DEPARTMENT OF TRANSPORTATION

In-Vehicle Work Zone Messages

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June 2017

Research Project
Final Report 2017-19

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Technical Report Documentation Page

1. Report No. MN/RC 2017-19	2.	3. Recipients Accession No.
4. Title and Subtitle In-Vehicle Work Zone Messages		5. Report Date June 2017 6.
7. Author(s) Curtis M. Craig, Jacob Achtemeier, Nichole L. Morris, Disi Tian, Brady Patzer		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Mechanical Engineering HumanFIRST Program University of Minnesota 111 Church Street SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. CTS #2016020 11. Contract (C) or Grant (G) No. (C) 99008 (wo) 184
12. Sponsoring Organization Name and Address Minnesota Local Road Research Board Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http:// mndot.gov/research/reports/2017/201719.pdf		

16. Abstract (Limit: 250 words)

Work zones present an increased risk to drivers and the work crew. To mitigate these risks, this study investigated the potential effects of in-vehicle messages to communicate work zone events to the driver. The researchers conducted literature reviews on risks imposed by work zones, along with design guidelines for any in-vehicle messaging system. The researchers then conducted a work zone safety survey to illustrate driver attitudes in Minnesota toward work zones, along with smartphone use and in-vehicle messages through smartphones. The survey found that a significant number of drivers make use of smartphones in the automobile, and they placed these smartphones in various locations throughout the vehicle. The survey was followed by a driving simulation study that tested drivers in two different types of work zones. Participants drove through these work zones three times, each with different messaging interfaces to communicate hazardous events to the driver. The interfaces included a roadside, portable changeable message sign, a smartphone presenting only auditory messages, and a smartphone presenting audio-visual messages. There was better driving performance on key metrics including speed deviation and lane deviation for the in-vehicle message conditions relative to the roadside signs. Furthermore, drivers reported significantly less mental workload and better usability, work zone event recall, and eye gaze behavior for the in-vehicle conditions relative to the roadside sign condition.

17. Document Analysis/Descriptors human factors, transportation safety, work zones, distraction, driver information systems, variable message signs		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 77	22. Price

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FINAL REPORT

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June 2017

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

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ACKNOWLEDGMENTS

The authors wish to acknowledge those who made this research possible. This study was funded and performed under MnDOT Contract Number 99008, Work Order Number 184. This report was prepared in consultation with and under the guidance of the members of the MnDOT Technical Advisory Panel and others, including Ken Johnson, Victor Lund, Joe Gustafson, Cory Johnson, Milford Ulven, Ronald Rauchle, Tiffany Kautz, Jeffrey Morey, Robert Vasek, and Steven Blaufuss. The research team would also like to thank Peter Easterlund, who was indispensable for his work as a simulation manager and programmer.

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EXECUTIVE SUMMARY

Work zones present an increased risk to drivers and the work crew. To mitigate these risks and lower the rate of crashes in work zones, this study investigated the potential advantages and disadvantages of in-vehicle messages to communicate work zone events to the driver. A potential positive outcome would be that drivers would be more aware of any risky work zone events and drive appropriately due to the immediacy of the in-vehicle messaging system. The potential downside would be the risk of driver distraction, as numerous cellphone studies have demonstrated the hazards of having communication technology in the automobile.

To investigate these possibilities, multiple literature reviews were conducted to illustrate the crash risks imposed by work zones and what factors exacerbate these risks, along with the ideal design guidelines for any in-vehicle messaging system. A work zone safety survey was conducted to uncover driver attitudes in Minnesota toward work zone safety. The survey also explored driver attitudes toward smartphones, smartphone use, and the potential application of in-vehicle messages through smartphones. The survey found that a significant number of drivers make use of smartphones in the automobile and that they place these smartphones in various locations throughout the vehicle with little commonality between respondents. Furthermore, the survey found that a subset of Minnesota drivers was skeptical of the validity of the warnings on roadside signs for work zones and were receptive to using electronic messaging systems. However, the possible issue of safety when driving with an in-vehicle system was identified by participants, indicating that empirical studies like this one were valuable.

Researchers at the HumanFIRST laboratory followed the survey with the design of the in-vehicle messages and the design of the simulated driving study to test the efficacy of the messaging system on driving safety. The simulated driving study tested drivers in two different types of work zones, a shoulder work route and a lane closure route. Participants drove through these work zones three times, each with different work zone events and messaging interfaces to communicate the hazardous events to the driver. These message interfaces included a roadside, portable changeable message sign (PCMS), a smartphone presenting only auditory messages, and a smartphone presenting audio-visual messages. Events in the work zone were typical, including slowed traffic, lane closure, heavy machinery, workers ahead, among others. The in-vehicle messaging smartphone was either mounted on the dashboard or placed in the passenger seat. During the drives, researchers recorded objective measures of driving performance subjective or reported variables such as event recall, mental workload, user-friendliness, and eye-tracking metrics.

The data analysis of the driving simulation study found that there was better driving performance on key metrics including speed deviation and lane deviation for both in-vehicle message conditions relative to the roadside signs. Furthermore, drivers reported significantly less mental workload, better usability, and greater work zone event recall for both in-vehicle conditions relative to the roadside sign condition. For eye-tracking, drivers took their gaze off the road less often for the in-vehicle messaging conditions, as drivers had to look over to read the roadside signs to understand the messages. Finally, the positive effects of in-vehicle messaging appeared to be elevated for the more difficult lane closure route in the driving performance data, suggesting that in-vehicle messages were helpful for more challenging roadway conditions.

The conclusions are twofold. First, if the in-vehicle messages are delivered in a controlled and driving-relevant manner, there appeared to be no effect of distraction and driving performance was improved. Second, placement of the smartphone did not appear to be a significant factor for driving performance

when there was an auditory component for the messages. The researchers recommend field testing in-vehicle message systems and exploring possible avenues of broad implementation.

CHAPTER 1: CRASH FACTOR IDENTIFICATION

1.1 INTRODUCTION

Work zones are a necessary component of our transportation infrastructure to promote safe travel on our roads; however, they may be hazardous because they disrupt traffic patterns and layouts of the roadway. Safety risks are mitigated by best practices, standards, and clear signage to communicate pertinent work zone information to motorists. Work zone signs are not always noticed by motorists, nor are they always followed when they are noticed. Previous research has found that work zone signs and speed limit signs are not effective in speed reduction (Fontaine, Schrock, & Ullman, 2001). There is a potential to reach motorists through an additional information channel separate from roadside signs, specifically through in-vehicle technology and messaging. Previous research has also demonstrated that drivers slow appropriately to intersections when they are provided advanced warning via in-vehicle signs (Caird, Chisholm, & Lockhart, 2008). The purpose of this study is to determine if drivers will respond to work zone warnings and information if they are presented in-vehicle in lieu of roadside signs. The following summary highlights the current risk factors of work zones.

1.2 ENVIRONMENTAL RISKS

1.2.1 Lighting and Weather Factors in Work Zone Crashes

Despite conventional wisdom assuming that crashes happen most often at night and under inclement weather conditions, most work zone crashes, approximately 78% in Minnesota, occur during the daytime and clear conditions (Dissanayake & Akepati, 2009; Weng & Meng, 2011; Minnesota Department of Public Safety, 2013). This propensity may be attributed to higher traffic volumes during the day and because construction happens most often in the summer months. Suboptimal lighting and weather also present serious risk in work zones (Garber & Woo, 1990). A comparison of work zone types found that fatal crash risk in maintenance work zones were greatest under nighttime conditions, while construction and utility work zone fatal crashes was greatest under daylight conditions (Weng & Meng, 2011). Conducting work zone construction and maintenance at night can be beneficial due to less traffic, less impact on congestion, and less impact from high summer temperatures (Arditi, Lee, & Polat, 2007). Conversely, work zones operating at night lead to poor visibility for drivers and higher incidences of fatigue and distraction (McAvoy et al., 2007), as well as poor visibility for workers, subsequently decreasing productivity and prolonging the duration of work zone operations.

Infrastructural elements are important for safe travel in work zones. Inefficient traffic control is associated with increased crashes in work zones (Ha & Nemeth, 1995; Weng & Meng, 2011). Poor lighting conditions (i.e., limited or no street lighting) are also known to increase fatal crash risks (Li & Bai, 2009), more so than poorly lit non-work zones (Daniel et al., 2000). Reflective materials and striping can help to increase the visibility of workers, signs, barrels, and barriers. However, dust created by construction activities, road debris, and dents and tears in the retro-reflective sheeting over time reduce visibility (McAvoy et al., 2007).

1.2.2 Road Conditions

Typical roadway factors that are associated with increased fatal crash risk include local roads and arterials (rather than interstate highways or freeways), asphalt paved roads, roadways that are straight and on a grade, curved and level, curve on a grade, and roadways with speed limits 60 mph or greater (Harb et al. 2008; Li, 2007).

Roadway geometry risk can be compounded by additional risky driving behaviors. Drivers may be more likely to speed on rural two-lane highways because of low traffic density and a lower likelihood of speed enforcement (Daniel et al., 2000; Li & Bai, 2009). Perceived road safety can promote riskier driving behaviors. Motorists are more likely to speed on divided roadways compared to undivided roadways, likely because they feel safer doing so. Thus, mean speeds and crash rates are higher in divided roadway work zones compared to undivided roadway designs (McAvoy, Duffy, & Whitney, 2011).

1.2.3 Work Zone Characteristics

Work zones disrupt the normal flow of traffic and driving behaviors, which contribute to increased crash rates compared to non-work zone roadways (Venugupal & Tarko, 2000). The same roadway, once converted into a work zone, is estimated to exhibit a 21.5% increase in crashes compared to its normal state (Khattake et al., 2002). There are several factors that can exacerbate the influence of work zones on crash rates, such as the presence of workers, construction machinery, and roadside construction barriers (Khattak et al., 2002). Other changes to the road, such as narrowing lanes of travel, traffic diversion, reduced roadway cross sections, and lane closures, force drivers to perform uncommon and therefore riskier driving maneuvers and may contribute to a higher rate of dangerous driving violations (Venugupal & Tarko, 2000; Bella, 2005).

