8. Two-way interaction of buffer presence and work zone activity level on variability of speed.**

Barrier type and work zone activity level interacted to significantly affect speed variability (F(2,42) = 6.62, p = 0.0032; see Figure 9). It was expected that speed would be more variable in the work zones with the high activity level and this was the case for both the channelizer and drum barriers. However, speed variability was not significantly different for the low and high activity areas with the concrete barriers in place. Speed was about 0.7 mph less variable in high activity work zones with the concrete barriers than with the other two barrier types. These results again suggest that participants perceived less risk or task difficulty and were more comfortable with the concrete barriers than the other two barrier types.

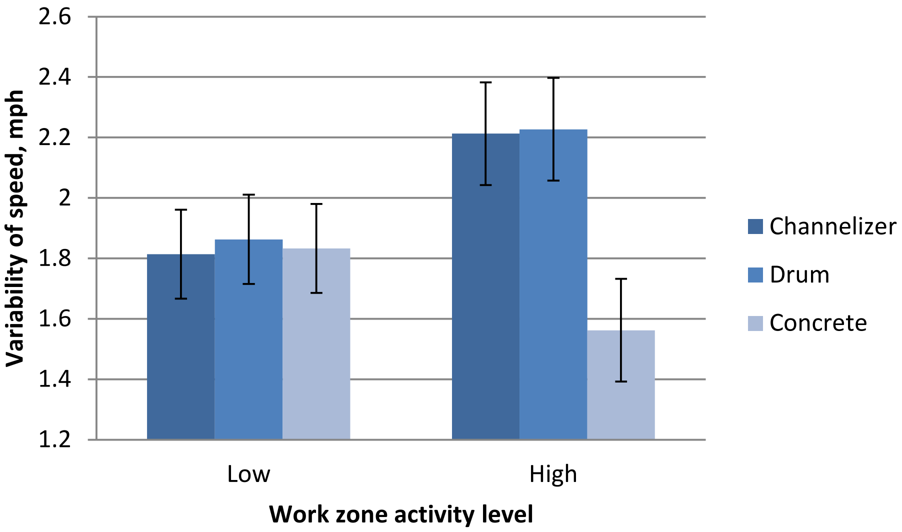


**Figure 9. Two-way interaction of barrier type and work zone activity level on variability of speed.**

***Average lane position***

Lane position averaged over each half of the work zone provides an indicator of the safety margin participants adopted in response to their perceived risk or difficulty as they experienced the various work zone configurations. A main effect of age was seen (F(1,20) = 7.33, p = 0.0136). Middle age participants had an average lane position of 3.24 ft to the left of the center of the driving lane while the senior participants were on average more than a foot closer to the barriers (2.05 ft to the left of center). This finding is contrary to the expectation that the senior participants would drive farther away from the barriers than the middle age participants. One potential explanation is that the seniors were reluctant to drive on the shoulder. In the post drive survey, only 2 of the 12 senior participants reported having to drive on the shoulder while 8 of the 12 middle age participants reported that sometimes they had to drive on the shoulder.

The effect of lateral buffer presence on average lane position was modulated by age (F(1,20) = 7.13, p = 0.0147). Senior participants did not change their lane position in response to the presence of a buffer but the middle age participants moved slightly closer to the barrier, from 3.39 ft to 3.09 ft left of center, when the buffer was present.

The type of barrier in the work zone had an effect on average lane position (F(2,40) = 65.12, p < 0.0001). Barrier type also significantly interacted with age (F(2,40) = 7.62, p < 0.0001) as well as age and gender (F(2,40) = 8.86, p = 0.0007; shown in Figure 10). All combinations of age and gender with the exception of senior males stayed the farthest from the drum barrier and got the closest to the concrete barrier. Senior males got slightly closer to the channelizer than the concrete barrier but the difference between the two was not significant. However, it is likely that the significance of three-way interaction is primarily due to the large differences between the middle aged females and the senior females. Overall, the analyses for average lane position reveal that the participants preferred to drive closer to the concrete barriers and that the middle age participants drove farther from the barrier, often driving such that the left tires of the participant car were on the left shoulder of the virtual roadway.

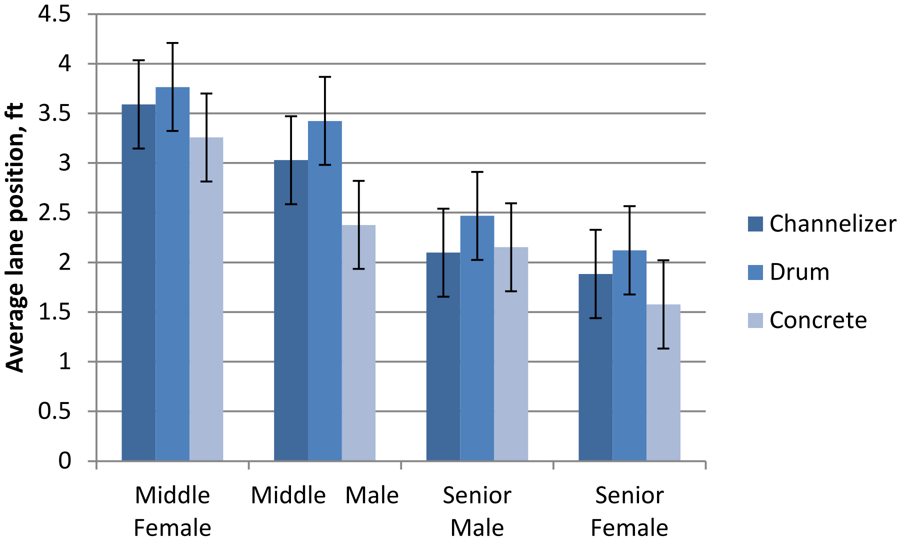


**Figure 10. Three-way interaction of age, gender, and barrier type on average lane position to the left of the center of the lane.**

***Variability of lane position***

The final dependent measure was variability of lane position as measured by taking the standard deviation of lane position for each half of the work zone. There was a main effect of barrier (F(2,40) = 14.93, p < 0.0001); lane position was more variable with the channelizers (0.56 ft) than with the drums or concrete barriers (0.44 ft). There was a significant two-way interaction of age and barrier type (F(2,40) = 5.11, p = 0.0106; see Figure 11). Middle age participants were more variable in their lane position with the channelizer barrier compared to both the drum and concrete barriers. Senior participants were also more variable in the lane with the channelizer barriers in place relative to the drum barriers. One possible explanation for these results is that because the drum and concrete barrier types are wider than the channelizers, they appear to provide additional lateral buffer space from the work zone activity which in turn decreases the participants' perceived risk.

