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EXAMINING DRIVER PERFORMANCE IN RESPONSE TO WORK ZONE INTERVENTIONS IN A DRIVING SIMULATOR

by

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of the requirements for the
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Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Industrial Engineering at the July 2010 graduation.

Thesis Committee: ______________________________
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Thomas Schnell

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Glory be to the Father, and to the Son, and to the Holy Spirit, now and forever. Amen.

To Orlando, my amazing husband and best friend,
this thesis and this degree wouldn’t have been possible without you.
Thank you for being there for me and for not giving up on me.
I cannot wait to start the next chapter of our lives together!

To Orly, Grace, Michael, and Emelia,
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I love you all more than you can ever imagine.

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ABSTRACT

Reductions in speed and, more critically, speed variability between vehicles are thought to reduce crash risk in work zones. Numerous factors, such as lane width and lateral clearance and activity level, have been shown to influence speed but very little research has considered how multiple factors might interact to affect driver performance in work zones. This study evaluated the effect of work zone barrier type, presence of a lateral buffer, and work zone activity level on measures of speed and lane position. Twelve middle aged and twelve senior subjects drove in a National Advanced Driving Simulator (NADS) MiniSim. The subjects drove faster and with less variability in work zones with concrete barriers. Measures of speed and lane position were more heterogeneous across groups with 42-inch channelizers compared to drums. Speed was reduced and more variable in work areas with a high level of activity than in areas with a low level of activity. On the whole, the presence of a lateral buffer reduced speed variability in the high activity areas but this response was not uniform across all drivers. This research demonstrates that driving simulators can be used to evaluate how work zone factors may interact with one another to affect driver performance for different driver groups. While the results from this study corresponded to observations from actual work zones, the driving simulator must be validated with on-road data before generalizations can be made.

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INTRODUCTION

Work zones pose a significant threat to both workers and motorists. In 2008, motor vehicle crashes in work zones resulted in 720 fatalities (Texas Transportation Institute, 2010) and over 40,000 injuries (Federal Highway Administration). Mohan & Gautam (2002) estimated the total cost of highway work zone crashes in the late 1990s to be about $6 billion per year. Roadway demand continues to rise without significant increases in capacity while at the same time our nation's highway system, much of it completed decades ago, requires increasing repair (Federal Highway Administration, 2008). The convergence of these two factors suggests that work zone safety will be a major concern for many years to come.

Many work zone safety efforts have focused on the speed and speed variability (i.e., vehicles traveling at different speeds) of the traffic stream. Frequently the speed limit is reduced some distance before and throughout a work zone to enhance safety for both motorists and workers. There is little doubt that crash severity increases with speed, but the role of speed on general crash risk is less clear. A review of the literature on this topic concluded that crash rates increase exponentially with increases in speed (Aarts & van Schagen, 2006). However, Garber & Gadiraju (1989) reported that the effect of speed on highway crash rates cannot be resolved because speed is confounded by road geometry (1989). A few studies of work zone crashes report on the role of speed in crash frequency. In a study of work zone crashes in Kansas (Li & Bai, 2009), speeding was a factor in 15% of the fatal crashes and 20% of the crashes causing injury. Bryden, Andrew, & Fortuniewicz (2000) report that excessive or inappropriate speed was a factor in about 25% of work zone intrusion crashes in New York state. Driving too fast for condition was a factor in 6% to 10% of fatal crashes in Georgia (Daniel, Dixon, & Jared, 2000).

A number of studies have found rear-end crashes to be the most prevalent type of work zone crash (Wang, Hughes, Council, & Paniati, 1996). For example, an investigation of work zone crashes in Virginia showed that 52% were rear-end collisions (Garber & Zhao, 2002). Speed differentials are of great concern in work zones where capacity is reduced, traffic density can be high, and flow of traffic can change quickly. Once a queue begins to form, it can grow at an alarming rate, sometimes over 30 mph (Maze, Schrock, & Kamyab, 2000). Both Garber & Gadiraju (1989) and Aarts & van Schagen (2006) agree that crash risk does increase with greater the differences between individual drivers' speeds. These kinds of results are often cited as evidence that reducing speed variability in the work zone traffic stream would lead to safer work zones.

A wide variety of traffic calming treatments have been considered for reducing speed in work zones (see Fitzsimmons, Oneyear, Hallmark, Hawkins, & Maze, 2009 for a recent review). One motivation for implementing speeding countermeasures is that compliance with the posted work zone speed limit "can decrease the speed variance and potentially improve work zone safety" (Benekohal, Wang, Chitturi, Hajbabaie, & Medina, 2009). However, with the exception of some limited success for enforcement of work zone speed limit through photo-radar systems or active law enforcement personnel (e.g., Benekohal, Chitturi, Hajbabaie, Wang, & Medina, 2008; Benekohal et al., 2009; Brewer, Pesti, & Schneider, 2006), speeding countermeasures are largely ineffective and any reductions in speed generally do not endure throughout the work zone (Benekohal et al., 2008; Medina, Benekohal, Hajbabaie, Wang, & Chitturi, 2009). In reality, the use of such techniques might actually be counterproductive and increase speed differentials between vehicles by inducing drivers near the enforcement site to decelerate at a high rate. Vehicles following behind must then decelerate at an even higher rate to avoid collision.

The general ineffectiveness of speed countermeasures in work zones is highlighted by the fact that the MUTCD calls for work sites to “be designed on the assumption that drivers will only reduce their speeds if they clearly perceive a need to do so.” Research has shown that a variety of factors, for example, lane width and clearance distance to fixed objects along the roadway, can influence drivers to slow down, presumably by creating situations that increase driver discomfort. The objective of this thesis is to investigate how some of these factors might interact with one another to influence driver performance in work zones. The term driving performance as used in this thesis refers to measures of both longitudinal and lateral vehicle control. Because achieving this objective by performing studies in active work zones would be impractical, time and resource consuming, data impoverished, and most importantly, potentially very dangerous, this study takes place in a driving simulator.

BACKGROUND

Work zones are designed according to a set of federal standards and guidelines and can consist only of approved devices. Different factors of work zone design have been shown to affect driver performance in various ways. Gathering performance data for individual drivers in actual work zones is challenging and has a number of other drawbacks that driving simulator studies can address.

Work zone design

Work zone layout

The design specifications for temporary traffic control zones (i.e., work zones) are described in Part 6: Temporary Traffic Control of the *Manual on Uniform Traffic Control Devices for Streets and Highways* (commonly referred to as the MUTCD, U.S. Department of Transportation Federal Highway Administration, 2009). There are four main components or areas in a work zone. Figure 1 illustrates these four areas for a stationary work zone on a roadway in which one of the two lanes is closed. In the advance warning area, motorists are informed through signs or other devices that temporary traffic control measures are located in the roadway ahead. In the transition area, traffic is diverted from its regular path with approved channelizing devices arranged in a taper. The activity area follows the transition area and is designated with longitudinal channelizing devices or barriers. In addition to the space where the actual work occurs, the activity area can also include longitudinal and/or lateral buffer space(s), which the MUTCD states can serve to both separate the traffic from the work space or other unsafe area and “provide some recovery space for an errant vehicle.” The decision