Increased work zone length appears to increase crash rates through a mere increase in exposure to the work zone environment; however, this increases plateaus after some time. Shorter work zones create significant speed differentials between lanes or at queues, which may increase crash rates of approaching traffic (Khattak et al., 2002). These findings suggest that longer continuous work zones may have a greater net safety benefit compared to multiple or successive smaller-scale work zones.

1.2.4 Work Zone Signage and Barriers

Variable Speed Limit (VSL) controls offer an alternative to speed limit signs, which respond to varying environmental conditions (e.g., congestion, construction, inclement weather, crashes, etc.) and display the appropriate speed for the given conditions (Lin, Kang, & Chang, 2004). Typical VSLs display variable speed limits, message signs regarding conditions ahead, and information regarding traffic congestion. VSL can improve driver compliance to the posted speed limit, which leads to less speed variability and lower crash potential over time (Committee for Guidance on Setting and Enforcing Speed Limits, 1998; Coleman et al., 1996; Lee, Hellinga, & Saccomanno, 2004). Previous work suggests VSLs improve speed compliance and mitigate traffic congestion prior to a queue on the roadway (Lin et al., 2004; Bertini, Boice, & Bogenberger, 2006).

Barricades are often employed to mark construction and maintenance work zones (Daniel et al., 2000) and channeling devices help drivers safely navigate through a work zone, which protects workers and mitigates crash rates (McAvoy et al., 2007). Improving work zone conspicuity (e.g., alternating orange and white retroreflective strips, warning lights on drums, etc.) can improve nighttime visibility and help to highlight lane edges, curves, and lane closures. Furthermore, previous research has found drivers travel at higher speeds when the edges of the work zone are marked with barrels, compared to marked barrels mounted with lights, suggesting that work zones with increased visibility increase drivers' perceived safety, leading them to drive less cautiously (McAvoy et al., 2007). This type of behavioral adaptation may also occur if a driver has had repeated exposure to the same work zone, which may similarly raise his or her comfort level and elicit risky driving behaviors.

Vertical and horizontal deflections are another useful safety tool employed in work zones. Vertical deflections (e.g., speed bumps/humps, cushions) decline minor injury crashes at twice the rate seen with safety cameras and significantly decrease serious injury and fatal crashes on low-speed roadways (e.g., 30 MPH) (Mountain, 2005). Additionally, horizontal deflections (e.g., pinch points, central hatching, traffic islands, roundabouts, etc.) are effective crash prevention tools relative to safety cameras on low-speed roadways, yet do not reduce injury crashes as much when compared to vertical deflections (Mountain, 2005).

1.3 DRIVER BEHAVIOR RISKS

1.3.1 Driver Characteristics

While driver characteristics cannot be controlled, it is important to understand the types of driver populations that tend to pose the greatest risk to traffic safety. Driver crash risk by group can be examined in two ways. First, crash rates can be examined by a group's proportion of all licensed drivers or registered vehicles. This method provides reliable data; however, it does not capture the difference in the amount that each group typically travels. Second, crash rates can be examined by a group's average vehicle miles traveled (VMT). This method considers the frequency and amount that each group tends to travel on the road, but VMT is an imprecise measure because it is typically determined by self-reported miles driven. Additionally, VMT is rarely included as a variable in examinations of certain groups, such as gender differences.

While teen drivers are often considered the riskiest driver demographic, drivers age 65 and older present the highest fatal crash risk on all roads by VMT (see Figure 1.1) and second highest risk by proportion of licensed drivers (NHTSA, 2010; Cicchino & McCartt, 2014). Given the typical crash risk, it is unsurprising that studies have found that older drivers are more likely to be involved in a fatal work zone crash than their younger counter parts (Li & Bai, 2009; Weng & Meng, 2011). Older drivers (65+ years) are involved in a high proportion of fatal work zone crashes between the afternoon hours of 4:00 pm and 8:00 pm. Interestingly, drivers between the ages of 35 and 44 were found most likely to be in a fatal work zone crash between 8:00 pm and 6:00 am (Li & Bai, 2009), and middle-aged drivers were found to be 1.17 times more likely to be injured or killed in construction work zones compared to younger drivers (Weng & Meng, 2011).

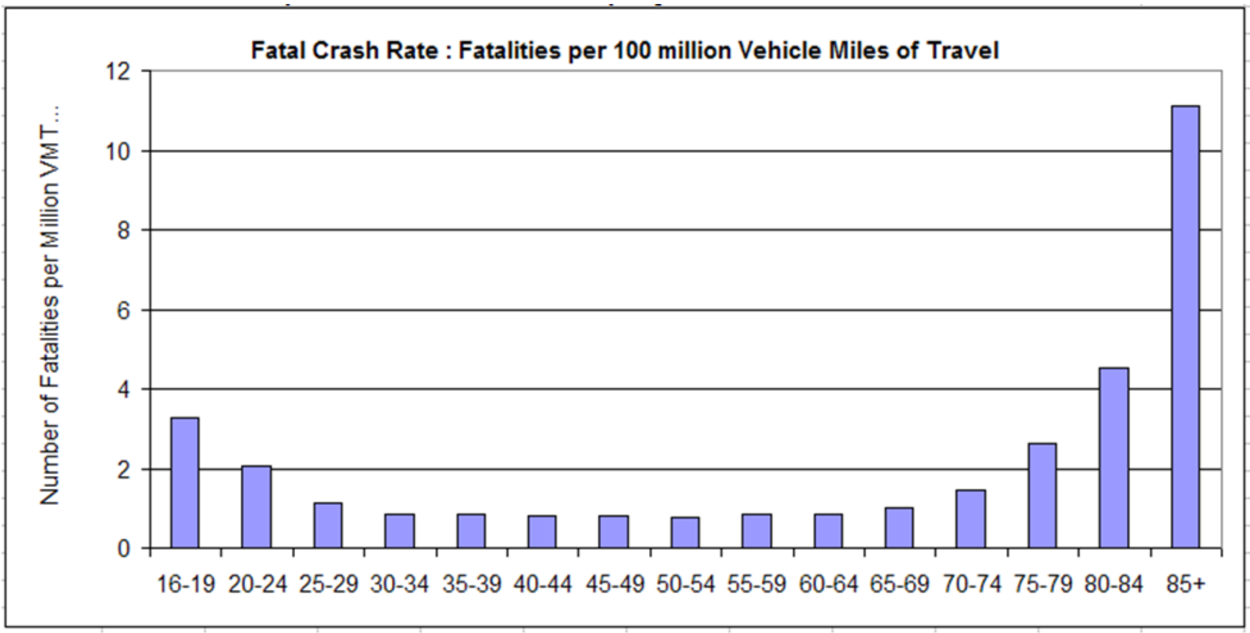

Figure 1.1 National fatal passenger vehicle driver crash involvements per 100 million vehicle miles traveled by age group, 2007 (Source: Cicchino & McCartt, 2014).

Male drivers have been found to pose a greater fatal crash risk than female drivers (Li & Bai, 2009). Crash data from five states (Iowa, Kansas, Missouri, Nebraska, and Wisconsin) consistently showed male drivers were more often involved in work zone crashes compared to female drivers (Dissanayake & Akepati, 2009). The type of work zone could be a factor in examining gender differences as Weng and Meng (2011) found that male drivers were more likely to be involved in construction and maintenance work zone crashes. However, female drivers were more likely to be involved in fatal utility work zone crashes.

Vehicle type has been found to affect crash risk in work zones. Drivers of older vehicles have been found to have a higher fatal crash risk compared to those of newer vehicles (Weng & Meng, 2011). While an overwhelming proportion of work zone crashes involve passenger vehicles, trucks and busses have been shown to be 4 (Li & Bai, 2009) to 10 times (Weng & Meng, 2011) more likely to be in a fatal crash compared to other vehicles. Moreover, compared to non-work zones, crashes in work zones are disproportionally more likely to involve trucks than other vehicles (Daniel, Dixon, & Jared, 2000).

1.3.2 Risk Taking Behaviors

One reason that certain demographic groups tend to be at higher risk for crash than others is that they are more likely to engage in certain driving behaviors that impact their safety. For example, although male drivers usually have the skills needed to drive safely, they are more likely to speed, especially when primed to behave "masculinely" (Schmid-Mast, Sieverding, Esslen, Graber, & Jancke, 2008) and more likely to drive under the influence of alcohol (Minnesota Department of Public Safety, 2013) than females. Similarly, older drivers and drivers in rural regions are less likely to wear a safety restraint, making them less likely to survive a crash (Weng & Meng, 2011). There are many shared risky driving behaviors that increase crash rates on both normal and work zone roadways. However, some behaviors are particularly problematic in work zones due to environmental and traffic conditions.

Since 1990, alcohol-related crashes, which accounted for approximately 41% of all fatal crashes in Minnesota that year, have steadily declined. As of 2013, 30% of all fatal crashes in Minnesota were alcohol related (Minnesota Department of Public Safety, 2013). It is clear, however, that alcohol is still a major contributing factor to fatal crashes despite the progress that has been made. Drug and alcohol impairment is a serious risk factor for crashes in work zones (Harb et al., 2008; Dissanayake & Akepati, 2009).