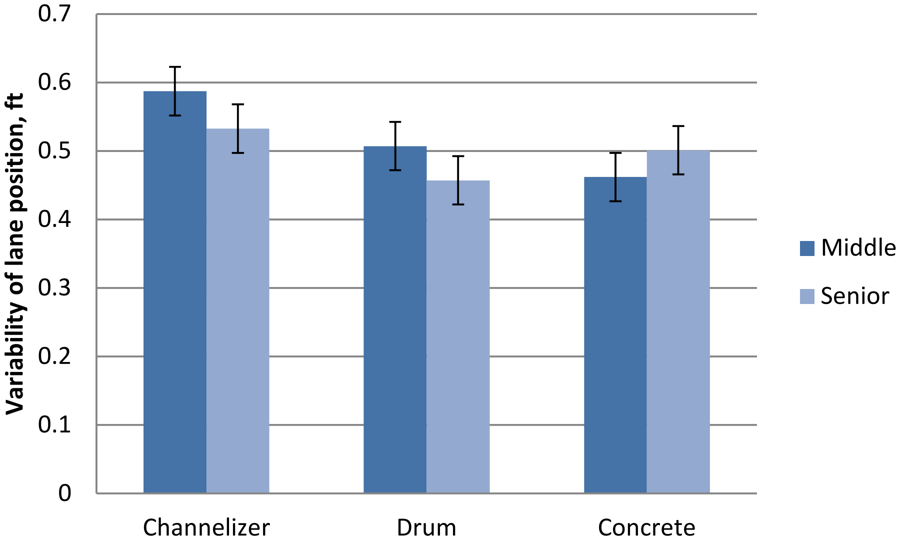


**Figure 11. Two-way interaction of age group and barrier type on variaiblity of lane position.**

There was a significant 2-way interaction of gender and buffer (F(1,20) = 8.73, p = 0.0078). Males were more slightly but significantly more variable in their lane position with the buffer than without. Females tended to be more variable in their lane position without the buffer than with it, but this difference was not significant.

Finally, there was a significant three-way interaction of barrier, buffer, and work zone half on variability of lane position (F(2,46) = 4.09, p = 0.0231; see Figure 12). The greatest variability of lane position was seen with the channelizer barriers in the first half of the work zone without a lateral buffer, and this was significantly greater than variability of lane position for all other combinations of barrier, buffer, and work zone half. No difference in lane position variability was seen for the first and second halves of the channelizer work zones when the buffer was present. The first half – second half differences for all of the other barrier-buffer combinations were not statistically significant. To the extent that variability of lane position indicates driver comfort with the demands of driving in the work zone, there appears to be a benefit of a lateral buffer as the drivers became acclimated to the work zones with the channelizers.

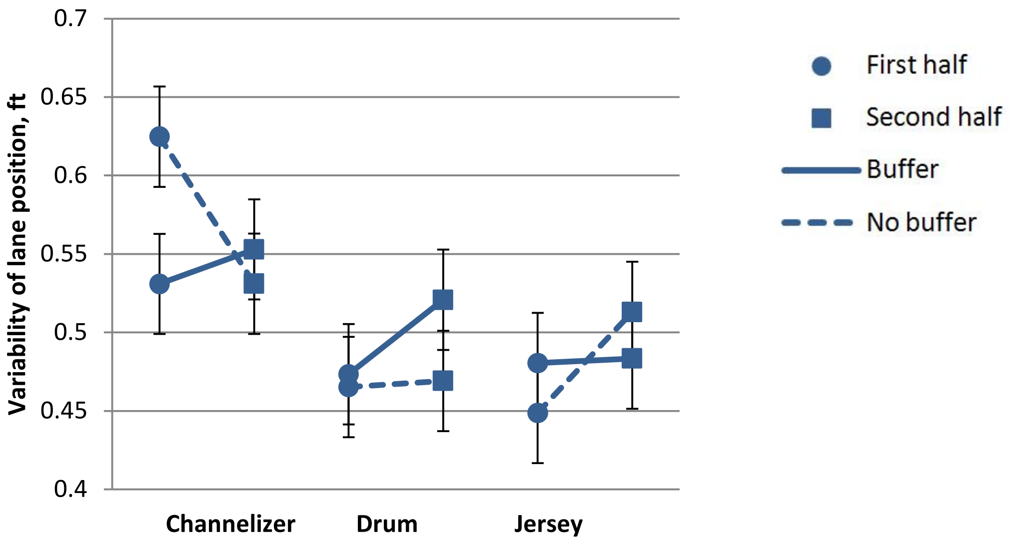


**Figure 12. Three-way interaction of barrier type, lateral buffer presence, and work zone half.**

## Change in driver performance for work zone activity level transitions

To evaluate the effect of changes in work zone activity level, changes in the driver performance measures were calculated for each kind of work zone transition (LL: low activity level throughout; LH: low activity level followed by high activity level; and HL: and high activity level followed by low). The changes in average speed, speed variability, average lane position, and variability in the lane from the 2000 ft before the transition to the 2000 ft after the transition were calculated. Each was evaluated using a statistical model that included the main effect of work zone transition type plus the interaction of work zone transition type with all possible combinations of age group, gender, barrier type, and buffer presence.

### *Change in average speed*

The interaction of work zone transition type and barrier type was significant (F(6,120) = 2.45, p = 0.0287) as was the four-way interaction of work zone transition type, barrier type, gender, and age group (F(6,120), p = 0.0238). The two-way interaction is shown in Figure 13. Across all participant groups, the LH transition resulted in a decrease of average speed of about 1 mph when the barrier consisted of channelizer devices. This was the only combination of barrier type and transition type that resulted in a decrease in speed. When the drums were in place, average speed increased by 1.1 mph when the work zone activity level did not change (LL) and by 2.2 mph when the activity level decreased (HL). Average speed was very consistent for all three transition types with the concrete barriers.