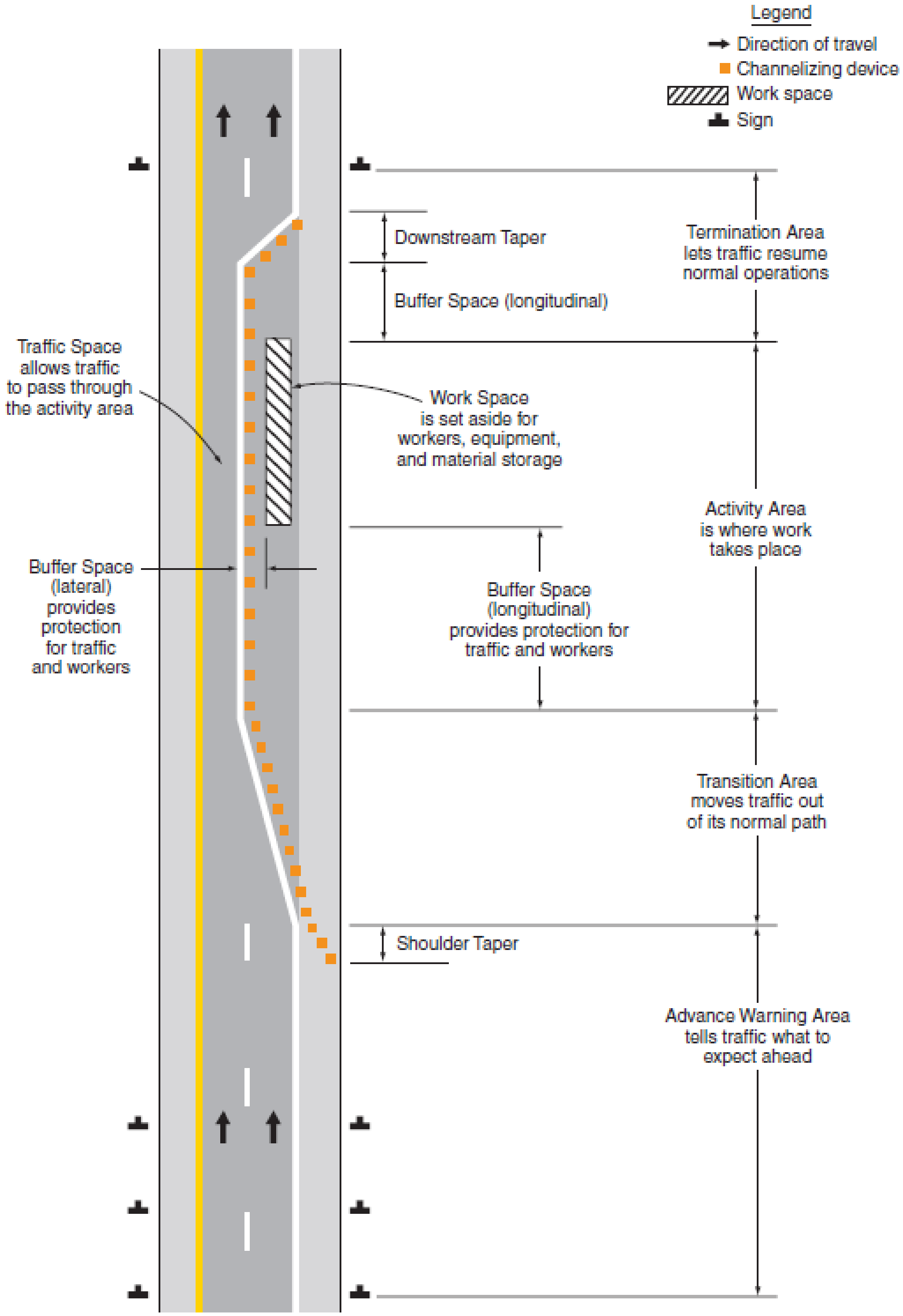


Figure 1. Component parts of a temporary traffic control (i.e., work) zone (U.S. Department of Transportation Federal Highway Administration, 2009)

to use one or both kinds of buffers and the dimensions of the buffers are left to "engineering judgment." Very little guidance is given in the MUTCD, particularly for the lateral buffer. The final part of the work zone is the termination area where traffic returns to its regular path and speed.

Channelizing devices and barriers

Part 6 of the MUTCD specifies categories of channelizing devices that serve "to warn road users of conditions created by work activities in or near the roadway and to guide road users." One category of these devices is drum type channelizers that are a minimum of 18 inches in diameter and a minimum of 36 inches high. Other category of channelizers is cones. Tall cones (greater than 36 inches) first appeared in the 2003 version of the MUTCD (Souleyrette, McDonald, & Kroeger, 2007). A commonly used device in this category, usually called a 42-inch channelizer or a trim-line channelizer, is used in a number of states (including Iowa) to demarcate the work zone in the activity area (i.e., for tangent channelization). These channelizers are often preferred over drums because their smaller footprint makes them easier to use and store, but they also present a smaller visual target for drivers. Only one study is known to have evaluated their performance. Souleyrette et al. (2007) evaluated how the tall cone channelizers performed as channelizing devices in the transition taper compared to drums. They concluded that drivers' behavior while merging for the closed lane with the two devices was very similar. While these findings suggest that the tall cone channelizers may be suitable for use in the transition area, no studies have evaluated how using tall cones for tangent channelization affects driver performance.

Drums, tall cones, and other channelizing devices specified in the MUTCD are often used in work zones that will only be in place for a short time. These devices do not provide any positive protection for the workers in the work zone. There are some work zones, for example, long-term, high-speed work zones, where the use of barriers "designed to help prevent penetration [of the work zone] by vehicles while minimizing injuries to vehicle occupants" (MUTCD, 2009) is appropriate. The most commonly used barriers are portable concrete barriers. Porter, Mahoney, & Ullman (2006) present guidelines for determining when such barriers should be used. The use of portable concrete barriers in work zones has been linked to a reduction in speed deviations for passenger cars (Porter & Mason, 2008). The different material properties of these devices and barriers can cause drivers to feel more or less comfortable in the work zone which then affects their choice of speed.

Factors that affect driving performance

The *Highway Capacity Manual* (HCM, Transportation Research Board, 2000) identifies several roadway features that affect free-flow speed of the traffic stream though the work zone. One of these is lane width. The HCM estimates that, relative to standard 12-ft lanes, 11-ft and 10-ft lanes on multilane highways will lead to reductions in free-flow speed of 1.9 and 6.6 mph, respectively. However, the HCM does not address the effect of lane width reductions in work zones. Chitturi & Benekohal (2005) observed free flowing traffic in four long-term work zones that consisted of a single open lane next to a concrete barrier without any lateral clearance or work activity. Seemingly the only noteworthy difference between the work zones was the widths of the open lanes. The observed free-flow speed reductions for the 16, 11, and 10.5-ft lanes relative to the standard 12-ft lane were -3.5 (i.e., an increase in speed), 4.4 and 7.2 mph. The same study estimated that eliminating the lateral clearance for the 12-ft lane resulted in a 5.6 mph decreased in free-flow speed. However, the factors of reduced lane width and reduced or no lateral clearance were not considered in combination, possibly due to the difficulty of finding or designing work zones that are essentially equivalent in all other factors.

While the actual lane width in a work zone is determined by the placement of the channelizing devices or barriers, the type of channelizing device or barrier may affect the perceived lane width. Shy distance is defined as “the limit of where a roadside object will be perceived as an obstacle by the typical driver to the extent that the driver will change the vehicle’s placement or speed. It is measured from the edge of the traveled way” (Mahoney, Porter, Taylor, Kulakowski, & Ullman, 2006, p. 38). The tendency of drivers to react to roadside objects, including work zone channelizing devices or barriers, has the potential to affect speed variability. This tendency can be counteracted by allowing adequate space for lateral clearance, also referred to as barrier offset. However, no literature reporting typical shy distances for specific channelizing devices or barrier types could be found. Souleyrette et al. (2007) reported the modal shy distance measured at the beginning of the taper for a sample of drivers to be about 6 ft for both drum and 42-inch channelizers. However, no statistical analyses were reported and shy distance was not measured in the active area of the work zone.

Lane width, lateral clearance, and barrier type can all interact to affect driver speed under normal driving conditions. Tay & Churchill (2007) investigated how different median barrier types affected driver speed on urban freeways. Using guidelines from the *Highway Capacity Manual*, they estimated the expected speed decrease due to the particular lane width and lateral clearance in six sites with barriers relative to two control sites without median barriers. With the exception of one site, the differences between the actual and expected mean speeds were large, and with the exception of another site, speeds actually increased rather than decreased. Relative to no median barrier, mean speeds were significantly faster in the two sites with just a concrete "F" barrier and significantly slower for the two sites with a concrete "F" barrier topped by a chain link fence. While the interpretation of the results cannot be widely generalized because barrier type was confounded with lane width and lateral clearance, the results suggest that barrier type can influence driver comfort and speed choice. In addition, in some situations drivers might perceive the barrier to provide a safety benefit and increase their speed in response. This study, which was completed in normal driving conditions, suggests that channelizer and/or barrier type, lateral offset, and lane width in work zones can interact with other factors to influence driver behavior in unexpected ways.

The type and intensity of the work being completed in the work zone is yet another factor that has been shown to influence the speed of drivers in a work zone. Dixon, Hummer, & Lorscheider (1996) measured capacity at different locations in the work zone and found that in work zones with moderate and heavy levels of work activity, the smallest bottleneck was not found in the advance warning area or at the taper, but rather adjacent to the activity area. Benekohal, Kaja-Mohideen, & Chitturi (2004) note that while commonly used formulas for estimating short-term work zone capacity include components that take into account the intensity of the activity taking place in the work zone (e.g., Krammes & Lopez, 1994), no guidance is given for selecting the value of the adjustment term. Rouphail & Tiwari (1985) defined an activity index calculated by assigning values to conditions like proximity of activity to the travel lane, the number of workers, the kind of equipment in use, the presence of a flagger, and the level of dust. Benekohal et al. (2004) propose that work zone intensity should be quantified as a ratio of the number of workers and amount of equipment in the work zone over the distance between the traffic lane and the activity area. Both approaches for quantifying work zone activity level suggest that increasing the distance between the travel lane and the work zone activity may help to mitigate the effects of work zone activity level on driver performance. Benekohal et al. (2004) also take into account whether the work zone is a long-term work zone with concrete barriers or a short-term work zone with cones or drums. Their calculations show that, regardless of work zone activity level, greater decreases in speed are expected in short-term work zones that long-term work zones. Unfortunately, the model for the short-term speed curve was developed using survey data rather than field data as was used for the long-term speed curve. Even if field data had been used, due to the different kinds of work zone activities typically conducted in short and long-term work zones, it could be difficult to find work zones with equivalent activities in order to evaluate the interaction of barrier type and activity level. In addition, neither Rouphail & Tiwari's nor Benekohal et al.'s methods for quantifying level of work zone activity take into account the length of the work space. In other words, the density of the work zone activity is not considered such that an identical amount of workers and machinery in a 1000-ft area would be quantified the same way in a 5000-ft area. Finally, no research that considers how intermittent work areas within a continuous work zone, a fairly common practice during roadway repair operations, affect driver performance could be found.

Clearly not all variability in driver performance in work zones can be attributed to roadway characteristics like lane width, work zone type, work zone activity level, and lateral clearance. The heterogeneity of the driving population is likely the greatest contributor to variability in the traffic stream. The two broadest ways to categorize drivers are by age and gender. An investigation of work zone crashes in Kansas (Li & Bai, 2009) suggests that looking at these driver categories can be useful. Male drivers accounted for 75% of the fatal crashes and nearly 2/3 of the injury crashes. Nearly one fourth of the fatal work zone crashes involved drivers age 65 and over. Given that only about 15% of Kansas drivers fall into this age group (Federal Highway Administration, 2003), it would seem that senior drivers are overrepresented in work zone crashes. Surprisingly drivers age 35-44 (19% of licensed drivers) also accounted for roughly one fourth of the fatal crashes. It is less clear why this age group would be responsible for such a significant portion of the crashes.