Impairment of any kind (e.g., alcohol, drugs, fatigue, etc.) is likely to increase the likelihood of other problematic behaviors associated with work zone crashes. Misjudging other vehicle speeds or distances, following too close, and distraction are all associated with increased crash risk (Harb et al., 2008). Li and Bai (2009) found that following too closely actually reduced the likelihood of getting involved in a fatal crash. This finding is consistent with the consensus across literature that higher traffic volumes, a condition that usually will lead drivers to follow too closely, is associated with less severe crashes because traveling speeds are lower. Additionally, impairment may cause drivers to be less likely to follow traffic controls, a behavior that makes drivers 3 times more likely to be involved in a fatal crash (Li & Bai, 2009).

Next to impairment, speeding or traveling too fast for conditions is the primary hazardous behavior that increases crash risk. Both crash risk and crash severity increase with speed (Mountain, 2005; Wilson, 2006). The National Highway Traffic Safety Administration (NHTSA) estimated that speeding contributes to approximately 30% of all injury and fatal crashes (McAvoy, Duffy, & Whiting, 2011). Drivers often underestimate the time and distance necessary to stop if a lead vehicle suddenly brakes, especially when traveling at higher speeds, contributing to approximately 30% of all injury and fatal crashes. Lower traveling speeds, however, still require adequate distance and are often underestimated as well. For example, vehicles traveling at 30 and 40 miles per hour require 23 meters and 36 meters, respectively, to safely stop (Mountain, 2005). Additionally, traffic density plays an important role in speed. Free-flowing traffic allows for higher traveling speeds, leading to an increase in single vehicle crashes, while denser traffic is more susceptible to the impact of dangerous speed differentials (i.e., increased standard deviation in speed) between vehicles, leading to an increase in multi-vehicle crashes (Daniel et al., 2000; Wilson et al., 2006; McAvoy, Duffy, & Whiting, 2011).

Following speeding, inattention and distraction are typically the next commonly factors cited contributing to crashes. In 2013, approximately 18% of all work zone crashes in Minnesota cited inattention/distraction as a first or second contributing factor to the crash (Minnesota Department of Public Safety, 2013). Distraction is difficult to determine at a crash site and previous versions of the Minnesota State Crash Report did not allow for easy discrimination of the types of distraction suspected. Per NHTSA, however, being “lost in thought” is the most prevalent form of inattention, accounting for approximately 18% of fatal crashes, while “conversing with passengers” accounts for approximately 15% of all internally distracted crashes (NHTSA, 2010). Distraction caused by cell phone use (e.g., calling, texting, or dialing) accounts for approximately 11% of distraction-related fatal crashes (NHTSA, 2010). Like impairment, distraction may lead drivers to engage in other risky driving behaviors and outcomes, such as disregarding traffic, less monitoring of mirrors, roadway, or speed limits, more “looked-but-did-not-see” errors, and slower response times (Li & Bai, 2009; Muttart et al., 2007). These behaviors have major implications for work zone safety since they could possibly result in a failure to appropriately or timely respond to advance warning signs and changing traffic patterns or safely change lanes. Many of these behaviors, such as failure to notice slowing or stopping traffic, are likely to lead to rear-end crashes, which comprise most work zone crashes (Wang et al., 1996; McAvoy, Duffy, Whiting, 2011; Dissanayake & Akepati, 2009). Interestingly, rear-end and sideswipe crashes are more likely to occur in work zones than non-work zones (Khattak et al., 2002).

1.3.3 Driver Behaviors within Areas of the Work Zone

When precise data about crashes within a work zone are made available, researchers can examine how crash risks and rates change within select sections. The Manual on Uniform Traffic Control Devices (MUTCD) divides work zones into four areas: 1) Advanced Warning Area, 2) Transition Area, 3) Activity Area, and 4) Termination Area (Dissanayake & Akepati, 2009). The new Model Minimum Uniform Crash Criterion (MMUCC) will allow for two additional distinctions within the work zone area: 5) Before the First Work Zone Sign and 6) After the First Work Zone Sign. These additional categories have not been integrated into many of the states' crash reports yet, so little data is available regarding crashes in relation to the first work zone sign. It is well understood, however, that the safety of traffic approaching a work zone is susceptible to congestion shock waves and sudden merging, which commonly result from the bottleneck effect at work zone lane closures (Venugupal & Tarko, 2000). Minimizing the traffic queue and improving incoming traffic flow can decrease the impact of dangerous speed differentials (Venugupal & Tarko, 2000; Lin, Kang & Chang, 2004).

There is mixed research regarding which of the defined areas are the most dangerous within a work zone. This may in part be due to inaccurate or incomplete crash reporting on the part of responding law enforcement. Garber and Zao (2001) reported that 70% of crashes occur in the Activity Area and few occur within the Termination Area, while Dissanayake and Akepati (2009) reported that 40-57% of crashes occur in the Activity Area. Rear-end crashes most often occur within the Advance Warning Area, likely due to slowing traffic in response to the work zone, and side swipe crashes increase in the Transition Area, likely due to increased lane changing behavior in this area (Garber & Zao, 2001). These types of crashes are consistent with the contributing factors to work zone crashes reported by the police, which include: failure to drive within a single lane, failure to reduce speed, failure to yield right of way, and failure to drive within the designated lane (Wang et al., 1996).

Research examining work zone behaviors in Italy revealed that drivers are more likely to travel closer to the posted speed limit when the travelling lane was narrowed (Bella, 2005). It appears that the drivers were less likely to abide by the posted reduced speed limit if the work zone did not appear to require it, indicating that the signage was unreliable or unreasonable. Other studies have similarly shown that drivers will self-select a travel speed, regardless of the posted speed, and will reject artificially low speed limits (McAvoy, Duffy, & Whitney, 2011). This may partially explain why more than 50% of fatal crashes in work zones occur at work zones that are idle (Daniel et al., 2000) because drivers are less likely to feel compelled to abide by speed limits and signage when no workers are present.

CHAPTER 2: SAFETY CULTURE SURVEY

2.1 INTRODUCTION

The purpose of the safety culture survey was to gather information from Minnesota drivers regarding their perceptions on work zone safety and how technology may be used as an effective information-providing tool during work zone navigation. Building an in-vehicle messaging system through a user-centered design required an in-depth examination of Minnesota drivers on how they typically interact with their smartphones, and what their needs are for receiving information about the work zone. Survey results also provide a greater understanding of the frustrations, desires, and concerns Minnesotan drivers may have about work zones while determining how technology may assist in these areas. The insights gained from the safety culture survey were instrumental in outlining the design of the experimental in-vehicle messaging technology used in the simulation study.

2.2 METHOD

2.2.1 Participant Selection

Minnesotan drivers were recruited to participate in this online survey through a wide variety of means. The survey link was posted on Craigslist, social media sites, message boards, and sent to a list of previous research participants. Participants were eligible if they were 18 years of age or older, lived in Minnesota (or drive most their miles on Minnesota roads), and held a valid driver's license. Incentive for participation was based upon a drawing to win a free iPad Air. A total of 120 people entered the survey; however, 10 did not complete it and 13 were ineligible because they did not live in Minnesota or drive much of their miles on Minnesota roads. The remaining 97 survey respondents (see Table 2.1) were included in the analysis.

Table 2.1 Safety survey participant demographics

Demographic Measures	
Gender (sex)	Male 38, Female 59
Age(years)	$M = 41$, $SD = 14$
Years Driving	$M = 25$, $SD = 14$
Residency	MN = 96, WI = 3

2.2.2 Procedure

Survey respondents were provided an internet link which routed them to the University of Minnesota online survey tool, where a total of 46 questions regarding work zone safety culture (Appendix A) and technology use (Appendix B) were administered using the University of Minnesota's Qualtrics survey system. Data collection took place from September 21st, 2015-November 25th, 2015. Participants were provided a brief description of the survey's purpose, and provided informed consent to participate, and completed the items within the survey. The survey content was presented to respondents in the form of free-response open ended entries, multiple-choice options, and five-point Likert scales from Strongly Disagree to Strongly Agree.

2.3 RESULTS

2.3.1 Summary of Survey Results

All respondents owned a cell phone and a majority were tech users (i.e., smartphone use, frequent texting, varied uses for smartphone, navigation experience, etc.). Overall, respondents gave positive feedback about how open they would be to a smartphone application that provided feedback about work zone information. Approximately 22% of respondents provided unsolicited concern that such an application must be designed with distraction as a key consideration for its use. Many drivers expressed a desire for verbal alerts, hands-free, audio-only, or voice activation features which is likely a learned behavioral adaptation to where their phone is typically placed. Only 5% of drivers reported routinely placed their phone in a dedicated mount. The remaining drivers reported keeping their phone in a console/cubby, cup holder, dash, lap, passenger seat, pocket, purse/bag, or hand. This highlights the need for automatic, verbal, push alerts to provide advanced warning information (i.e. the most frequently requested feature) to drivers regarding work zones and less emphasis on visual warnings. Approximately 10% of drivers stated that a financial incentive was needed to influence their use of the application. A larger percentage (20%) were open to using the application with no reservations, while an additional 42% of participants held some reservations until issues of distraction were resolved and certain features incorporated (e.g., real-time/accurate updates, traffic information, etc.), or sufficient research demonstrated its safety benefit.

Drivers who reported higher levels of annoyance with work zones tended to have less trust in roadside signage, and relied on other drivers for cues. These drivers were receptive to the use of an application to aid their navigation in work zones. Drivers with more concern for work zone safety reported that they heeded the information of signs over other drivers and have less annoyance with work zones. Drivers who reported feeling uncomfortable, uneasy, or overwhelmed in work zones tended to report less confidence in work zone signs' ability to reliably communicate safety information; however, these drivers tended to report a stronger desire to use a smartphone application to receive work zone safety information.