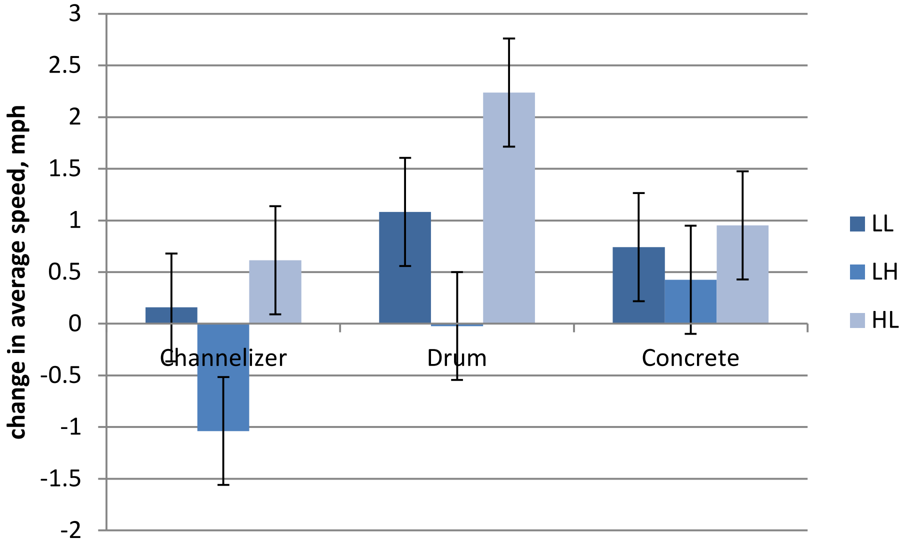


**Figure 13. Two-way interaction of work zone transition type and barrier type on change in average speed.**

To interpret the 4-way interaction, the interaction of barrier type and transition type were compared within and between each between-subjects group (see Figure 14). Senior males exhibited the largest change in average speed, an increase of 4.7 mph, during the HL transition when the drums were in place. Middle age females also had a significant increase in average speed for the HL transition with the drums (2.7 mph). Middle age males increased their speed with the drum barrier by 1.5 mph and 1.7 mph for the LL and HL transitions, respectively. Speed changes for middle males with the other barriers were smaller in magnitude and more uniform. Middle age females had a relatively large speed decrease of 2 mph in the LH transition with the channelizer devices but changes in average speed were extremely small for the same transition with the drum (0.3 mph) and concrete (-0.4 mph) barriers. Similar results were seen for the senior males in the LH transition: decrease of 1.2 mph for channelizer, 0.5 mph increase for drum, and 0.4 mph increase for concrete barriers. Finally, senior females had a slight but significant decrease in speed in response to the HL transition (1.1 mph) with the channelizers while all other combinations of age, gender, and barrier type showed steady or increasing speed for the HL transition.

#### *Change in variability of speed*

Change in variability of speed during the work zone activity transitions was not significantly affected by any of the combinations of independent measures, age, and gender.

#### *Change in average lane position*

There was a significant three-way interaction of gender, work zone transition type, and barrier type (F(6,120) = 3.61, p = 0.0025; see Figure 15). On the whole, females did not change average lane position in a notable way for any combination of barrier type and transition type. Males moved significantly closer to the work zone (0.5 ft) when the work zone activity level did not change and the channelizer barriers were in place. They also moved a statistically significant distance away from the work zone when the activity level transitioned from low to high, by more than 0.2 feet for the channelizer barrier type and by 0.3 feet for the drums.

#### *Change in variability of lane position*

Change in variability of lane position during the work zone activity transitions was not significantly affected by any of the combinations of independent measures, age, and gender.

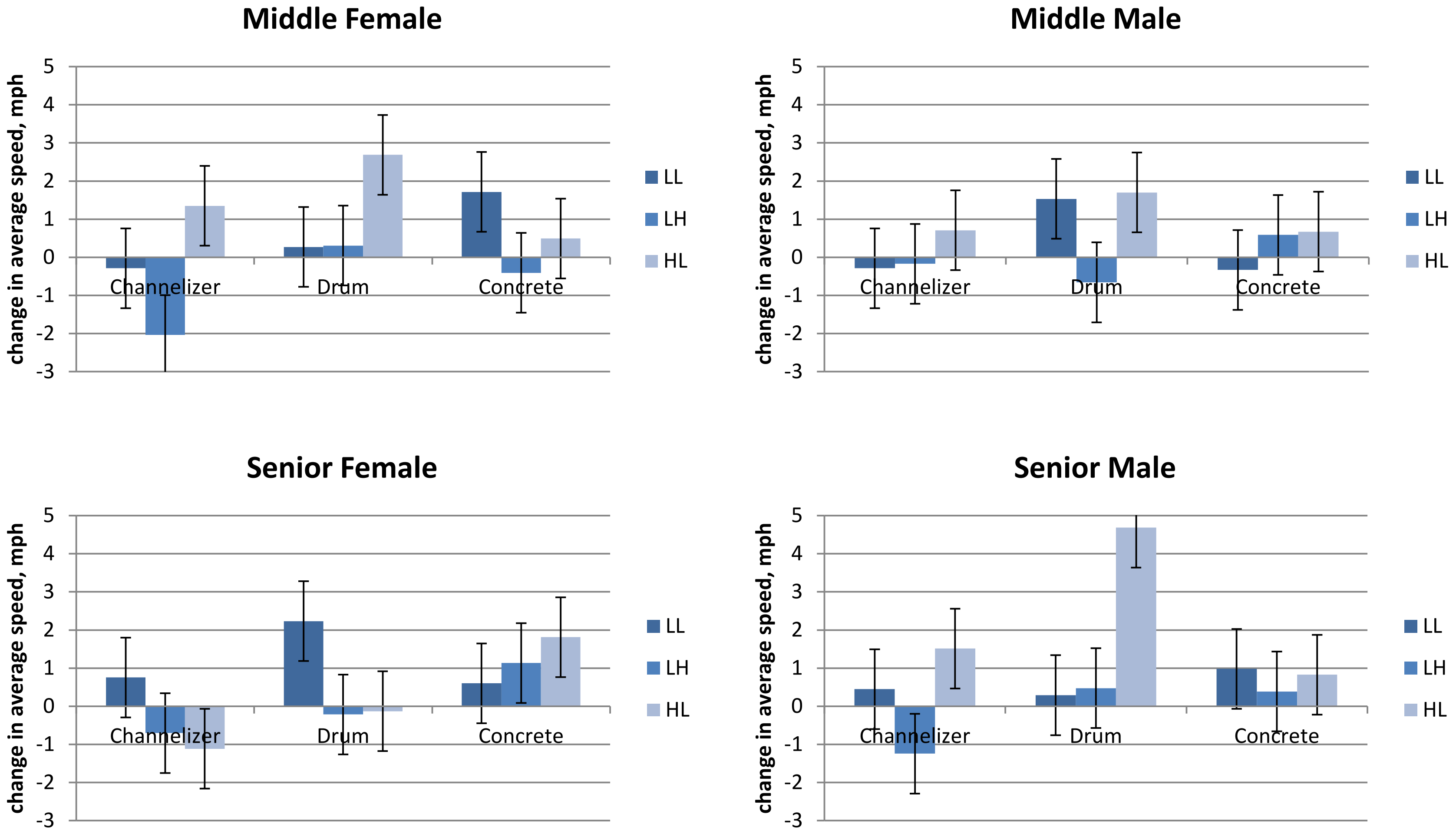


Figure 14. Four-way interaction of work zone transition type, barrier type, age group, and gender on change in average speed.