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 (ΔV_{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 & Y. Hassan, 2005) and a driving simulator study (Bella, 2007) that investigated driver response to curves found the two measures to be significantly different. Using ΔV_{85} rather than MSR_{85} to assess speed differentials led "to an underestimation of the difference of the speeds adopted by drivers" (Bella, 2007). Such results suggest that evaluating the performance of individual drivers in response to varying work zone conditions it is a worthwhile endeavor.

In summary, numerous individual work zone characteristics can affect driver behavior in work zones. However, the effects of these various factors cannot be considered in isolation. They act in combination with one another to affect each individual driver's perception of the work zone as a whole. Each driver's assessment of the work zone results in some level of comfort or discomfort that is exhibited through his or her driving performance.

Driving simulators for 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 deploying and retrieving automatic vehicle counters. Even when these 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.

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, subjects can be recruited from different populations of drivers, and additional data can be acquired from indexes, tests, or surveys of driving style and history. In actual work zones it is impossible to control for conditions like driver inattention or distraction. With driving simulators it is possible to see how performance is affected when the driver is not fully engaged in the driving task.

Implementing an untested work zone configuration on an actual roadway can have fatal consequences. Driving simulators make it feasible to evaluate work zone designs in a safe, virtual environment. A significant obstacle for *in situ* work zone research is selecting equivalent areas 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 exact same set 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.

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, and 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 Administration, 2010).

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 driving 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."

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 and there are some research questions that can only be evaluated in actual driving conditions.

Two specific studies investigating driver response to both real and virtual work zones illustrate the range of outcomes. The first study investigating driver speed while approaching and traveling through a virtual work zone found a high level of relative validity because the pattern of results in the simulator closely matched those measured in the actual work zone (Bella 2005). On the other hand, a simulator study investigating the effect of steady-burn warning lights on speed in a nighttime work zone found that speed was generally constant in the simulator, while in the actual work zones drivers slowed down near the middle of the work zone and speed up near the end (McAvoy, Schattler, & Datta, 2007). The paper does not give enough methodological details to ascertain why the simulator fidelity was inadequate to evaluate the effect of the warning lights, but these results illustrate why driving simulator validation is an essential step in order to transfer simulator results to actual driving.

Research aims and expected results

Based on the review of previous work zone and simulator research as well as the capability afforded by the target simulator for the manipulation of various roadway characteristics, three work zone factors were selected for investigation: work zone barrier type, presence of a lateral buffer, and work zone activity level. An experiment was designed to evaluate how these factors, both individually and in combination, affect longitudinal and lateral control of individual drivers from different age and gender groups.

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. In this study, combinations of work zone factors that reduce speed variability but do not lead to high speeds, extreme lane positions, or highly variable lane position would likely represent a safety benefit.

For this study, it was expected that work zones with high levels of activity would lead to an increased perception of risk and drivers would respond accordingly by lowering their speed (hence increasing speed variability) and increasing the lateral distance between themselves and the activity (i.e., increase in lateral position and variability of lateral position. It was expected that the presence of a lateral buffer would mitigate the perceived risk in busy work areas and lower the magnitude of the driver response.

In previous work zone studies, drivers have exhibited higher and less variable speeds with concrete barriers. These results suggest that on the whole barriers were perceived to decrease risk by providing a physical and visual barrier between the driver and the work zone. However, in this study of individual driver response, it is possible that some drivers will find the prospect of collision with the concrete barrier to increase their perceived risk. Similarly, opposing hypotheses could be drawn for the other two barrier types.

METHODS

Study design

This study was a mixed design with three within-subject factors and two between-subject factors. One within-subject factor was work zone barrier type and contained three treatments: drum, 42-inch channelizer (herein referred to only as “channelizer”), and concrete barrier. (Note that although drums and channelizers are categorized by the MUTCD as channelizing devices and are not in the strict definition of the word “barriers,” the first factor is named “barrier type” because all three treatments act to separate the driving lane from the work zone activity.)

The second within-subject 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 six experimental drives.

The third factor consisted of two levels of work zone activity (low and high). In order to evaluate the effect of changing activity levels within a single work zone, the activity levels were 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 type of activity level transition appeared once in each of the six drives and the order of appearance was randomized across the drives. Thus each subject experienced eighteen different work zones during the study.

The order in which the six drives were presented to the subjects 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 be driven consecutively. 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 A.

Subjects

Twenty-four subjects participated in this study. They 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), so there were six subjects in each between-subjects group. One subject from each group was randomly assigned to each of the six drive orders. Each subject had at least 19 years of driving experience and drove at least three times per week. Eight of the middle age subjects and ten of the senior subjects reported that they drive every day.

Simulator description

The simulator selected for this study was the National Advanced Driving Simulator (NADS) MiniSim (see Figure 2). 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 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 inches, the display offers a field of view that is 132 by 24 degrees. The simulated vehicle dynamics modeled those of a Chevy Malibu. The dynamics model, visual scene, and data stream were all updated at 60 Hz.

Figure 2. The National Advanced Driving Simulator (NADS) MiniSim

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.

Work zone layout

The distance from the simulated vehicle's starting position to the first sign for the first work zone was 7000 ft. The advance warning area of the work zone was 5040 ft long and contained three pairs of signs, one sign located on each side of the roadway (see Figure 3). 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 was the transition area, which consisted of a taper of drums that closed the right lane over a length of 760 ft.

In the activity area of the work zone, the right lane was closed for a total of 9000 ft and one of the barrier types (channelizers, drums, or concrete barriers) formed the boundary of the work zone (see Figure 4). 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 advance warning area 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 work zone, followed by a pair of stop signs 400 ft ahead.

Figure 3. Signs in the advance warning area of the work zone

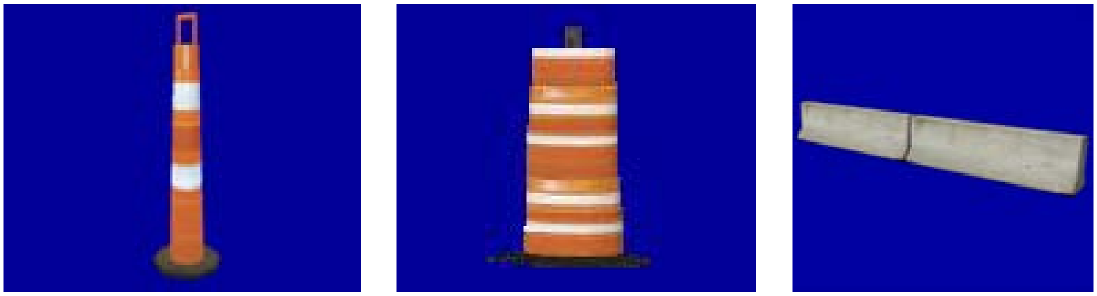


Figure 4. Three different barrier types evaluated in this study: 42-inch channelizer, drum, and concrete barrier

Work zone vehicles and workers

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 B. 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 subject vehicle approached (see Appendix B 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 either dynamic or static. The dynamic vehicles followed one of four different types of paths and were programmed to start moving as the subject approached. Images of the work zone vehicles and diagrams of the dynamic vehicle paths can be found in Appendix B. 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 activity area did not contain any vehicles or workers in order to create a longitudinal buffer in the work zone. The next 8000 ft of the activity area was divided into two 4000-ft activity zones. Work zone objects were placed in each activity zone according to one of two work zone activity levels. High activity zones had the following number of objects *in each 500-ft segment*:

- 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.

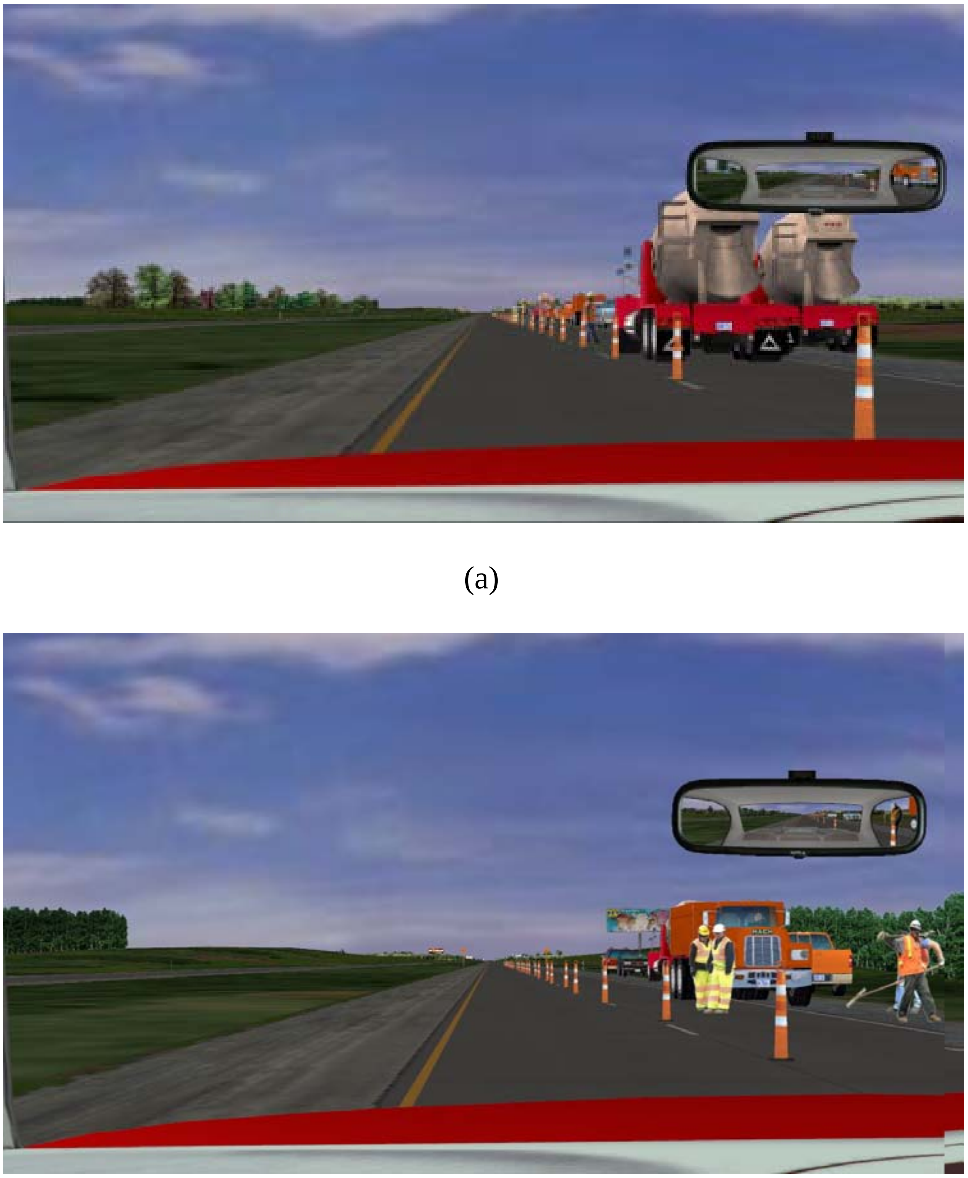
Low activity zones included the following number of objects *in each 4000 ft zone*:

- 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.

Each high activity zone had approximately six times the number of objects as each low activity zone. Only the high activity zones contained the dynamic vehicles and workers. The motion of each dynamic vehicle or worker was initiated by either a location-based or time-based trigger, depending on the precision required for the subject to be able to see the object in motion as he or she approached it.

Lateral buffer

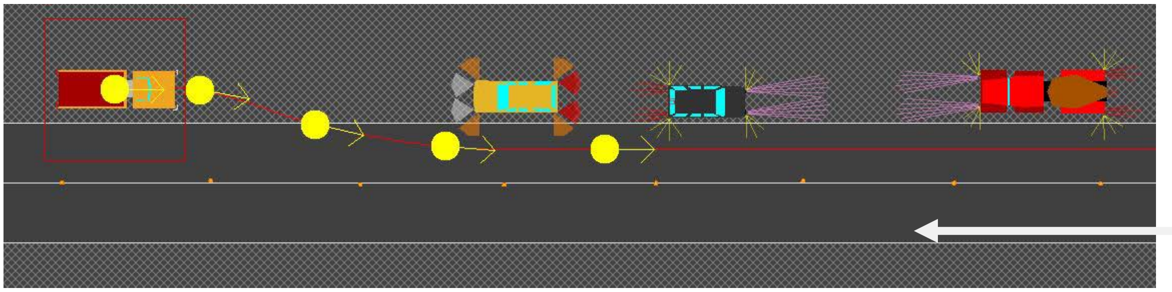
In order to evaluate the effect of a lateral buffer between the work zone objects and the barriers, the positions of all of the vehicles and workers in the activity area were shifted four feet toward the shoulder and the position of the barriers did not change. Because the MUTCD states that “the width of a lateral buffer should be determined by engineering judgment” (p. 555 of 2009 ed.), the width was determined by considering what lateral buffer would be realistic if this were a real work zone as well as how the buffer appeared in the simulator. Figures 5 and 6 show the lateral buffer from the driver’s and bird’s eye perspectives, respectively.



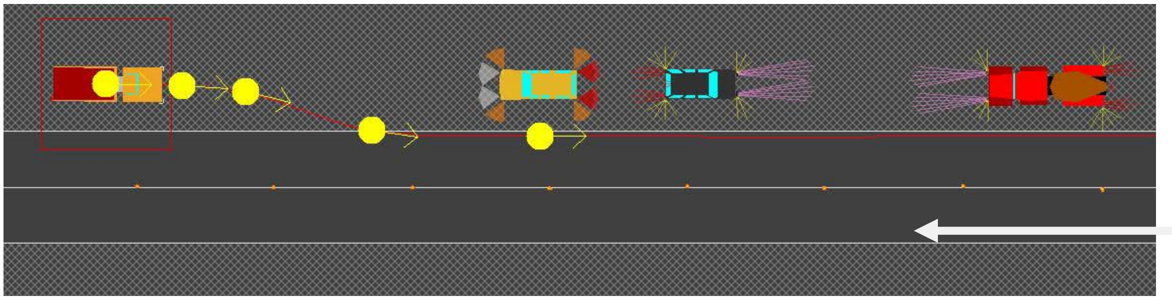
(a)

(b)

Figure 5. Driver's view of a work zone without (a) and with (b) a 4-ft lateral buffer



(a)



(b)

Figure 6. Bird's eye view of the simulated driving environment in the Interactive Scenario Authoring Tool (ISAT). The small arrows and nodes indicate the pullout path of a dynamic work zone vehicle. The large arrows indicate direction of travel of the simulated vehicle. Figure 6(a) shows the set up for the no lateral buffer condition. Figure 6(b) shows the 4-ft shift to create the lateral buffer.

Protocol

When the subjects 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 C) about how to operate the simulator were given. Then the subject drove a practice scenario that contained one work zone and took approximately seven minutes to complete. The approach to the work zone was identical to 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 switched to drums for another 4500 ft and the work zone concluded with another 4500 ft of concrete barrier. The scenario also contained one instance of all the work zone vehicles and workers that were also present in the experiment scenarios. Before and after the work zone there were several different speed zones (either 50 or 70 mph). The subjects 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 shortly by two stop signs. The subjects were instructed to brake to a stop when they saw these signs. The instructions also describe the symptoms of simulator sickness and the subjects were instructed to stop driving immediately if they started to feel ill or uncomfortable.

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

The six experimental drives were completed in two 3-drive blocks with a 5-minute break between them. The experimental drives each took about twelve minutes to complete and were presented in the order the subject had been randomly assigned to. Instructions were read aloud to the subject before each drive (see Appendix C for the instructions read to the subjects). After the sixth experimental drive was completed, the subject 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 calculated by taking standard deviation. Distance at which the subject merged for the closed lane in the work zone was also calculated. Analyses were completed for two sets of summarized data. One set summarized driver performance within each 4000-ft activity zone. In order to investigate the effects of changing the activity level in the work zone, a second data set summarized the change in driver performance in the 2000 ft after the transition to the second activity zone relative to the 2000 ft feet before the transition. All statistical analyses were completed in SAS 9.2 using the mixed linear model (PROC MIXED) with subject as a repeated measure. The significance level (α) was set to 0.05.

RESULTS

Effect of factors within each activity zone

Driver performance was evaluated for each activity zone of the active area (i.e., the first 4000 ft after the longitudinal buffer or the next 4000 ft after that) in each work zone. The mixed linear model included age group, gender, activity level, whether the activity zone was the first or second one in the work zone, buffer presence, and work zone barrier type as well as all 2, 3, and 4-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 activity zone order 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). Subjects 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 7). All four subject groups drove significantly faster with the concrete barrier than with the drums. All groups with the exception of the 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.

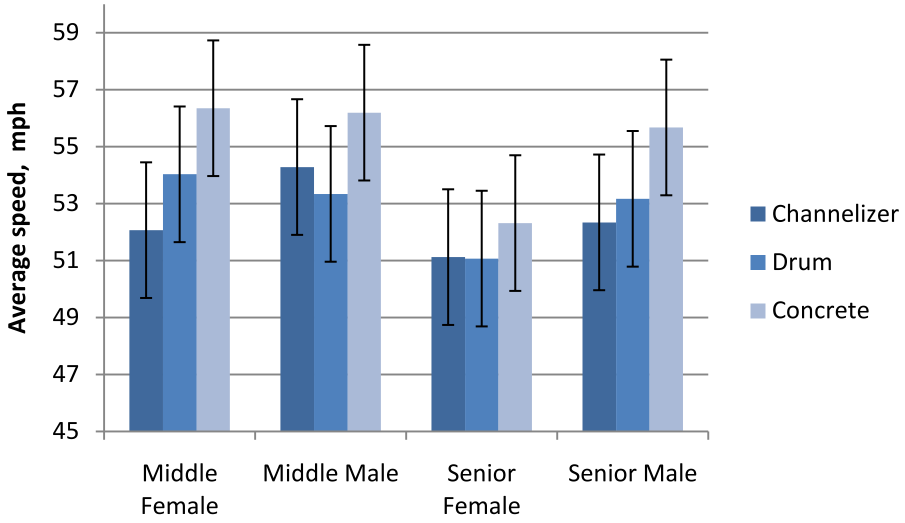


Figure 7. Three-way interaction of age group, gender, and barrier type on average speed

The three-way interaction of age, barrier, and buffer was significant (F(2,42) = 3.97, p = 0.0263; see Figure 8). 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. However, the effect of buffer for the channelizer barrier type was in the opposite direction as expected for the senior subjects. In the work zones with the channelizer barrier type, average speed for the senior subjects was 1.6 mph higher without the lateral buffer than with it. Average speed for seniors in work zones with drums did not significantly change when the lateral buffer was present. Though the presence of a 4-ft lateral buffer had the expected effect for the middle age group for all barrier types, the effect for the senior age group depended on barrier type. The presence of the buffer overall led to a slightly but significantly faster average speed in the work zone (53.8 mph compared to 53.2 mph, F(1,20) = 5.63, p = 0.0277). The interaction of buffer and age group was significant (F(1,20) = 7.8, p = 0.0112).