2.3.2 Survey Results Breakdown

2.3.2.1 Phone Use and Location While Driving

Drivers were surveyed about their willingness to use their phone for calling or texting while driving (see Table 2.2). Interestingly, there were some inconsistencies when the question was packed (e.g., would you under any circumstances…?) versus unpacked (e.g., would you under this condition…?). It is not uncommon for people to report an attitude or belief in absolute terms (e.g., I never speed) and reverse this statement when offered caveats (e.g., I would speed if I was late for a job interview). Six drivers reported they would not, under any circumstances, make or receive a phone call while driving; however, only four of the six persisted such statement when asked about individual circumstances in which they might (e.g., alone on the roadway or at a stoplight or stop sign). A similar reversal was found for texting. Forty-two drivers reported they would not, under any circumstances, send or read a text message while driving; however, only 38 of the 42 maintained they would never text when offered unpacked circumstances for times they might be so inclined. These findings suggest drivers' perceived safety in specific circumstances (e.g., alone on the roadway) encourages phone manipulation while driving, similarly mirroring the effect on speeding under circumstances of urgency in completing a drive (e.g., going to work in a timely manner).

Table 2.2 Driver calling and texting frequency while driving

Are you willing in some circumstances to make or answer a phone call while you are driving?	**Number of responses**
Yes	91
No	6
Under what circumstances might you make or receive a phone call while you are driving a vehicle?	**Number of responses**
Never	4
Alone on road	42
Stopped at stop sign or stoplight	60
Stopped in traffic	46
Cruising down highway	42
Traveling at low speeds	34
Any time while driving	42
Are you willing in some circumstances to make or read a text message while you are driving?	**Number of responses**
Yes	55
No	42
How often do you make or receive text messages while you are driving a vehicle?	**Number of responses**
Never	38
Alone on road	19
Stopped at stop sign or stoplight	51
Stopped in traffic	33
Cruising down highway	12
Traveling at low speeds	8
Any time while driving	10

Drivers were asked the location that they typically place their phone while driving. This is an important design consideration in determining the importance of visual and auditory information presented regarding the work zone. While a phone mount is the most optimal place for the phone to be placed to allow the driver to quickly and easily glance at visual information, or use peripheral vision, and clearly receive redundant, auditory information (i.e. visual and auditory cues) which improves recognition, it was suspected that most drivers do not store their phone in this way. Many drivers responded with two locations they typically place their phone. A frequency was taken for locations which received a single response (i.e. "Typical placement") and a frequency was taken for locations which were paired with additional responses (i.e. "Occasional placement"). The greatest frequency of drivers reported placing their phone in their vehicles console or cubby or cup holder (see Table 2.3). These places cannot account for most drivers, however, since many drivers instead reported placing their phone on the dash, in a purse or bag, on their passenger seat or lap, and even in their pocket with great frequency. Infrequent locations reported included placement in a phone mount (i.e., most optimal placement for an app-based message system) or, likely most distracting, in their hand.

Table 2.3 Driver reported typical and occasional placement for their phone while driving

Phone placement	Responses for primary placement	Responses for secondary placement
Console/cubby	14	6
Cup Holder	9	7
Dash	11	4
Purse/Bag	11	3
Passenger Seat	10	4
Lap	6	9
Pocket	10	2
Mount	5	0
Hand	3	0

2.3.2.2 Driving Safety Culture Questions

Drivers were asked a series of questions designed to elicit their perceptions relating of caution and safety involving work zones, work zone signing and other structures, the influence of other drivers and behavioral influence, and technology acceptance in work zones. Drivers rated each statement on a 5-point Likert scale stating the extent to which they agreed or disagreed (see Table 2.4 and 2.5).

Table 2.4 Selection of Agreements and Disagreements on Safety Culture

Safety Culture Questions	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
I am concerned about safety when I drive through a work zone.	1%	2%	15%	38%	43%
My driving behavior changes when I pass through an active work zone.	0%	1%	4%	45%	49%
Speed limits during live work in a work zone should be lower than an empty work zone.	1%	4%	7%	37%	51%

Table 2.5 Selection of Agreements and Disagreements on Safety Culture (continued)

Safety Culture Questions	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
Work zone warning and alerting signs are safe and do their job well.	1%	7%	20%	56%	16%
I am often wishing there would be a more tech-savvy way of being notified of upcoming work areas while driving.	2%	9%	29%	35%	25%
Typically, work zone signs give enough warning for drivers.	3%	19%	25%	51%	3%
Cones and barriers are sufficient to show clear direction in a work zone, such as in a lane closure.	2%	30%	24%	39%	5%
Electronic signs do a better job at allowing me to understand what is changing or what to expect in a work zone.	1%	5%	34%	47%	12%
I am likely to use a smart phone app that would alert and inform me about upcoming hazards or conditions in a work zone.	10%	18%	20%	36%	16%
An app would provide more up-to-date work zone information than conventional signage.	5%	11%	28%	42%	13%
I would trust an app's accuracy in keeping me alerted to current road work conditions.	8%	15%	25%	45%	5%
I comply with work zone messages, such as posted lower speed limits, even when no workers are present.	1%	13%	16%	46%	23%
In general, motorists are very careful while driving through a work zone.	9%	42%	28%	21%	0%
Work zones are an annoyance by slowing my commute time.	6%	15%	26%	35%	18%

The researchers performed principle component analyses (PCA), or dimension reduction, on the responses to examine the emergence of common survey item elements originally hypothesized prior to the survey's administration. The four hypothesized themes were the satisfaction with current work zone signage and environment, perceived safety and driving behaviors while navigating work zones, desired aspects for improvements for information through signage or equipment cues, and attitudes towards the use of smartphone-based technology development and use in the work zone. In order to examine the fit of the work zone safety culture survey questions with the hypothesized common themes, each of the 23 safety culture questions were subjected to the Cattell scree test (Cattell, 1966). Scree test results found that the four a priori groupings captured much of the variability of the data (for more details, see Achtemeier & Morris, 2016).

Overall, drivers report satisfaction with Minnesota work zones and its signage. Some notable results, however, demonstrate that drivers largely have greater trust in electronic means of communicating up-to-date work zone information compared to static signs. This is then unsurprising that drivers showed strong acceptance for the use of a smartphone application to access the most timely and accurate information about work zones. Interestingly, drivers did not demonstrate high levels of the “above average phenomenon” since most respondents (41%) neither agreed nor disagreed that they were above average in driving abilities. Drivers did not extend the same confidence in other drivers since 51% disagreed or strongly disagreed that other drivers are careful in work zones.

CHAPTER 3: DESIGN OF WORK ZONE SAFETY MESSAGES

3.1 INTRODUCTION

An extensive literature review was performed to assess the current state of empirical data regarding the usability and safety of in-vehicle messaging systems. The researchers studied various aspects of the design considerations for an in-vehicle smartphone-based messaging system for communicating the dynamic states of work zones. Factors considered included cognitive workload, perception psychophysiology, and language appropriateness. Reviewing the appropriate literature ensured that the designed messages for application use would be of the utmost quality to bolster user acceptance and, most importantly, driver safety.

The conclusions drawn from the extensive literature review were incorporated into the work zone use cases. The use cases were as follows: Stopped or slowing traffic, workers on site, lane closures/exit closures, heavy machinery entering road, resurface/resealing of pavement, drainage ditch/median repair, signaling installation or repair, bridge inspection/repair, and miscellaneous road repairs. In accordance with the best practices of safety and usability for in-vehicle messaging, the top selected use cases were explored to develop appropriate messages. Each use case was paired with an auditory and visual message (see Tables 5-7). These audio and visual interface designs will be subsequently tested under various conditions in the driving simulation study.

3.2 LITERATURE REVIEW FOR WARNING DESIGN

3.2.1 Auditory Message Design

3.2.1.1 Annoyance

A critical component to the design of in-vehicle audio messages includes the consideration of user-perceived annoyance of the message. Kryter (2013) describes annoyance, alternatively referred to as perceived noisiness, as the psychological judgement of a listener and their tendency to rate sounds as unwanted, unacceptable, objectionable, and the degree to which the sound feels like noisiness. High levels of annoyance are detrimental to the effectiveness of the auditory message, as too much cognitive arousal can psychologically affect the willingness of the user to listen to an alert; Marshall and colleagues (2007) discuss findings in the anesthesiology profession that observed technicians disabling important alerting systems during anesthetic administration based on the level of annoyance reported by technicians. Annoyance is generated from repeated exposure of auditory information, even when physical traits of an auditory alert are carefully designed (Lee et al., 1999). The design implications of annoyance were carefully considered throughout the iterative message design process in the current work, ensuring that the proposed messages for experimentation in simulation were of the highest quality possible. Additionally, this indicates a high threshold by which only safety or route critical messages should be administered to drivers to avoid the perception of repeated or over exposure.

3.2.1.2 Message Appropriateness

The fit and relevancy of content in auditory messages establishes the overall effectiveness of the message. If auditory alert messages are made without considering the various aspects of appropriateness, the intended goal of the message for the user will be likely unmet (Lee, Gore, &

Campbell, 1999; Marshall, Lee, & Austria, 2007). Satisfactory message appropriateness is achieved when the design structure of the message fulfills criteria that is based on the context of the situation (Marshall, Lee, & Austria, 2007). In driving, specifically in the case of navigation in a work zone, appropriateness of messages would consist of a combination of factors, for example, the timing of an alert that notifies a driver of an upcoming lane closure that provides a reasonable window for corrective action, yet does not occur so early before the closure that the driver may forget. A drawback of verbal messages not experienced by icon messages is that the timing of the message is compounded by the duration of the utterance (Cao, Castronovo, Mahr, & Muller, 2009). Succinct verbal messages help to minimize the length of time it takes for drivers to perceive and recognize the information being conveyed. Repeated alerts that occur too early for an event, such as the lane closure ahead, are likely to become disregarded by users if they deem them inappropriate. Indeed, continuous repeating of alerts and messaging has been shown to lead to annoyance (Kryter, 2013), as well as behavioral adaptation that leads to disregard of the message and its content (Weise & Lee, 2004). Conversely, if message timing is consistently insufficient, at best drivers may become frustrated with the system, potentially disabling or abandoning their use of the system, and at worst inappropriate messaging during the lane closure may lead to harm. Message appropriateness is a subjective measure that is made from the sum of design considerations that include cognitive components (i.e., urgency, annoyance) in addition to physical auditory characteristics (i.e., tone waveform and frequency).