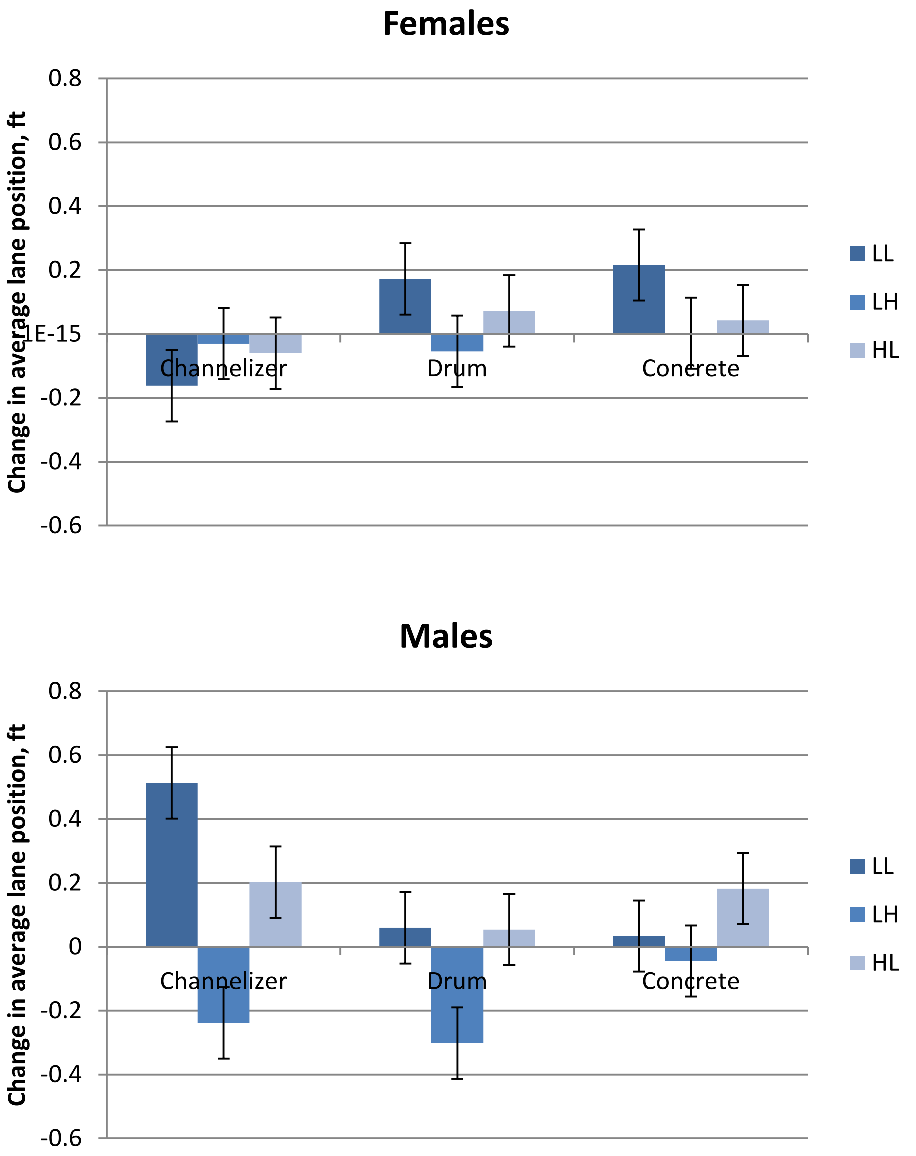


**Figure 15. Three-way interaction of work zone activity level transition type, barrier type, and gender on change in average lane position.**

# DISCUSSION

## Effect of barrier type

The first research question posed was “What effect do different barrier types have on driver performance?” Three types of devices used to define the activity area of the work zone were evaluated. The concrete barrier, used almost exclusively in long-term work zones due to the resources required to store, transport, set up, and remove them, resulted in faster but less variable speeds in the work zone. These results are aligned with previous research (Benekohal et al., 2004; Porter & Mason, 2008). The participants in this study drove closest to the concrete barrier with relatively low variation in lane position. One participant commented, “The jersey [concrete] barriers were the best objects to drive next to, I felt they provided the clearest line and straightest line to judge against. I also felt the workers were the most protected by them.” Another stated, “With a jersey [concrete] barrier I felt comfortable that no workers would step in front of me, but was concerned I might scrape the edge of my car. The workers were fairly well hidden by the barrier.” Although the participants in this study drove faster and closer to the concrete barriers, these barriers also showed a benefit of less variability in speed and lane position.

The drum and channelizer barrier types, typically used for temporary or moving work zones, resulted in similar performance for both speed and speed variability across the different work zone configurations. One exception was that in the channelizer work zones the senior participants drove significantly slower with a lateral buffer than without, but this difference in average speed was not observed in the work zones with the drums. In addition, differences were seen in the participants’ responses to the transitions in work zone activity level. Across all drivers, the drums led to a significant increase in average speed when the work zone activity decreased as well as when the activity level remained low. The drums never led to a significant decrease in average speed for any of the activity level transition types for any of the between-subjects groups. Conversely, the channelizers led to a significant decrease in average speed when the work zone activity level increased. Work zone conditions that lead to even small decreases in speed deserve special consideration because these effects can be magnified through the traffic queue. Even slight decreases in speed can cause backups inside and upstream of the work zone that can in turn lead to large speed differentials between the vehicles that have already reduced speed for the work zone and those still approaching. Once a queue begins to form, it can grow at an alarming rate, sometimes over 30 mph (Maze, Schrock & Kamyab, 2000).

Considering measures of lane position, participants tended to stay farther away from the work zones with the drums; however, lane position with the channelizers was significantly more variable, particularly in the first area of the work zones without a buffer. Considering all the results, this simulator study suggests that drums and channelizers can affect driver performance differently. On-road evaluations are warranted to determine if one type of device can offer a safety benefit in some work zone configurations, particularly because the 42-inch channelizer is commonly used as a longitudinal work zone boundary on high speed roadways.

### Effect of lateral buffer presence

The second research question considered what effect the presence of a lateral buffer in the work zone would have on driver performance in the simulator. It was expected that the presence of a lateral buffer would increase average speed but also offer a safety benefit by reducing speed variability, particularly in high activity work areas. At a high level, this is what was found. Across all participants, variability of speed was significantly greater in high level areas without a buffer. When a buffer was present, speed variability in the high activity areas was no different from that in the low activity level areas. However, the effect of the buffer on average speed differed by age group. While the middle age participants' average speed increased with the buffer for all barrier types, the older participants' speed with the buffer depended on barrier type. Average speeds across different driver groups were more similar without the buffer, especially for the drum and channelizer barrier types. In conclusion, the results suggest that under some combinations of conditions, the presence of a lateral buffer might help to reduce individuals' speed variability but under other conditions might actually exacerbate speed variability within the traffic stream in the work zone. Additional on-road and driving simulator research can help reveal the complex interactions of age group, barrier type, and buffer presence. Additional research must also be conducted to evaluate the effect of other traffic in the work zone, which was not considered in this study.