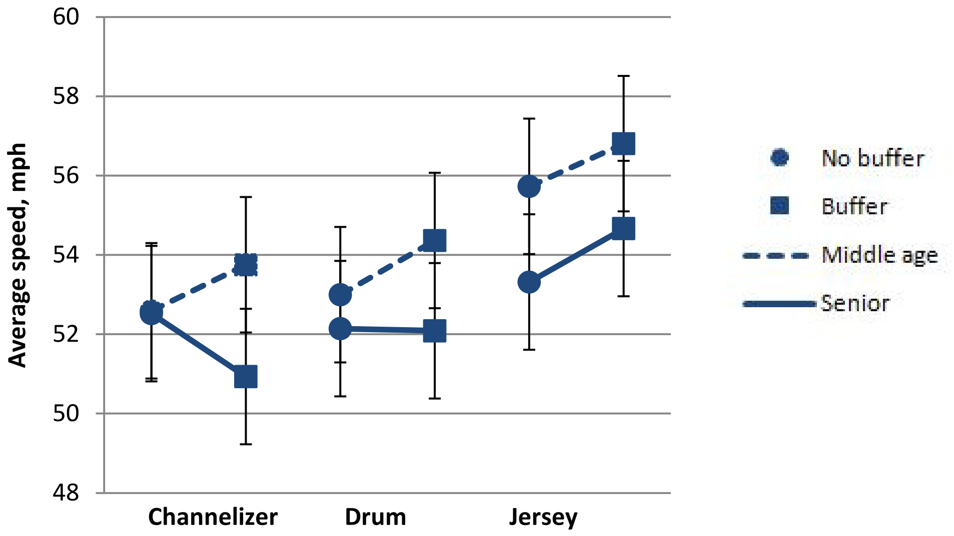


Figure 8. Three-way interaction of barrier type, buffer presence, and age group for average speed

Variability of speed

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

Variability of speed was also significantly affected by the presence or absence of a lateral buffer in the work zone (F(1,20) = 6.38, p = 0.0201) with speed being slightly more variable without the buffer (2.0 mph) compared to with it (1.8 mph). The interaction of buffer presence and work zone activity level was also found to be significant (F(1, 21) = 4.94, p = 0.0373). As shown in Figure 9, when the lateral buffer was present, speed was similarly variable for both levels of work zone activity (SD of speed was 1.8 mph). Without the buffer, speed was more variable in high activity zones (2.2 mph compared to 1.8 mph for low).

The main effect of barrier on variability of speed was significant (F(2,40) = 6.89, p = 0.0027). Speed variability was lower with the concrete barriers in place (1.7 mph) compared to the channelizers and the drums (both 2.0 mph). The interaction of barrier and work zone activity level was also significant (F(2,42) = 6.62, p = 0.0032; see Figure 10). 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. Speed was actually less variable in work zones with the high level of activity and the concrete barriers in place. These results suggest again that subjects perceived less risk or task difficulty and were more comfortable with the concrete barriers than the other two barrier types, but it is not clear why variability of speed for the concrete barriers was greater for the low work zone activity level than for the high work zone activity level.

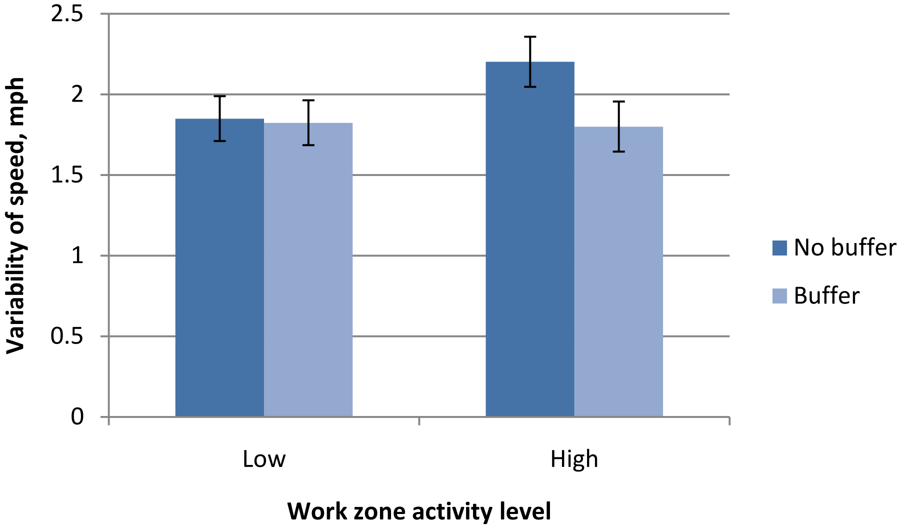


Figure 9. Two-way interaction of buffer presence and work zone activity level on variability of speed

Figure 10. Two-way interaction of barrier type and work zone activity level on variability of speed

Average lane position

Lane position averaged over each activity zone provides an indication of how risky or difficult drivers perceived the task of driving near the work zone to be. A main effect of age was seen (F(1,20) = 7.33, $p = 0.0136$). Middle age subjects had an average lane position of 3.24 ft to the left of the center of the driving lane while the senior subjects 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 subjects would drive further away from the barriers than the middle age subjects. One potential explanation is that the seniors were reluctant about driving on the shoulder. In the post-drive survey, only 2 of the 12 senior subjects reported having to drive on the shoulder while 8 of the 12 middle age subjects 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, $p = 0.0147$). Similar to the results for average speed, senior subjects did not change their lane position in response to the presence of a buffer but the middle age subjects 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 11). 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. It is likely that the significance of this 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 subjects preferred to drive closer to the concrete barriers and that the middle age subjects drove further from the barrier, often driving on the shoulder .

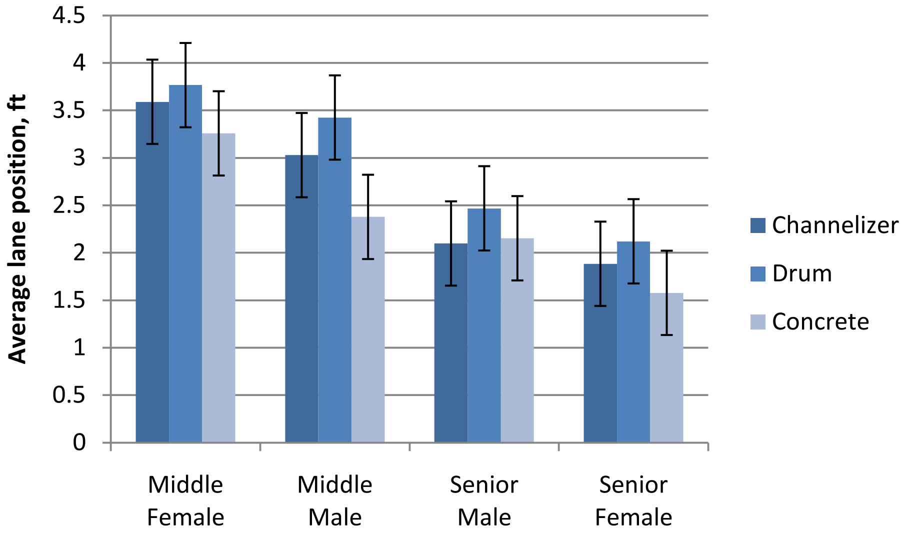


Figure 11. Three-way interaction of age, gender, and barrier type on average lane position to the left of the lane center. An increase in average lane position indicates movement away from the barrier.

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 zone in the activity area. 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 12). Middle age subjects were more variable in their lane position with the channelizer barrier compared both the drum and concrete barriers. Senior subjects 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 an additional lateral buffer space from the work zone activity which in turn decreases the subjects' perceived risk.

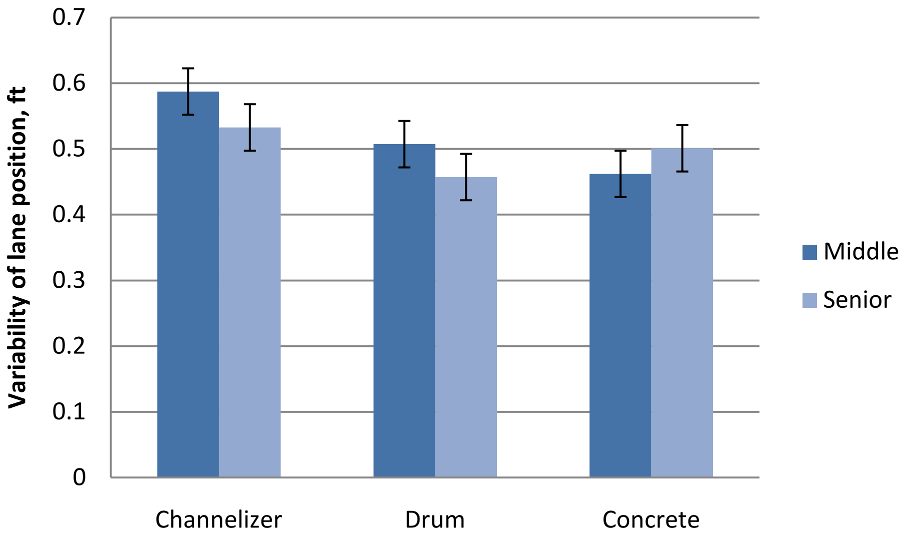


Figure 12. Two-way interaction of age group and barrier type on variability of lane position

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 13). The greatest variability of lane position was seen with the channelizer barriers with no buffer in the first half of the work zone and this was significantly greater than variability of lane position for all other combinations of barrier, buffer, and work zone part. Variability in lane position significantly decreased for the channelizer without a buffer in the second half of the work zone. However, 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 with the channelizers.