3.2.1.3 Sound Urgency

Urgency is a subjective, perceived psychological phenomenon that is influenced by the types of sound used in an auditory alert, such as bursts, beeps, or buzzers, and message semantic content (Haas & Edworthy, 1996). Urgency of a message can be communicated through various audio design means, such as loudness, frequency of tone, tone pulsation, and time between tones (Haas & Edworthy, 1996; Edworthy, Hellier, & Rivers, 2003; Marshall et al., 2007). While communicating information of importance is necessary, producing alerts that contain too much perceived urgency can result in negative consequences (e.g. distraction) that may lead to situations less ideal prior to the alert (e.g. distracted driving).

Marshall and colleagues (2007) explored urgency by presenting alerts in different tone types with an in-vehicle messaging system, and reported profound insight into tone design impacts on user perceived urgency and annoyance. Results indicated that short tone duration (25 milliseconds) provided less annoyance, but lower urgency compared to longer tone durations (100 milliseconds). Although the longer tones also increased reported annoyance by participants, overall communication of urgency was greater for participants with longer tones. The delay between sounds presented influenced perceived urgency and annoyance, where short delays between tones increased annoyance and urgency in participants, and long delays were significantly less annoying, however, much less urgent. These findings suggest that frequency of repeated tones is indicative of an urgent situation, yet it brings a proportional amount of perceived annoyance with it.

Speaker gender has shown to influence the perceived urgency of messages communicated by spoken words. Studies conducted in laboratory controlled acoustic environments (Edworthy, Hellier, & Rivers 2003) have shown that female voices can inflect more emotive capacity in the form of urgency. This is explained by female dynamic range in terms of pitch, which is a foundation for alerts and alarms in other areas of industry, such as manufacturing and medical fields (Marshall et al., 2007). There is a limitation to using female voices, however, since older drivers tend to have age-related hearing losses which make it more difficult to clearly distinguish parts of speech (e.g, “s”, “f”, or “th” fricative or consonant sounds) spoken by a higher-pitched, female speaker making the resulting perception sound like "mumbling (Daughtery & Welsh, 1966).

The approach to finding a comfortable median of sufficient urgency while keeping minimal levels of annoyance is discussed by Marshall and colleagues (2007), where results during a navigation driving task suggested that a balance of increasing the amount of times an alert is given in a time period (i.e. alert duty cycle), amount of pulse duration (length of sound), amount of inter-pulse intervals (dead-time between sounds), and the sound frequency intensity (in Hz) are all measures that provide high levels of urgency without excessive annoyance when used in conjunction with another. The current designs discussed in the present work were created with each sound design variable and their respective trade-offs in a way that maximize message understanding in participants, while attempting to keep unwanted annoyance to a minimum.

3.2.1.4 Word Choice

The selection of word choice in message content is the most important and impactful aspect of an effective alerting system. While the acoustic properties of an alert carry significant influence on the overall effect on how the message is perceived, the semantic content of the message is the driving force of the desired communicative end goal. Here, the project motivations are to communicate up-to-date and accurate work zone information to drivers in the aim of increasing driver situational awareness of the roadway, thereby reducing potential risk for collision or work zone intrusion.

Older drivers are known to most heavily rely on auditory messages of navigational or informational systems, so it is important to design messages with their needs and limitations in mind. Importantly, the structure should not impose additional workload on the driver and should contain three or less sets of information at one time (Barshi, 1997). Moreover, the messages should be in succinct, list form (e.g. lane closure, ahead, 2 miles) rather than in sentence prose (e.g. Lane closure is ahead in 2 miles). Finally, the context of the message should lead the prompt (e.g. Reduce speed, traffic ahead, 1 mile) to best guide the driver on their expected action (Dingus et al., 1997).

Hellier and Adams (2002) found that word choice has a profound impact on the listener's sense of urgency, where words that had more specific definitions (e.g. danger) were more effective at communicating a sense of urgency than others (e.g. beware, attention) with more flexibility in definition or casual use (Hellier and Adams 2002). Intonation and inflection of word delivery in a messaging system also effect the semantic comprehension of word choice, because urgency is contingent upon more factors than only sound aesthetic and word use alone (Edworthy & Haas,1996; Edworthy, Hellier, & Rivers, 2003; Hellier & Adams, 2002). For example, pitch dynamics in verbal communication were found to greatly influence levels of perceived urgency by listeners attending to spoken words related to the current work (Edworthy, Hellier, & Rivers, 2003; Hellier & Adams 2002). Differences in perceived urgency of words like danger, warning, caution, and hazard occur when pitch range increases, as Hellier and Adams (2002) found. This finding is similar to the research on nonverbal auditory information previously discussed, suggesting overlap between both modalities of auditory perception.

3.2.2 Visual Message Design

The requirements for visual message design are equally, if not more, important to the considerations for auditory messages since they require drivers to divert their eyes away from the road. Thus, it is crucial that the visual information be presented in a way that drivers can efficiently view and comprehend the visual message. A large body of literature provides criterion to which the design should adhere.

3.2.2.1 Display Criterion

The display of an interface is most effective when in the line of sight, and potentially safer to use in vehicle than a centrally located area, such as the console or middle dashboard. The suggested position of a display is forward and slightly off centered from the direct user's immediate line of sight (UMTRI, 1994). The contrast ratio of an icon or symbol in a display should be at minimum a three to one ratio, where seven to one is most recommended (Richard, Brown, & McCallum, 2007). Icon symbols in a display are best effective at the 1.43° visual angle, with a floor of 0.69° for implementation (Richard et al., 2007). At arm's length (25 in.), the icon is optimal at .65 in. or larger. Federal mandate requires text size to be 0.26°, though optimal text size is suggested at 0.40° (Richard et al., 2007). Text or letter symbols in a display are best effective at least a visual angle of .50° visual angle for key elements (.25 inches at arm's length), .33° visual angle for critical elements, and .266° visual angle for noncritical elements (Campbell, Lyle, Carney, & Kantowitz, 1998). Display screens are recommended to be up to 15° from the forward-road viewing position in the driver seat (United Nations, 2010). Doubling the relative luminance of the display to background luminance has been shown to be an effective brightness of display screens (United Nations, 2010).

Color coding of relevant urgent information, such as a speed reduction prompt, or entrance of a work zone, should be conventional, meaning bright shades of reds and yellows where applicable. Non-urgent information, such as lane merges notified well in advance, can follow the calmer colors like green and blue (United Nations, 2010). Finally, drivers have been shown to produce different effects in a simulator when point of view of the nearby (dashboard) and distant (roadway) are controlled. When the dashboard and road are shown naturally, drivers adhere to consistent center line deviation, but are sporadic in steering correction. Conversely, drivers only shown the roadway and not the dashboard surround produce a consistently smooth steering input, but deviate greatly from the centerline of the road, and therefore their lane. Placement of displays should be in regions on the dashboard or HUD (windshield) that optimize a balance (Hofmann, Rinkenauer, & Gude, 2008).

3.2.2.2 Reducing Driver Distraction

Device displays that require manipulation by the driver in a reaching manner are reported as having a 900% increase in crash probability. In addition, the NTHSA attributes reading while driving as a crash probability factor of about 400% increase. For these reasons, displays are to be designed with a safe balance of information and distracting properties (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Different display designs including discrete, digital, analog, alphanumeric, and symbols are effective at their respective time. For instance, an imminent high risk event would want to rely on symbolism of such an event, like a collision, instead of using an alphanumeric text display (Richard et al., 2007).

Drivers are significantly more likely to crash or experience a near-crash episode if their focus of sight deviates from the forward, roadway position. Glances in the direction of the center console, radio, and shifter area account for the most frequent crashes and near-crash incidents (60%), so displays should be incorporated into the primary region of forwards driving on the dashboard (Klauer et al., 2006). Color coding of relevant urgent information, such as a speed reduction prompt or entrance of a work zone, should be conventional, meaning bright shades of reds and yellows where applicable. Non-urgent information, such as lane merges notified well in advance, can follow the calmer colors like green and blue (United Nations, 2010).

3.3 WORK ZONE MESSAGING DESIGN

The current design of work zone messages was made by carefully following the various guidelines in literature previously, in addition to specific guidelines presented by the United Nations, UMTRI, and Richard and colleagues (2007) listed in the next section. Ensuring that the current proposed designs fit standards, guidelines, and recommendations in the literature was of utmost importance. While distraction is of great consideration and is often cited as a reason for "auditory-only" messaging, the literature provides a strong precedent for the importance incorporating auditory and visual information to aid perception and comprehension of warning messages.