### Effect of work zone activity level

The third research question asked "What effect does the level of activity in the work zone have on driver performance?" Participants in this study were presented with two different levels of work zone activity that remained constant throughout each 4000-ft work zone half. The results show that average speed was about 1 mph slower in high activity areas compared to low activity areas. As expected, the average speed increased when the work zone activity level changed from high to low. The expected decrease in average speed in response to the transition from low to high activity was observed only for the channelizer barrier type. However, speed tended to increase in the second area of the work zone, which would counteract the expected decrease in average speed. Variability of speed was significantly higher in high activity areas without a lateral buffer and in high activity areas where the channelizer and drum were the barrier types. These results suggest that work zones with lengthy longitudinal buffers or intermittent areas of work activity have the potential to increase crash risk. As drivers become acclimated to the work zone, they tend to speed up. When they are suddenly confronted by the high activity portion of the work zone, they are more likely to make abrupt speed and/or lane adjustments that can then be magnified up the traffic stream. These effects can be exacerbated when the headway distances between vehicles does not allow for adequate preview of the work zone conditions ahead which then prevents drivers from making more gradual adjustments to their speed and lane position. The effect of headway distance on driver performance in response to sudden changes in work zone activity would be an appropriate topic for a future driving simulator study.

### Interactions

The numerous interactions found in this study illustrate the importance of considering work zone factors in combination rather than isolation. For example, if one wanted to evaluate the shy distance drivers are likely to adopt for a given barrier or channelizer, this evaluation must take into account what kind of work zone activities are taking place, how far the activity is from the traffic flow, what the lane width is, etc. The subjective findings from the post-experiment survey illustrate this as well; although the width of the open driving lane was the same for all of the drives in the simulator, a majority of the participants in the study (7 of 12 middle age participants and 9 of 12 older participants) reported that the width of the open driving lane was reduced in some of the work zones. Their perceived width of the lane was affected by one or more of the other experimental conditions: barrier type, lateral buffer, or activity level in the work zone. The ability to study numerous factors in combination is a tremendous benefit of evaluating work zones and other driving environments in simulators.

## Speed variability

The work zone experts consulted in this study as well as the work zone literature suggest that reductions in speed variability reduce crash risk in work zones. The overall variability in driving performance exhibited in work zones can be thought of as having both inter-driver (i.e., diversity of the driving population) and intra-driver (i.e., how a particular driver varies their performance in response to changing roadway conditions) components. Most work zone research considers the change in the 85th percentile velocity ($\Delta V_{85}$) for two locations (e.g., somewhere in the advance warning area and in the taper) as the measure of speed variability. Because the measure is only concerned with how the distribution of speed has changed for the entire traffic stream from one discrete point to another, it provides an indication of the inter-driver variability. An alternative approach that considers the response of each individual driver is the 85th percentile of a distribution comprised of the change in each individual driver's speed (maximum speed reduction, MSR) in response to the conditions being evaluated. Both an on-road study (Misaghi & Hassan, 2005) and a driving simulator study (Bella, 2007) that investigated driver response to curves found $\Delta V_{85}$ and $MSR_{85}$ to be significantly different. Using $\Delta V_{85}$ rather than $MSR_{85}$ to assess speed differentials led "to an underestimation of the difference of the speeds adopted by drivers," in this case about 6 km/h or about 3.7 mph (Bella, 2007). Such results suggest that evaluating the performance of individual drivers in response to varying work zone conditions as this study did is a worthwhile endeavor. The underestimation of speed differentials in work zones (i.e., assuming drivers will not slow down as much as they actually do) also leads to overestimation of vehicle capacity and throughput in the work zone, longer than anticipated queue lengths, and greater speed differentials where drivers enter the queue.

### Generalizing to actual work zones

The relative differences between work zone conditions in this simulator study, e.g., drivers having a higher average speed for the low activity areas relative to the high activity areas, should generally hold true on the road. Of course, a critical component to using driving simulators for the design of work zones as well as other design purposes is to validate the simulator findings with on-road studies. The greatest limitation to generalizing the results of this study to actual work zones is that the NADS MiniSim has not yet been validated for these kinds of research questions. Speed perception, for example, is one aspect of driving that can be difficult to replicate in driving simulators, especially fixed-based simulators like the one used in this study. Due to a lack of vestibular cues and a deficiency of visual and audio cues, the participants in this study likely had to rely on the speedometer more than they would in real life in order to maintain their desired speed. They also likely made greater efforts to maintain a speed near the 55 mph advisory speed posted for the work zone than they would in the real world. All of the middle age participants and 10 of the senior participants reported on the post-experiment survey being aware of their speed in the work zones.

The relative differences in speed for the various work zone conditions examined in this study provide evidence that the MiniSim likely exhibits at least some level of relative validity. Drivers had a lower average speeds in the high activity work zones, drove faster and were less variable in their speed with the concrete barriers, and speed variability decreased in high activity work zones when there was a buffer. All of these results match findings from *in situ* work zone studies. Nonetheless, simulator validation is essential for being able to reap the full benefits driving simulators can offer for work zone design and safety research.

Another limitation of all simulator research is that the participants are aware that there are no consequences to their actions, i.e., there is no risk to driving in a simulator. Nonetheless, participants in driving simulator research studies most often drive in a reasonable and responsive manner. In this study, driving performance varied according to the work zone conditions, suggesting that drivers were engaged in the task of driving in the virtual environment.

The participants in this study drove in isolation with no other traffic. It is possible that driver performance would be different if the participant vehicle was being followed or was following other traffic, and future research should definitely consider the effects of these conditions on driver behavior. One of the many advantages that driving simulators can offer work zone researchers is the ability to collect continuous data. The driver performance data collected in this study can be input to traffic simulation software to determine the effect an individual driver can have on the traffic stream when he or she is the leader of a platoon (group of cars).

# CONCLUSION

This project has demonstrated the feasibility and benefit of using driving simulators to investigate work zone interventions. In this study combinations of three different work zone characteristics (barrier type, presence of lateral buffer, and level of work zone activity) were investigated for participants in four different age-gender groups. The results suggest that participants were most comfortable driving in work zones with concrete barriers and that drums and channelizers affected driving performance differently depending on the work zone conditions. While for some combinations of conditions, the presence of a 4-ft lateral buffer demonstrated a benefit of less variable speed, average speed across all four driver groups was more similar without the buffer, particularly for the drum and channelizer work zones. Areas of high work zone activity caused drivers to reduce their speed and their speed tended to be more variable than in low activity areas.

Although there are many work zone interventions that cannot be evaluated using driving simulators, this project has demonstrated that driving simulators can be used to help identify ideas that have merit for on-road testing. Simulator studies offer a number of benefits, including safety, having control over the environment and traffic, the capability to replicate work zones with slight variations, being able to precisely measure the effects of the work zone characteristics on individual driver performance, and being able to screen and survey the participants.