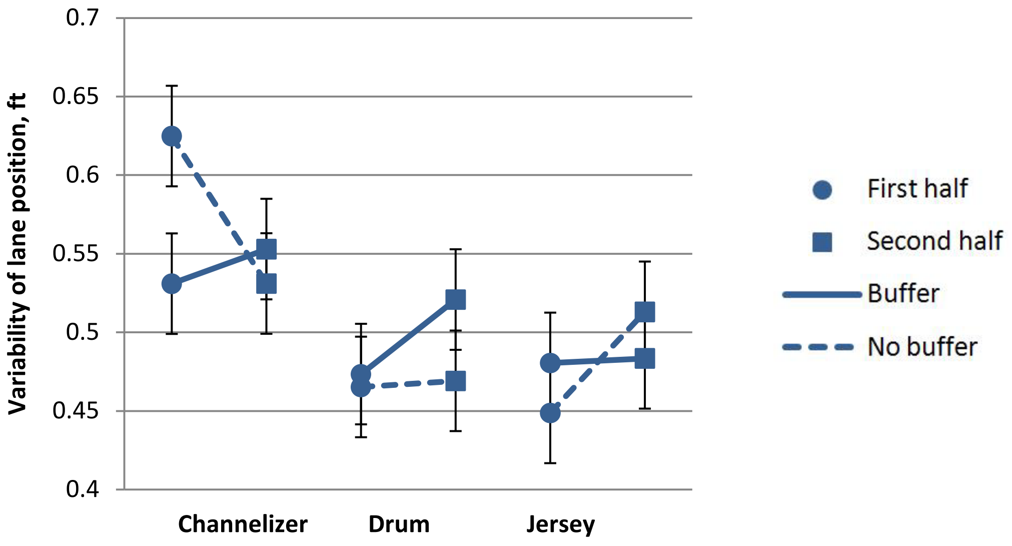


Figure 13. Three-way interaction of barrier type, lateral buffer presence, and activity zone order (first or second activity area in the work zone)

Change in driver performance for activity level transitions

To evaluate the effect of changing the work zone activity level in combination with the other factors on driver performance, change 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 main effect of work zone activity transition type was found to be significant (F(2,37) = 8.04, p = 0.0013). The average speed changed significantly for only the HL transition. Speed increased by an average of 1.3 mph in these transitions. In the LL transition where the activity level did not change, the average change in speed was 0.7 mph. The average change in speed was -0.2 mph for the LH transition and this was significantly less than the other two transition types.

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 14. 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 barrier type – transition type combination 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 and by 2.2 mph when the activity level went from high to low. Although the concrete barrier led to an increase in mean speed for all three transition types, none of the increases was large enough to be significant.

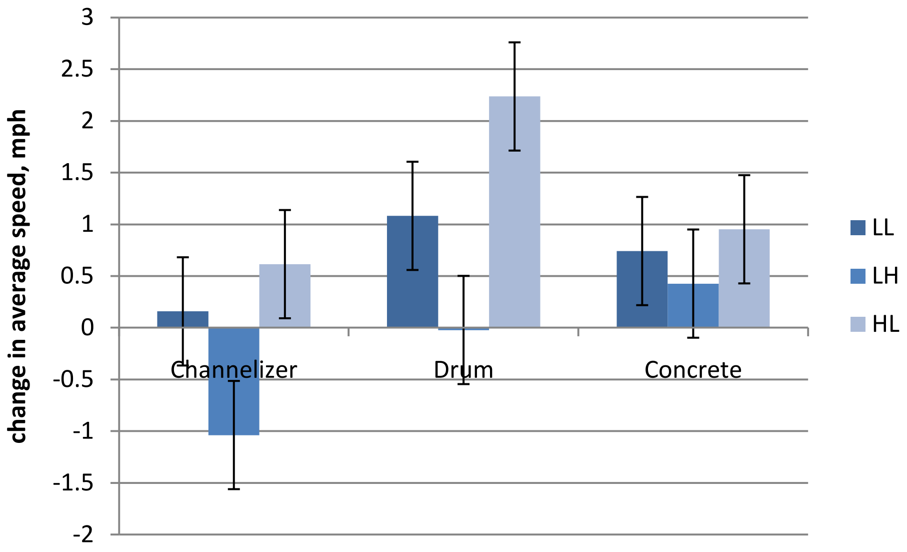


Figure 14. Two-way interaction of work zone transition type and barrier type on change in average speed

To analyze the 4-way interaction, the interaction of barrier type and transition type were compared within and between each between subjects group (see Figure 15). 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 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. Oddly, senior females had a decrease in speed in response to the HL transition with the channelizers (1.1 mph) while all other combinations of age, gender, and barrier type showed steady or increasing speed for the HL transition.

The final significant interaction for change in average speed was a 4-way interaction of work zone transition type, buffer, age, and gender ($F(3,60) = 3.61$, $p = 0.0182$). Generally it was expected that the presence of the buffer would help moderate the decrease in average speed expected when the activity level in the work zone increased. This was the observed result for both the middle females and the senior males. Changes in average speed for the LH transition for the middle age males were small. However, the results for the senior females were counterintuitive with a non-significant 1.0 mph increase in average speed for the LH transition without a buffer and a non-significant 0.8 mph decrease in average speed with a buffer. It was unclear beforehand whether the presence of the buffer would moderate, enhance, or have no effect on changes in speed for the HL and LL transitions and unfortunately the results do not show any clear trends that help resolve the uncertainty about their effect.

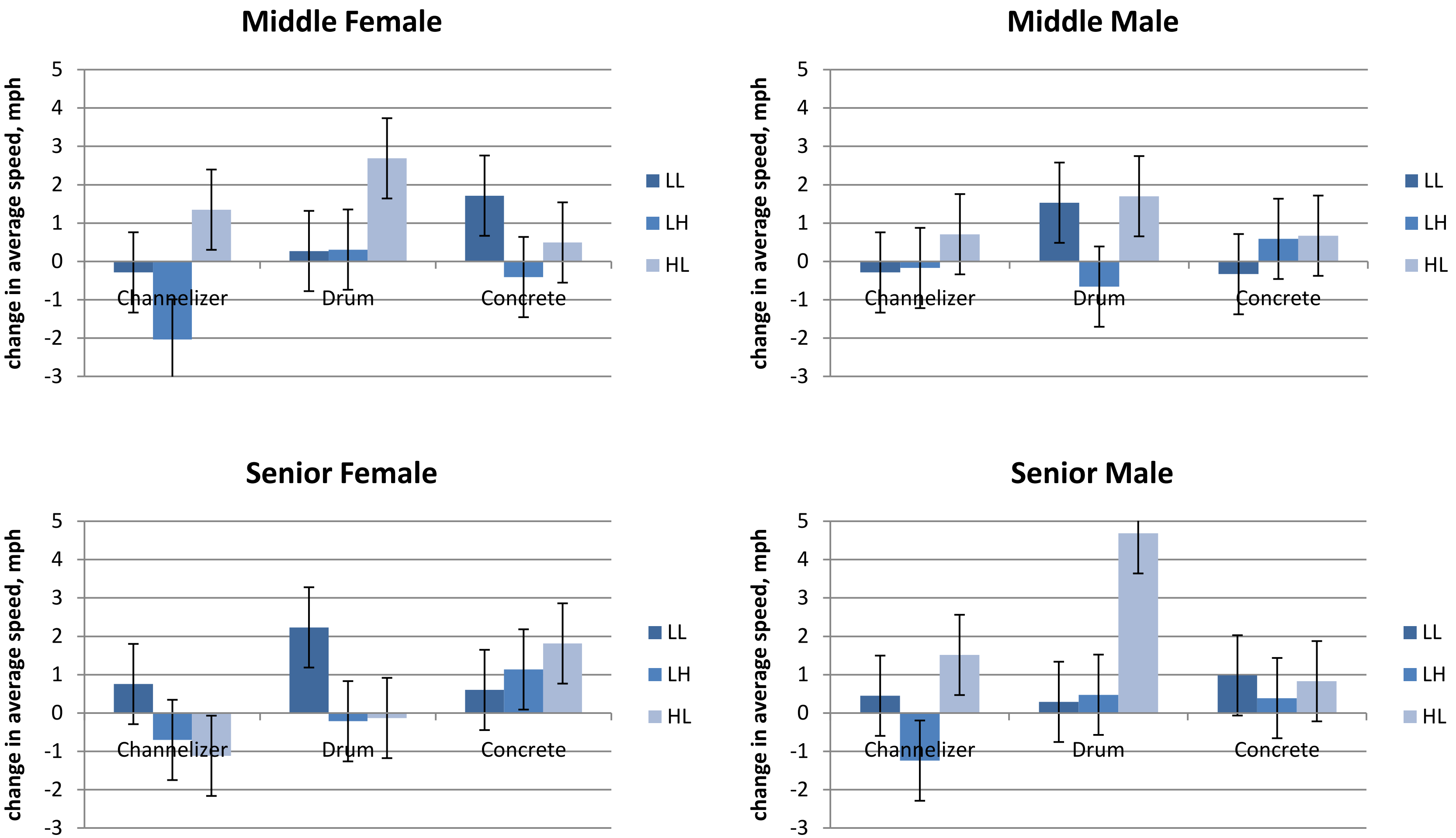


Figure 15. Four-way interaction of work zone transition type, barrier type, age group, and gender on change in average speed

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 or subject variables.