3.3.1 Messaging System Guidelines

- In-vehicle warning systems designs need to be distinguishable from all other stimuli in the driving environment while satisfying needs including the identification and alerting of a specific roadway feature, distance relative to the feature and vehicle, and appropriate reaction time notifications of a dangerous feature (United Nations, 2010).
- Warning systems are fundamentally effective only if the system is composed of both auditory and visual stimuli. System creation for detecting and reporting road features should be focused on implementing appropriate usage of both outputs (United Nations, 2010).
- Flashing of displays during warnings are effective, and reported best usable when refresh rates are near 4kHz (United Nations, 2010).
- When considering auditory alerting, care is to be taken to avoid a startling response when messages are outputted from the device. General guidelines suggest 15-25dB above cabin noise, although this number will vary situationally (United Nations, 2010, UMTRI 1994). Moreover, comprehension of speech information by older drivers is best facilitated when the auditory signal is at least 15 dB higher than the background noise (Tun & Wingfield, 1999).
- Warning messages should not incorporate two or more of the same modality of stimuli; instead, the warning system needs to use a pairing of auditory and visual stimuli modality, as to prevent perceptive and cognitive loading errors (Richard et al., 2007).
- Warning messages in the event of a potential threat are recommended to terminate during corrective action. An example requiring warning message termination would be corrective steering or braking, as monitored by device g-meters (Richard et al., 2007).
- Coupling warning tones and speech is <u>not</u> advised, as it is likely to lead to increased cognitive processing time for the driver (Richard et al., 2007).
- Synthetic speech is recommended for use in warning systems, as research found drivers were more apt to treat synthetic speech messages as pressing and novel (Richard et al., 2007). Digitized natural speech, however, is recommended over synthetic speech for older drivers as they may have difficulty understanding computerized speech and may have an increase in mental workload.
- In the use of synthetic speech, gender of the speaker is an important consideration, although prior research suggests benefits and drawbacks to both male and female speakers. Richard and colleagues (2007) concluded that male voices were more intense and attention demanding at the same volume as female voices (Richard et al., 2007), while Edworthy, Hellier, and Rivers (2003) suggest that the dynamic range of pitch in female voices can influence urgency of a message.

3.3.2 Designed Interface Messages

Table 3.1 Interface messages for northbound (shoulder work) work zone environment

Northbound Route			
Message Placement	Audio-Only Message	Audio-Visual Message (Icon)	VMS
Mile Marker 1.5 Start of Transition/ Advanced Warning Zone	"Slow Traffic Ahead" "Half Mile" "Reduce Speed"		CAUTION SLOW TRAFFIC AHEAD
Mile Marker 3 Near end of Transition/ Advanced Warning Zone	"Debris in Lane…" "Half Mile" "Use Caution"		CAUTION RIGHT LANE NARROWS
Mile Marker 4.5 Upstream in Activity Zone	"Trucks Entering Roadway" "Half Mile" "Use Left Lane"		CAUTION TRUCKS ENTERING ROADWAY
Mile Marker 5.75 Downstream in Activity Zone	"Heavy Machinery Ahead" "Quarter Mile" "Use Caution"		CAUTION HEAVY MACHINERY AHEAD
Mile Marker 7 Downstream in Activity Zone	"Crash Ahead" "One Mile" "Reduce Speed"		CAUTION CRASH AHEAD

Table 3.2 Interface messages for southbound (lane closure) work zone environment

Southbound Route			
Message Placement	Audio-Only Message	Audio-Visual Message (Icon)	VMS
Mile Marker 1.25 Introductory Drive (Before Transition Zone)	"Work Zone Ahead" "1 Mile" "Reduce Speed"		REDUCE SPEED WORK ZONE 1 MILE
Mile Marker 2.75 Transition/ Advanced Warning Zone	"Loose Gravel Ahead" "Half Mile" "Use Caution"		CAUTION MERGE LEFT RIGHT LANE CLOSED
Mile Marker 2.25 Start of Activity Zone	"Active Work Zone" "Next 5 Miles" "Use Caution"		CAUTION ACTIVE WORK ZONE NEXT 5 MILES
Mile Marker 5.5 End of Upstream of Activity Zone	"Workers Ahead" "Half Mile" "Be Alert"		CAUTION WORKERS AHEAD
Mile Marker 6.5 Downstream in Activity Zone	"Stopped Traffic Ahead" "One Mile" "Be prepared to stop"		SLOW DOWN STOPPED TRAFFIC AHEAD

CHAPTER 4: QUANTITATIVE EXPERIMENT ON WORK ZONE MESSAGES

4.1 INTRODUCTION

After reviewing crash risk issues in work zones, surveying public attitudes about smartphone placement within the vehicle along with work zone safety, and reviewing the design literature to create effective work zone messages, the HumanFIRST lab directly tested the question of whether in-vehicle messages could be effective for promoting safer driving behavior within a work zone. A study was conducted testing an in-vehicle messaging system against an external PCMS system on visual attention, driving performance, mental workload, and user-technology opinions while performing a driving task through a simulated work zone.

4.2 METHOD

4.2.1 Participants

A total of forty-eight drivers were recruited to participate in the simulation study and were divided into two experimental groups, each receiving an in-vehicle messaging system in a different location (i.e., screen placement on the dashboard, passenger seat) within the vehicle. All participants were presented two roadways with realistic work zone scenarios modeled after Minnesota Hwy-169 from Belle Plaine to Jordan, Minnesota. Participants performed the driving task through the simulated work zones using the HumanFIRST full-cab driving simulator. Within the two phone placement groups (e.g. dash or passenger seat-mounted), participants completed a total of six drives, each varying in their presentation order through counterbalancing using a Latin square. All participants were over the age of 18, held valid driver's licenses, were normally sighted (i.e., acuity of 20/40 or better), had no history of cognitive or neurological injuries (e.g. traumatic brain injury, stroke), and no history of motion-related sickness. Few participants with eye glasses were excluded from the study due to eye tracking data acquisition constraints. Participation took approximately two hours and participants were remunerated $25/hr for their participation. Table 4.1 describes participant demographic information.

Table 4.1 Participant demographics

Participants	Age Mean (*SD*)	Age Range	N
Males	24.6 (*4.3*)	19-35	25
Females	29 (*6.9*)	20-41	23
Total	**25.3 (*5.8*)**	**19-41**	**48**

4.2.2 Materials and Apparatus

Participants were presented a consent form and driving history questionnaire that inventoried their driving habits and demographic information, see Appendix B. After each drive, participants filled out three forms: Situational Awareness Inventory (Appendix C), the Rating Scale of Mental Effort (RSME) (Appendix D), and the System Usability Scale (SUS) (Appendix E). These forms were utilized to gain an understanding of participant opinion on the in-vehicle messaging systems by collecting quantitative and qualitative subjective usability measures data.

4.2.2.1 Driving History Questionnaire

The driving history questionnaire (Appendix B) captured the demographic information of the participants, in addition to their representation in the motor vehicle transportation fleet. The survey prompted questions related to the driving habits and road usage frequency and annual distances travelled. For example, survey items included an inquiry into the type of roadways that participants were most accustomed to and used most frequently (e.g. "Do you drive frequently on: Highways? Main Roads other than Highways? Urban Roads? Country Roads"). To gain an understanding of driver interaction and engagement of using their cellular devices while driving, several questions related to technology use were included in the driving history questionnaire, which were the same as those used in the Safety Survey.

4.2.2.2 Situational Awareness Inventory

The Situational Awareness Inventory (Appendix C) is a qualitative tool that prompts participants to engage in a free-recall exercise to test their memory of the events and messages during their drives. Experimenters explained the purpose and procedure of completing the form, which included instructions provided at the top of the form, with the remainder of the form open for manual writing entry. Participants were asked to write down any details related to the messages and events of the work zone drives to the best of their ability. The purpose of employing the Situational Awareness Inventory form was to gain an insight into the impact of the work zone drives on participant situational awareness and corresponding recall. The use of recall is a typical way to measure situation awareness, and in this context, assesses whether participants have utilized the first level of situation awareness: *perception of data* (Endsley, 1995). Responses were coded and entered in a database for further analysis.

4.2.2.3 Rating Scale Mental Effort (RSME)

The Rating Scale of Mental Effort (Appendix D) presents participants with a vertically displayed scale that contains ratings of mental effort. The scoring ranges from 0-150, with a score of 0 indicating absolutely no effort in using the system, with 150 representing a degree of mental effort surpassing extreme mental effort. Participants rated their perceived mental workload on the RSME. The best possible rating possible was 0, expressing had to use absolutely no mental effort to complete the task with the interface. The average RSME score of approximately 30 places the participants perceived mental effort for both interfaces as just above "a little effort" and below "some effort."

4.2.2.4 System Usability Scale (SUS)

The System Usability Scale (Appendix E) is a subjective measures metric used to survey participant outlook on the usability traits of an interactive system. The survey is a modified Likert scale variant. In the current work, participants rated their perceived usability of each messaging system type (e.g. audio-visual, audio-only, PCMS) on the SUS. The total rating possible was 100 points, which expressed they would like to use the in-vehicle messaging system, they found it unnecessarily complex, easy to use, was well integrated, etc. The lowest SUS score possible was 0, indicating that the participant felt the system they experienced was unusable, obtrusive or annoying, or disorganized and unintuitive. An average SUS score is 68, which regards the system as useable and relatively efficient for the user.

4.2.2.5 HumanFIRST Full-Cab Driving Simulator and Eye Tracking Acquisition System

The driving sessions were performed using a 2002 Saturn SC2 complete chassis driving simulator furnished by Realtime Technologies, Inc (see Figure 4.1). The full-car simulator provided realistic control feedback in the form of brake power assist and resistance-based steering. Participants viewed the two-lane two-way median divided rural highway simulated environment by means of a 210 degree (2.5 arc-minutes per pixel) forward visual 5-screen array, complimented by LCD screen door mirrors and a posterior-projecting sixth screen to visualize the rearward roadway. A small 7" LCD screen was utilized to serve as a smartphone and was in the interior of the simulator (see Figure 4.2). The Koolertron LCD display was placed on either the center stack of the dashboard area, or on the passenger seat base depending on experimental condition. These locations represent the feedback from the In-Vehicle Messaging study's preliminary safety culture survey work that assessed where drivers kept their phones and how they interacted with in-vehicle technology (e.g. 511, Maps) while driving.

Figure 4.1 HumanFIRST immersive driving simulator.

Figure 4.2 LCD screen used to deliver work zone messages.