This study is one of the first to evaluate work zones in a driving simulator. The next steps include replicating components of this study in actual work zones and comparing the results to validate the simulator findings. As the relationships between driving performance in various simulators and the real world are better understood, the generalizability of simulator studies will increase and so will their usability for solving real-world design problems.

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# APPENDIX A – LETTER TO EXPERTS

Date: May 8, 2009

Subject: Request for your expert opinion regarding techniques for improving work zone safety.

Dear Sir,

Our team at the University of Iowa, with the support of Smart Work Zone Deployment Initiative (SWZDI) and the University of Iowa Injury Prevention Research Center, has identified a number of ways to improve work zone safety on highways. Innovations in work zone safety can significantly reduce the threat posed to both motorists and work zone personnel. Driving simulators offer a cost effective means of evaluating and validating potential work zone interventions. Our overall objective is to demonstrate the feasibility of using a driving simulator to model work zone safety interventions and to assess how such interventions affect driver behavior.

The first step to achieving this goal was to conduct a broad search of the literature to identify a variety of potential work zone interventions and assess their suitability for assessment in a driving simulator. Our literature survey indicates that speeding is a persistent issue and that more effective means of reducing speed in work zones could result in fewer crashes, near-crashes, and fatalities. Issues associated with path regulation in the work zone are also concerning.

Our next step is to obtain expert opinions on work zone interventions to select a promising work zone intervention that can be implemented in one of the driving simulators on The University of Iowa campus and evaluated with a sample of Iowa drivers. Would you be willing to assist us by offering your feedback? If so, please read through the attached document that summarizes the information we have gathered. We would like your assessment of our direction and for you to verify that we have not omitted any vital details in our literature survey. We would also like to know about any other important issues that you think significantly affect work zone safety and whether studying an intervention to address those issues in a driving simulator would be of value. Please email Sameer Khan at ksameer@engineering.uiowa.edu to inform us whether you can accommodate our request. Although we would prefer to schedule a time to talk with you by phone, you may also offer your feedback via email. If you are unable to accommodate our request, would you please consider referring us to another individual in your department who might assist us? Thank you very much for your time.

Sincerely,

Prof. John D. Lee*
Principle Investigator

Michelle L. Reyes
Prof. Linda Ng Boyle*
Co-Investigators

Sameer Khan
Graduate Research Assistant

The summary of the four categories of work zone interventions found earlier in this document was attached to this letter.

*Professors Lee and Boyle were part of the project team prior to their departures from the University of Iowa at the close of the Spring 2009 semester.

# APPENDIX B – EXPERIMENTAL DESIGN

**Table 8. Counterbalancing of work zone order, lateral buffer, and barrier type over the six drives**

| | Work zone transition order | | | Lateral Buffer (in ft.) | Barrier type |
|---|---|---|---|---|---|
| Drive A | LL | LH | HL | 0 | Channelizer |
| Drive B | LH | HL | LL | 0 | Drum |
| Drive C | HL | LL | LH | 0 | Concrete |
| Drive D | LH | LL | HL | 4 | Drum |
| Drive E | LL | HL | LH | 4 | Channelizer |
| Drive F | HL | LH | LL | 4 | Concrete |

**Table 9. Latin square used to create six different driver orders**

| | Sequences of drives | | | | | |
|---|---|---|---|---|---|---|
| Order 1 | A | D | C | E | B | F |
| Order 2 | B | A | E | C | F | D |
| Order 3 | F | E | B | D | A | C |
| Order 4 | C | F | D | B | E | A |
| Order 5 | E | B | F | A | C | D |
| Order 6 | D | C | A | F | D | B |

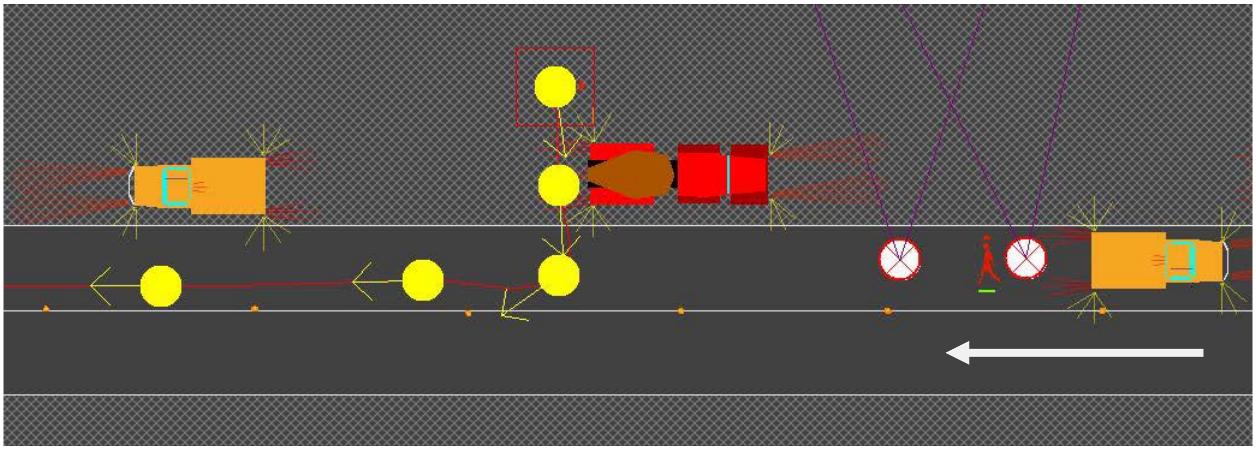
**Table 10. One participant from each between-subjects group was assigned to each drive order**

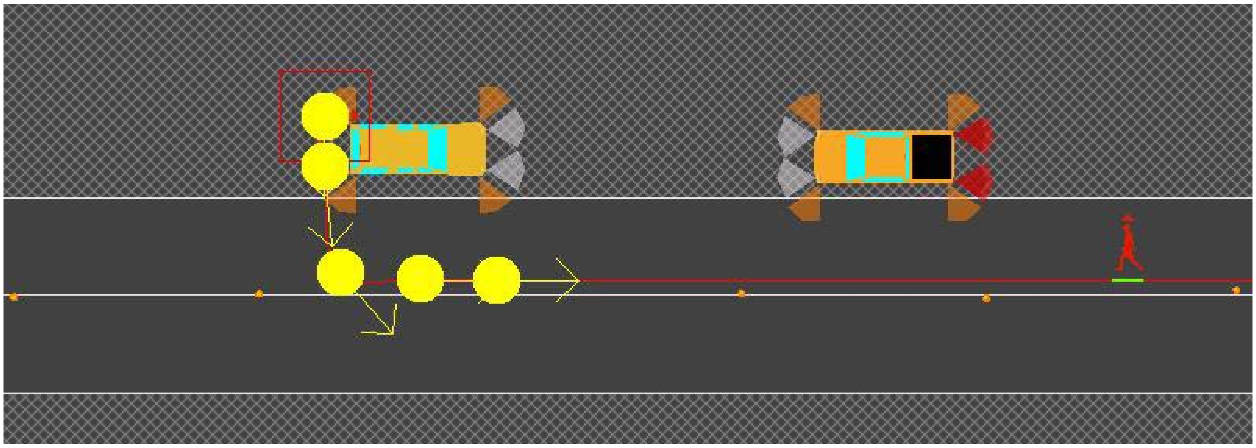
| | | Age group | | | |
|---|---|---|---|---|---|
| | | Young | | Older | |
| Gender | Male | 6 participants | Order 1 | 6 participants | Order 1 |
| | | | Order 2 | | Order 2 |
| | | | Order 3 | | Order 3 |
| | | | Order 4 | | Order 4 |
| | | | Order 5 | | Order 5 |
| | | | Order 6 | | Order 6 |
| | Female | 6 participants | Order 1 | 6 participants | Order 1 |
| | | | Order 2 | | Order 2 |
| | | | Order 3 | | Order 3 |
| | | | Order 4 | | Order 4 |
| | | | Order 5 | | Order 5 |
| | | | Order 6 | | Order 6 |