Change in average lane position

There was a main effect of work zone transition type on change in average lane position (F(2,37) = 8.66, p = 0.0008). Subjects tended to move closer to barrier (0.13 ft) without a change in work zone activity level (LL transition). An increase in activity level (LH transition) led to a small but significant shift of lane position away from the barrier (0.11 ft). The HL transition did not lead to a significant change in average lane position.

The three way interaction of gender, work zone transition type, and barrier type was significant as well (F(6,120) = 3.61, p = 0.0025; see Figure 16). 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 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 or subject variables.

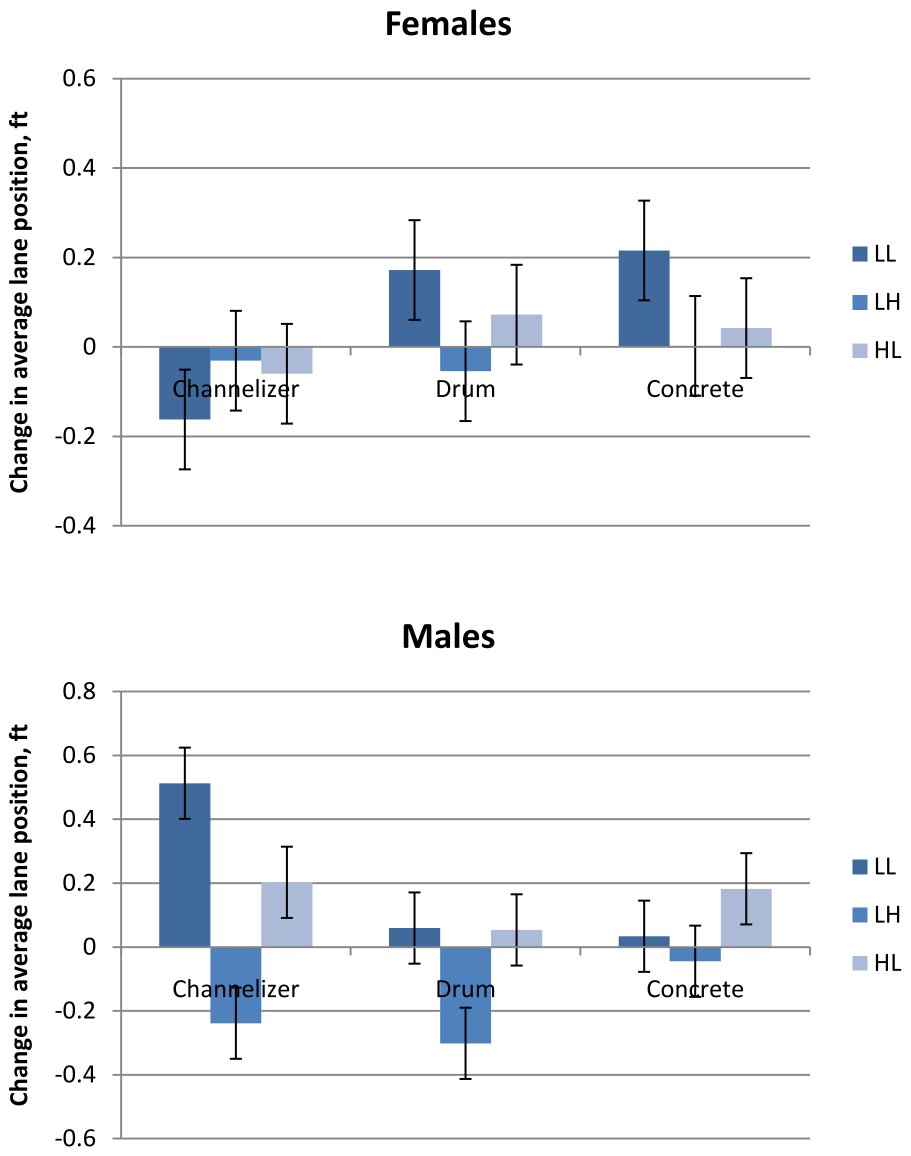


Figure 16. Three-way interaction of work zone activity level transition type, barrier type, and gender on change in average lane position

DISCUSSION

Effect of barrier type

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). With the concrete barrier, speed variability was actually lower with the high level of work zone activity than with the low activity level. The subjects in this study drove closest to the concrete barrier with relatively low variation in lane position. One subject 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 subjects in this study drove faster and closer to the concrete barriers, the barriers also showed a benefit of less variability in speed and lane position.

The drum and channelizer barrier types, typically used for short-term or moving work zones, are quite similar to one another and resulted in similar performance for both speed and speed variability overall. However, subjects demonstrated a significant decrease in speed with an increase in work zone activity level with the channelizer barrier type but not for the drum or concrete barrier types. In addition, the older subjects drove significantly slower with a lateral buffer than without in the channelizer work zones but not in the drum work zones. Overall the findings suggest that the channelizers can lead to more heterogeneous speed performance across different drivers and conditions compared to the drums. 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.

Comparing average lane position for the drum and channelizer barrier types, subjects tended to stay further away from the work zones with the drums; however, lane position with the channelizers was significantly more variable, particularly without a buffer in the first area of the work zone. Overall, the results of this simulator study suggest that although drums and channelizers are functionally similar, drums led to more uniform performance across subject groups and could potentially offer a safety benefit. On-road evaluation of the 42-inch channelizers' performance as a longitudinal work zone boundary may be warranted.

Effect of lateral buffer presence

This study considered the effect the presence of a lateral buffer in the work zone 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 subjects, variability of speed was significantly greater in areas of high activity without a buffer. When a buffer was present, speed variability in the high activity areas was no different from that the low activity level areas. However, the effect of the buffer differed by age group. While the middle age subjects' speed increased for all barrier types, the older subjects' speed varied by barrier type. When the work zone activity level changed from low to high, senior females tended to have an increase in average speed without a buffer and a decrease in average speed with a buffer. This was an unexpected and counterintuitive result, and the data did not reveal any trends for the effect of buffer on change of speed in LL or HL transitions. In conclusion, the results suggest that there may be some benefit to implementing a lateral buffer in work areas with high levels of activity; however, there is also the possibility that a buffer may increase overall speed variability in the traffic stream if only some of the drivers are sensitive to the presence of the buffer.

Effect of work zone activity level

Subjects in this study were presented with two different levels of work zone activity that remained constant in each activity area. 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 work spaces have the potential to increase crash risk. As drivers become acclimated to the work zone, they tend to increase their speed.

However, when they are suddenly confronted by the high activity area of the work zone, they may 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 do not allow for adequate preview of the work zone conditions ahead and drivers do not have time to make 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 the drives, a majority of the subjects in the study (7 of 12 middle age subjects and 9 of 12 older subjects) 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.

Generalizing to actual work zones

The generalizations to actual work zones that can be drawn from this study are limited for a number of reasons. The greatest of these 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 subjects 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 subjects and 10 of the senior subjects 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 subjects are aware that there are no consequences to their actions, i.e., there is no risk to driving in a simulator. Despite this fact, the vast majority of these subjects and thousands of other people who have participated in driving simulator studies drove in a reasonable and responsive manner in the simulator. 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 subjects in this study drove in isolation with no other traffic. It is possible that driver performance would be different if the subject 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 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 how several work zone factors interact to affect driver performance. 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 subjects in two different age groups. The results suggest that subjects were most comfortable driving in work zones with concrete barriers and that channelizers led to performance that was more heterogeneous across groups compared to drums. For some combinations of conditions, the presence of a lateral buffer demonstrated a benefit of less variable speed, but for other conditions the buffer had an opposite effect than was expected. 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. This effect was mitigated by the presence of a lateral buffer or a concrete barrier. Although the results cannot be generalized to actual work zones without validation of the simulator, this effort successfully demonstrated the usefulness of driving simulators for investigating driver performance in response to work zone interventions.