For the In-Vehicle Messaging project, the HumanFIRST research team installed a state of the art four camera eye tracking system furnished by Smart Eye AB (Gothenburg, Sweden) into the driving simulator. The eye tracking system's camera placement provides robust eye tracking data collecting while performing the driving tasks in the simulator. A forward-facing camera provides record of the simulated drive environment, which is later used in data analysis by juxtaposing the in-cab eye tracking data with the scene camera during the drive. This coupling of video and eye tracking data, provided by the EyesDx MAPPS (Cedar Rapids, IA) software suite allowed the research team to observe and analyze the real-time gaze and fixation data of the participant's visual attention at any point during the drive. The MAPPS software allowed the research team to visualize where in the driving environment participants were focusing their attention while they navigated through the work zones.

4.2.3 Simulated Work Zone Route and Characteristics

The road chosen to act as the simulated route for this experiment was selected on the characteristics of the roadway, which in the case of US-169's span from Belle Plaine and Jordan, Minnesota (see Figure 4.3) featured gentle curves with little variance in super-elevation. The roadway's environment was typical of Midwest farmland and included a horizon line that appeared as distant wooded areas, providing participants with a simulated world that did not appear busy, therefore reducing the likelihood for participants' visual attention to be drawn away from the forward roadway.

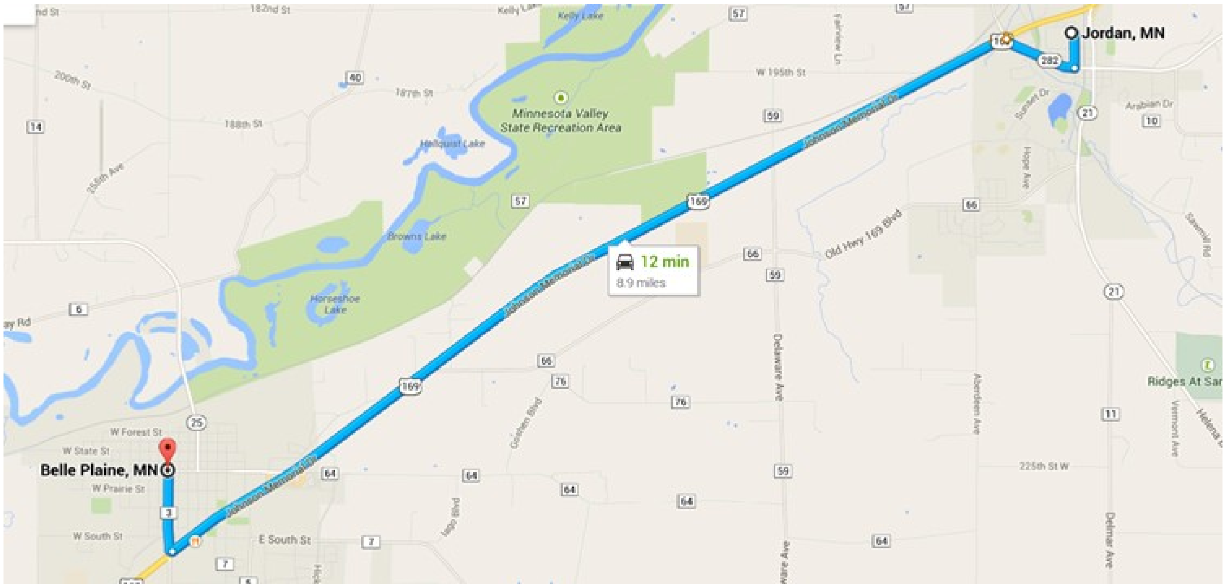

Figure 4.3 Modeled MN US Hwy 169 roadway containing simulated work zones.

The simulated road US-169 design was a two-lane, two-way median-divided highway with a speed limit of 55MPH. The experimental road spanned 9.2 miles (14746 m) in total, consisting of 2 miles (3219 m) of open road (Introductory drive), 1.2 miles (1871 m) of road including speed limit signage leading up to the work zone transition (Transition/ Warning), 5 miles (8047 m) of active work zone road work (Shoulder/ Lane Closure), and ending with 1 mile (1609 m) of road without work zone related activity to conclude the driving trial (Conclusion drive). The design of the work zone regions in the simulated drives follow the Minnesota and Federal MUTCD layout standards.

The roadway was segmented into two different drive layouts based on the US-169 route. The northbound drive (open lane) featured shoulder work without consequence to either lane of travel, while the southbound drive contained a right-lane lane closure (closed lane) that required drivers to utilize only the left lane.

4.2.4 Work Zone Messaging: In-Vehicle and Roadside

The work zone simulation presented drivers with information about the upcoming conditions of the work zone beyond the standard advanced warning signage. Each route contained five events with corresponding advanced warnings such as: workers on site, heavy machinery ahead, reduced speeds, stopped traffic, and debris in roadway. The messages were presented to drivers either on the roadside (via portable changeable message sign (PCMS)) or in-vehicle (via smartphone). The roadside messages presented via PCMS allowed for the message onset and duration (i.e., approximately 6 seconds) to be precisely matched with the in-vehicle messages to ensure adequate control of data analysis capabilities. For the in-vehicle presentation of the messages, the designed interfaces created by the research team in Task 3 were presented through the 7-inch LCD display (see Figure 2). The LCD display will, depending on the participant’s experimental group, was placed on the dash of the vehicle or will be laid in the passenger seat (screen up). The work zone messaging interface, depending on the driving route, presented either an audio-visual message or an audio-only messages at the same locations within the work zone in which the roadside PCMS messages would have come into view (see Table 4.2).

Table 4.2 Example of three messaging types pertaining to the same event within the southbound route

Southbound Route (Lane Closure)			
Message Placement	Audio-Only Message	Audio-Visual Message (Icon displayed)	PCMS
Mile Marker 1.25 Introductory Drive (Before Transition Zone)	"Work Zone Ahead" "Half Mile" "Reduce Speed"		

4.2.5 Procedure

During recruitment, the researchers screened the participants for study eligibility by asking recruits a series of questions that pertained to well-being in the simulator, health history, and demographic information. Items on the recruitment screening list included the participants must have had a valid driver's license for more than two years and travelled an average of 4,000 miles or more, no history of traumatic brain injury or stroke, visual acuity 20/40 or better without glasses, and no history of motion sickness. The recruitment screening protocol ensured that participants interested in engaging in the study would fit the needs for quality data collection, in addition to consideration for participant health and well-being.

Participants were presented a consent form that detailed the purpose of the study, the expectations of the participants for the duration of the study, any disqualification criteria, cautionary disclaimers on the risk for simulation discomfort or sickness, and resource information for the researchers and post-study information and help. The researchers clearly identified the tasks that the participants would be asked to perform during the consent briefing. Any questions, concerns, or other ambiguities were addressed before participants formalized their consent. Following the consent protocol, eligible participants were prompted to complete a field vision test using the Snellen Acuity Chart (Snellen, 1862) at the 20/40 and 20/20 visual acuity levels. Their color vision was tested by employing the Ishihara color vision assessment (Ishihara, 1960), ensuring that their vision was capable of appropriately viewing the work zone signage and roadway features within the simulated environment.

After the visual acuity and color vision tests, experimenters briefed the participants on the study and the expected tasks they were requested to perform over the duration of the study. Participants were informed that they were to perform the sequence of six driving trials segmented by the completion of the RSME (Appendix D), SUS (Appendix E), and Situational Awareness Inventory (Appendix C) questionnaires. Experimenters also provided a disclaimer about the possibility for participants to develop simulator sickness, a form of motion sickness experienced by a small proportion of people who engage in the driving simulation task. Before the briefing and consenting process was completed, experimenters asked participants if there were any questions related to the expectations or the required study task and offered to clear any ambiguities or concerns participants may have had.

Following the consenting and briefing protocol, experimenters escorted participants to the simulation vehicle, where the seat and steering wheel adjustments to accommodate the participants were performed. The participants were given the opportunity to perform a practice drive in the simulator, which consisted of a free-drive on a simulated rural Minnesota two-way two-lane divided highway roadway design. The practice drive was structured so that participants could familiarize themselves with the controls and operation of the simulator, experience the motion dynamics of the simulated environment to ensure discomfort or simulator sickness wouldn't materialize.

To increase the level of mental load and internal distraction of participants while they drove through the work zones, they were asked to engage in a secondary mental task. The mental task, known as the "count back task", involved participants verbally counting backward from 300 in increments of 3. Drivers were asked to count backwards continuously throughout each drive. Participants were first given the opportunity to practice while the car was stopped and again during their practice drive. They were instructed to guess the number when they lost track of their placement and continue with the counting even when they had become aware of making an error.

After participants successfully performed the practice drive without observed or self-reported indications of simulator sickness or general discomfort, the experimenters repeated the driving instructions and secondary task instructions before beginning the first experimental drive. Experimenters repeated the driving instructions before each drive trial began to ensure participants clearly understood the study's expectations.

4.3 RESULTS

4.3.1 Driving Performance Results

The following analyses were each initially conducted with a 3 × 2 × 2 (Modality, Position, Route) mixed factorial ANOVA, with follow-up analyses when appropriate. Modality of the interface and route were repeated-measures variables, while position of the smartphone was a between-subjects variable.

4.3.1.1 Average Speed

The impact of the experimental variables on average speed during the drive was tested. There was a main effect of route, F (1,45) = 364.092, $p < .001$, $\eta^2 = .889$. The southbound closed lane route (M = 48.488, SE = .324) elicited slower average speeds from participants than the northbound open lane route (M = 54.022, SE = .504). There were no other significant effects.