# APPENDIX C – WORK ZONE OBJECTS AND PATHS

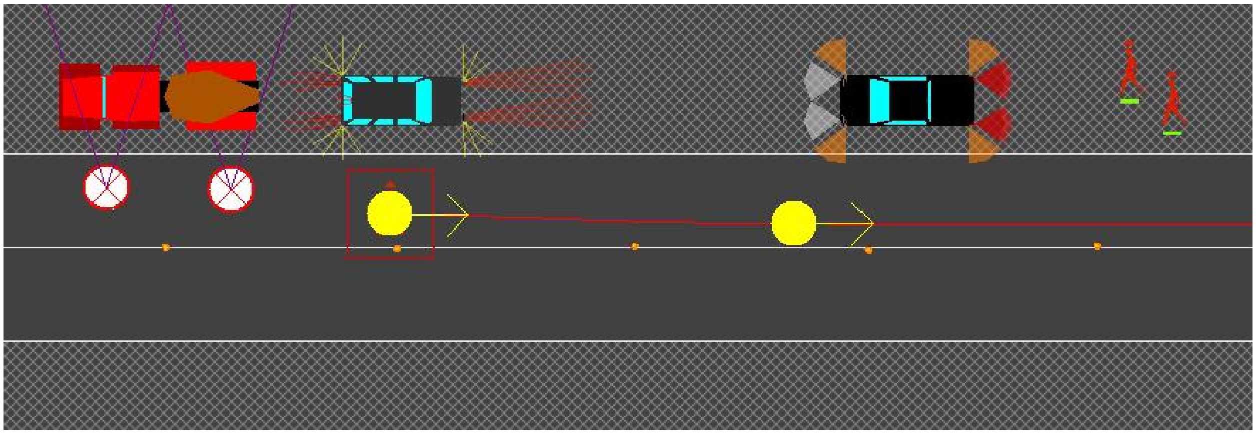
Dynamic worker models

Dynamic worker paths





Dynamic worker paths, cont.