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APPENDIX A: EXPERIMENTAL DESIGN

Table A1. 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 A2. 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

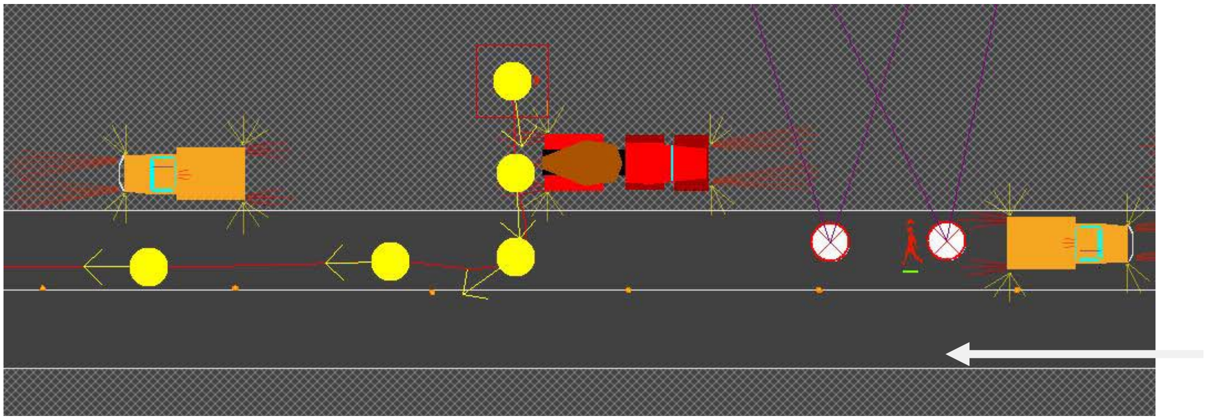
Table A3. One subject from each between-subjects group was assigned to each drive order

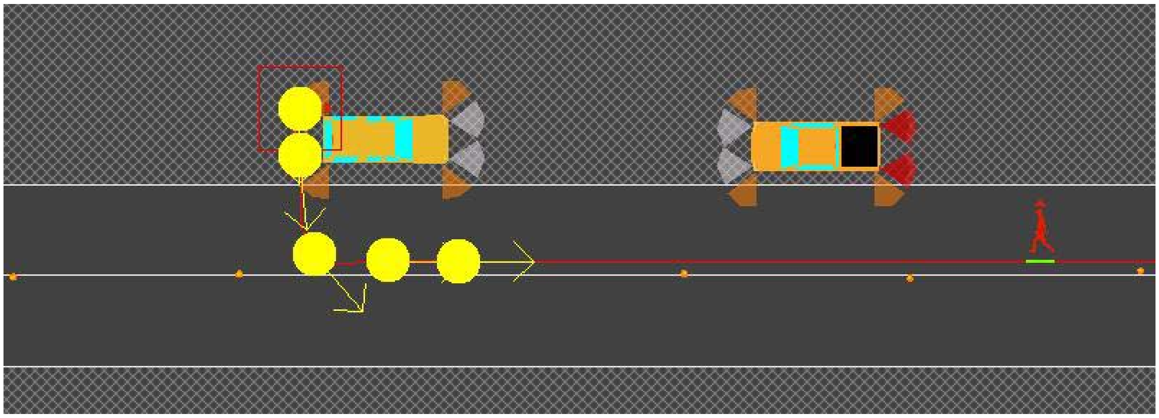
		Age group			
		Young		Older	
Gender	Male	6 participants	Order 1	6 participants	Order 1
			Order 2		Order 2
			Order 3		Order 3
			Order 4		Order 4
			Order 5		Order 5
			Order 6		Order 6
	Female	6 participants	Order 1	6 participants	Order 1
			Order 2		Order 2
			Order 3		Order 3
			Order 4		Order 4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

APPENDIX B: WORK ZONE OBJECTS AND PATHS

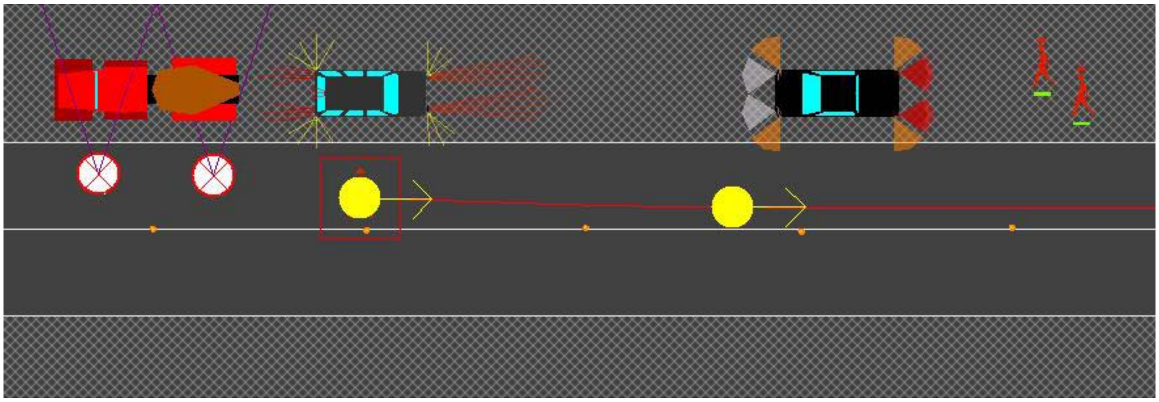
Dynamic worker models

Dynamic worker paths





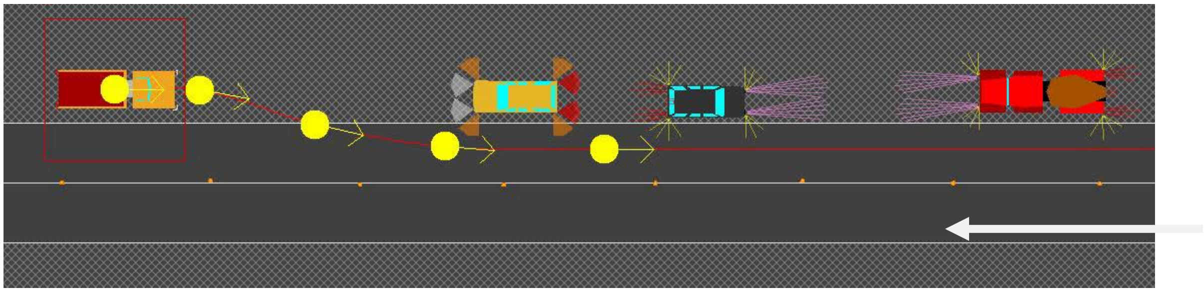
Dynamic worker paths, cont.

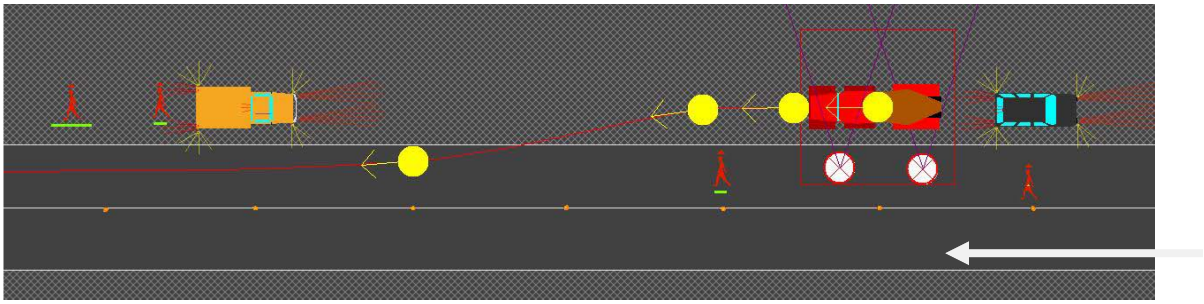


Static worker models

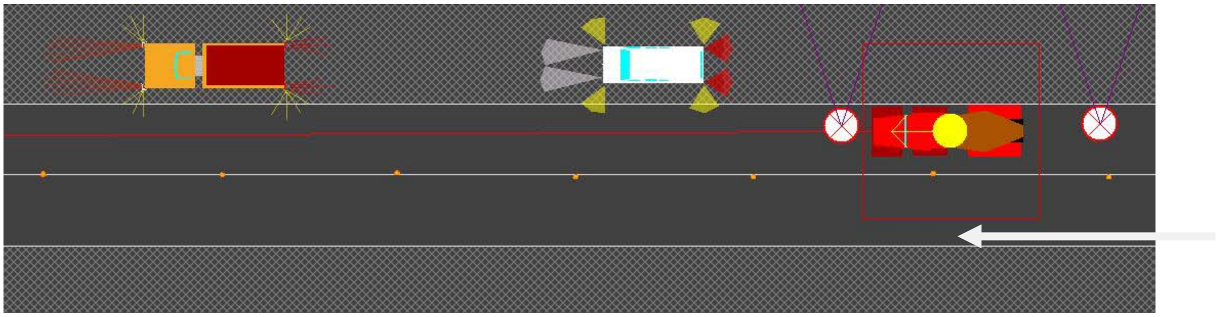
Work zone vehicle models

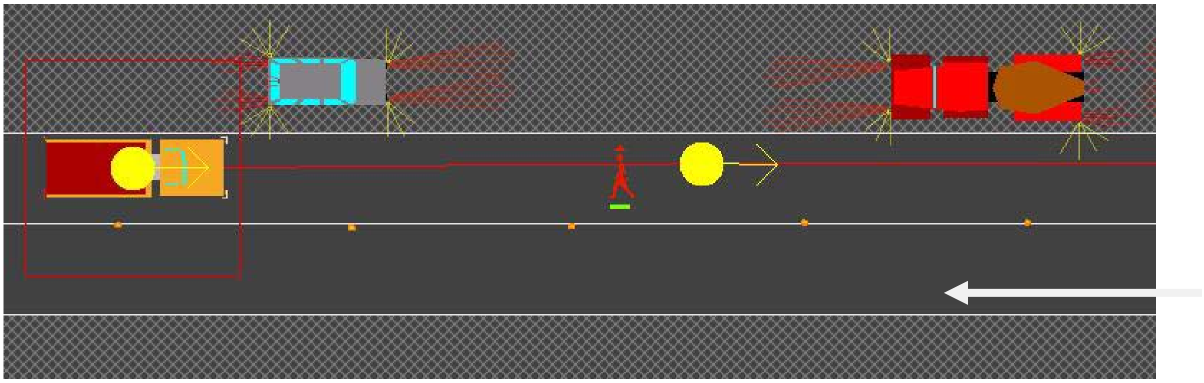
Dynamic work zone vehicle paths





Dynamic work zone vehicle paths, cont.





APPENDIX C: INSTRUCTIONS TO SUBJECTS

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 the 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.