Static worker models





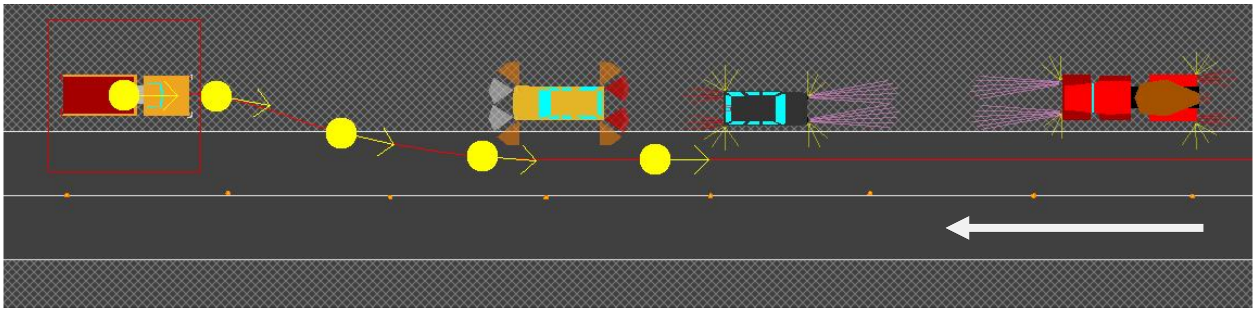


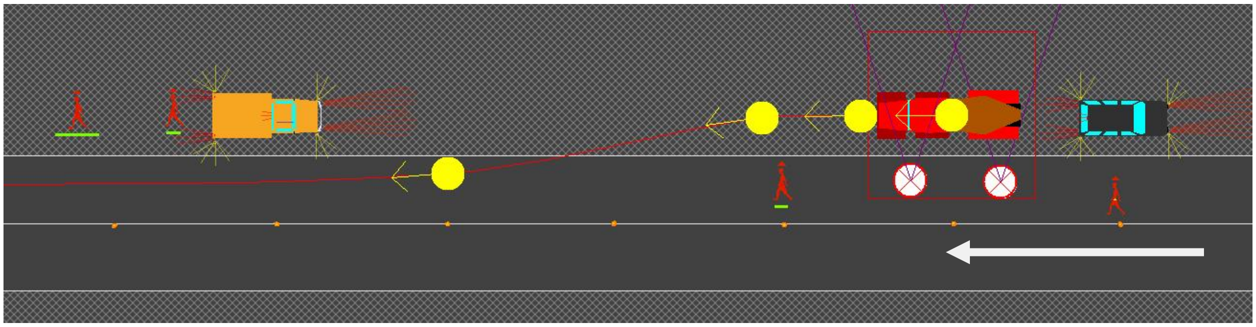




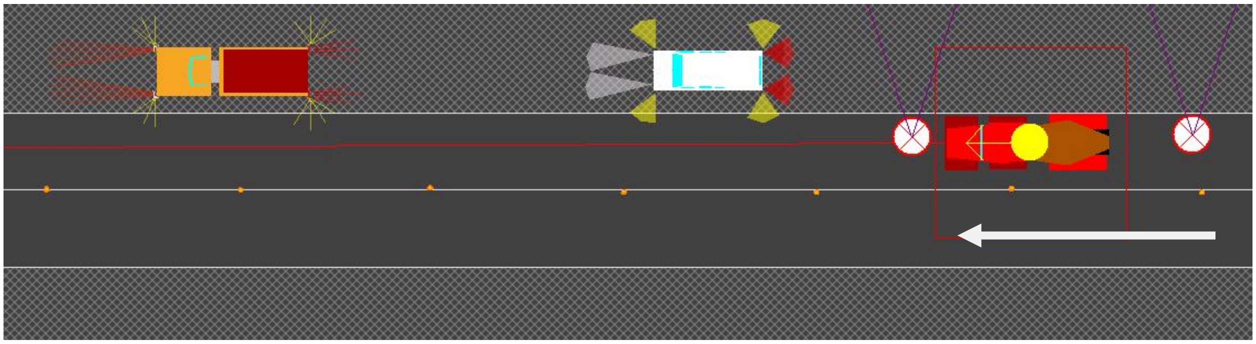

Work zone vehicle models

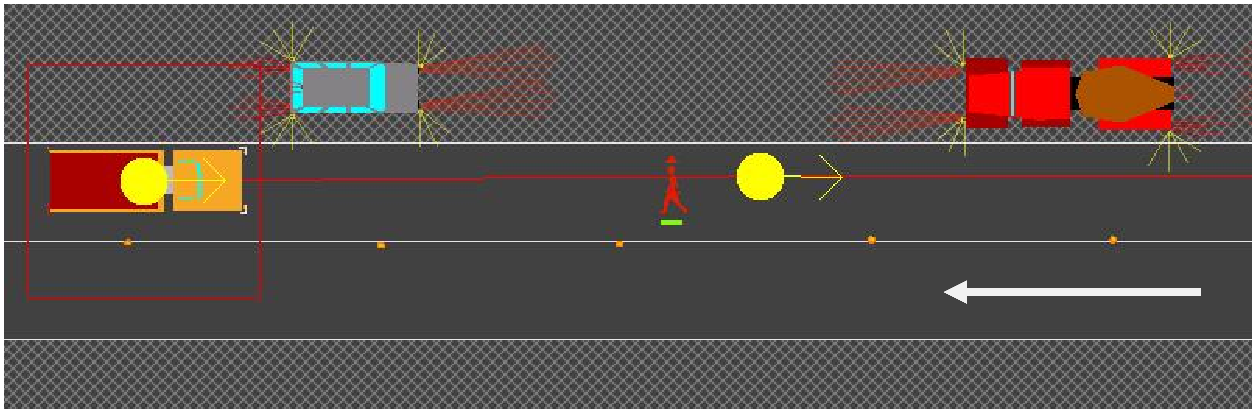
Dynamic work zone vehicle paths





Dynamic work zone vehicle paths, cont.





# APPENDIX D – INSTRUCTIONS TO PARTICIPANTS

## Practice drive instructions

*(Ask participant to sit in the driving simulator. Help them adjust the seat. Pushing the lever located at the bottom center of the seat all the way to the left allows it to slide and pushing it all the way to the right locks it into place.)*

Today you will be driving in a NADS MiniSim developed by the National Advanced Driving Simulator. This simulator models a car with automatic transmission. The controls consist of a gear shift, steering wheel, accelerator pedal, brake pedal, and turn signal that work just like they do in a real car. The three large screens display the virtual world that you will be driving through today. Your first drive will give you a chance to get used to how this simulator operates. The experience of driving the simulator feels similar to but obviously not the same as driving a real vehicle. Therefore, some people may experience a kind of motion sickness called simulator sickness while driving in the simulator. Symptoms of simulator sickness include discomfort, headache, stomachache, nausea, and dizziness. If you experience any of these symptoms at any time during the practice drive or at any other time today, please let me know right away. I will be just on the other side of the partition wall. In the unlikely event you become nauseated, you can use the convenience bag located here under your seat or there is a waste basket in the corner.

The practice drive today takes place on a rural, two-lane interstate highway. Please pay attention to the speed limit signs and try to drive as close to the posted speed as possible. Do not drive more than 90 miles per hour as the vehicle dynamics model in the simulator begins to become unstable at speeds higher than this. During the drive, you will encounter a work zone. As you approach and drive through the work zone, try to drive as you would if it were a work zone in the real world. The end of the drive is indicated by a pair of “stop ahead” road signs closely followed by a pair of stop signs. When you see these signs, begin to gradually brake to a stop. It is not necessary for you to come to a stop before you pass the stop signs. The practice drive will last about 7 minutes. Do you have any questions about the practice drive?

If at any point you want to stop driving, just tell me so. The drive will take a few moments to load. Please do not begin to drive until I tell you to do so. Then put the car into drive and press on the accelerator.

## After the practice drive

How are you feeling? Are you experiencing any symptoms of simulator sickness?

Do you feel comfortable driving the simulator? Would you like to complete the practice drive again?

Are you ready to begin the experimental drives?

## Experimental Drive 1 instructions

There are six experimental drives today. They all take place on the same roadway as the practice drive. Each drive will last about 12 minutes. During each drive, you will encounter 3 different work zones. Throughout the entire drive, try to operate the simulator as you would if it were a real car on a real roadway in the real world. If you normally drive in the right lane of the interstate, please drive in the right lane between work zones and merge for the closed lane at the point in time you would merge in the real world. Drive at a speed that reflects your comfort level with the driving conditions without exceeding a speed of 90 miles an hour. When you reach the end of the drive, you will again see the two “stop ahead” signs followed by the two stop signs. When you see these signs gradually brake to a stop and put the car into park. Do you have any questions?

Remember that you can stop the drive at any point. Be sure to let me know right away if you start to feel any symptoms of discomfort or illness while driving. I will start the drive now, but please wait until I tell you to start driving.

**Experiment Drives 2 and 3 instructions**

Just like the previous drive(s), try to operate the simulator as you would in the real world. Drive at a speed that reflects your comfort level with the driving conditions without exceeding a speed of 90 miles an hour and gradually brake to a stop when you see the stop signs. Remember that you can stop the drive at any point. Be sure to let me know right away if you start to feel any symptoms of discomfort or illness while driving.

Do you have any questions? I will let you know when you can begin driving.

**Break After Drive 3**

At this point in the study, we would like you to take a 5-minute break. Would you like to show you where you can get a drink of water or use the restroom?

**Experimental Drive 4**

Just like the previous drives, try to operate the simulator as you would if it were a real car on a real roadway in the real world. If you normally drive in the right lane of the interstate, please drive in the right lane between work zones and merge for the closed lane at the point in time you would merge in the real world. Drive at a speed that reflects your comfort level with the driving conditions without exceeding a speed of 90 miles an hour and gradually brake to a stop when you see the stop signs. Remember that you can stop the drive at any point. Be sure to let me know right away if you start to feel any symptoms of discomfort or illness while driving.

Do you have any questions? I will let you know when you can begin driving.

**Experiment Drives 5 and 6 instructions**

Just like the previous drive(s), try to operate the simulator as you would in the real world. Drive at a speed that reflects your comfort level with the driving conditions without exceeding a speed of 90 miles an hour and gradually brake to a stop when you see the stop signs. Remember that you can stop the drive at any point. Be sure to let me know right away if you start to feel any symptoms of discomfort or illness while driving.

Do you have any questions? I will let you know when you can begin driving.