4.3.1.2 Average Speed During Event Messages

The impact of the experimental variables on average speed during the presentation of event messages was tested. There was a main effect of route, F (1,45) = 75.344, $p < .001$, $\eta^2 = .621$. The southbound closed lane route (M = 53.322, SE = .411) elicited slower average speeds from participants during work zone event messages than the northbound open lane route (M = 56.452, SE = .559). There were no other significant effects.

4.3.1.3 Speed Deviation

The average variance in speed was measured by speed standard deviation to determine if there were significant changes in speed over the course of the drives. There was a main effect of route, F (1,46) = 27.649, $p < .001$, $\eta^2 = .375$. The southbound lane closure route (M = 13.863, SE = .342) elicited greater speed deviation from participants than the northbound shoulder work route (M = 11.577, SE = .401). There was also a main effect of interface modality, F (2,92) = 3.474, $p = .035$, $\eta^2 = .070$. Post-hoc follow up analyses found the speed standard deviation score for the PCMS condition (M = 13.117, SE = .354) was significantly greater than the audio-visual condition (M = 12.267, SE = .319), t (47) = 2.828, $p = .006$. There was no difference between the audio-visual condition and the audio-only condition (M = 12.777, SE = .392), t (47) = 1.373, $p = .131$, and the audio-only and PCMS conditions, t (47) = .847, $p = .326$. There were no other significant effects.

4.3.1.4 Speed Deviation During Event Messages

Speed standard deviation was also measured during event messages to determine if there were significant changes in speed during work zone message presentation. There was a main effect of route, F (1,45) = 5.952, $p = .019$, $\eta^2 = .115$. The southbound lane closure route (M = 1.081, SE = .061) elicited less speed deviation from participants than the northbound shoulder work route (M = 1.187, SE = .068) during event messages. There was also a main effect of modality, F (2,90) = 6.700, $p = .002$, $\eta^2 = .124$. Post-hoc follow up analyses found the speed standard deviation score for the PCMS condition (M = 1.024, SE = .056) was significantly smaller than the speed standard deviation for the audio-visual condition (M = 1.243, SE = .080), t (47) = 3.652, $p = .001$, and the audio-only condition (M = 1.134, SE = .073), t (47) = 2.389, $p = .028$. There was no difference between the Audio-Visual condition and the audio-only condition, t (47) = 1.541, $p = .109$. There were no other significant effects.

4.3.1.5 Lane Deviation

Overall average lane deviation as measured by lane standard deviation was considered. There was a main effect of route, F (1,45) = 161.512, $p < .001$, $\eta^2 = .781$. The southbound lane closure route (M = 1.806, SE = .012) elicited greater lane deviations from participants during the overall drive than the northbound shoulder work route (M = 1.260, SE = .040). There were no other significant effects.

4.3.1.6 Lane Deviation During Event Messages

There was a significant modality × route interaction for lane standard deviation during work zone message presentation, F (2,90) = 11.361, $p < .001$, $\eta^2 = .201$. Breaking down the interaction by modality of the interface, there are no significant differences between northbound lane deviations (M = .289, SE = .025) and southbound lane deviations (M = .269, SE = .028) for the audio-only condition, t (47) = .549, $p = .586$, as well as the northbound (M = .278, SE = .029) and southbound (M = .259, SE = .027) routes in the audio-visual condition, t (46) = .530, $p = .599$. However, for the PCMS condition, there was a significant difference between northbound lane deviations (M = .250, SE = .021) and southbound lane deviations (M = .377, SE = .037), t (47) = 3.816, $p < .001$ (see Figure 4.4).

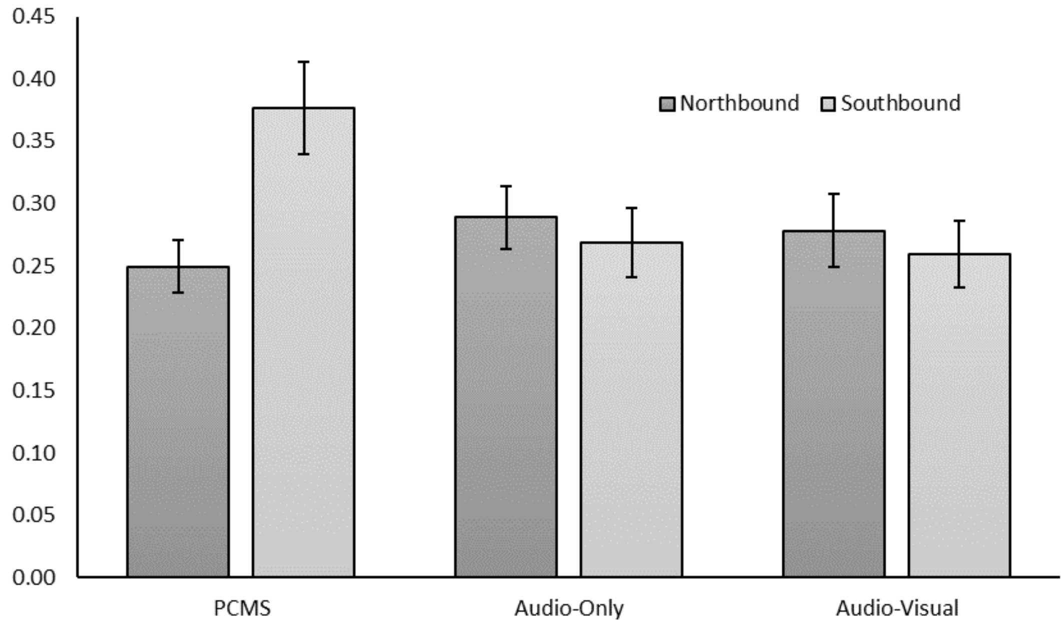

Figure 4.4 Lane deviation (*SD*) with standard error as error bars.

4.3.2 Subjective Measures Results

The following analyses were each initially conducted with a 3 × 2 × 2 (Modality, Position, Route) mixed factorial ANOVA, with follow-up analyses when appropriate. Modality and route were repeated-measures variables, while position was a between-subjects variable. An exception is the overall preference measure, which was analyzed with a chi-square test for the three modalities.

4.3.2.1 Overall Preference

Participants that experienced each of three work zone information delivery methods, the standard PCMS roadside signage, in-vehicle messaging system with auditory alerts, and in-vehicle messaging system with audio-visual alerts reported their preference after the study. The auditory-only message modality was preferred by a total of 38 participants, 8 preferred the audio-visual modality, and only two participants chose the PCMS signs as their preferred source of work zone information. To validate these findings, the chi-square test of goodness of fit statistical measure was employed to determine whether the three message modality formats were equivalently preferred, which was not the case, X^2 (2, N = 48) = 46.5, $p < .001$.

4.3.2.2 Mental Workload

To examine the level of cognitive effort each messaging modality imposed on the participants while performing the drive, data from the RSME (Appendix D) was analyzed. There was a main effect of messaging system modality, Greenhouse-Geisser corrected, F (1.664,74.883) = 12.691, $p < .001$, η^2 = .217. Post-hoc follow up analyses found the RSME score for the PCMS condition (M = 52.596, SE = 2.880) was significantly greater than the auditory-only condition (M = 43.351, SE = 2.990), t (46) = 4.008, $p <$ .001, and the audio-visual condition (M = 41.904, SE = 3.110), t (46) = 4.647, $p < .001$. There was no difference between the audio-only and audio-visual conditions, t (46) = .638, p = .409 (see Figure 4.5).

Additionally, no other significant main effects or interactions were unveiled in the analysis of workload by modality.

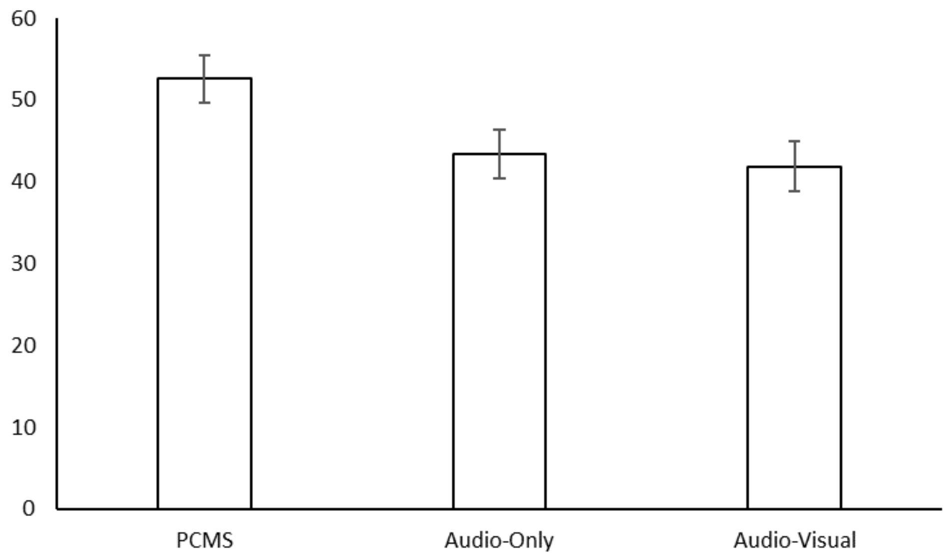

Figure 4.5 RSME scores measuring mental workload for each modality.

4.3.2.3 System Usability and Integration

System Usability Scale (SUS) scores were the dependent variable. A main effect of message modality was observed F (1.635, 73.597) = 26.733, $p < .001$, $\eta^2 = .367$. Post-hoc examinations found the SUS score for the PCMS (control) condition (M = 73.162, SE = 2.314) was significantly less than the audio-only condition (M = 86.284, SE = 1.782), t (46) = 6.344, $p < .001$, and the audio-visual condition (M = 86.234, SE = 1.721), t (46) = 6.320, $p < .001$ (see Figure 4.6). No statistical difference between audio-only and audio-visual messaging modalities were found.

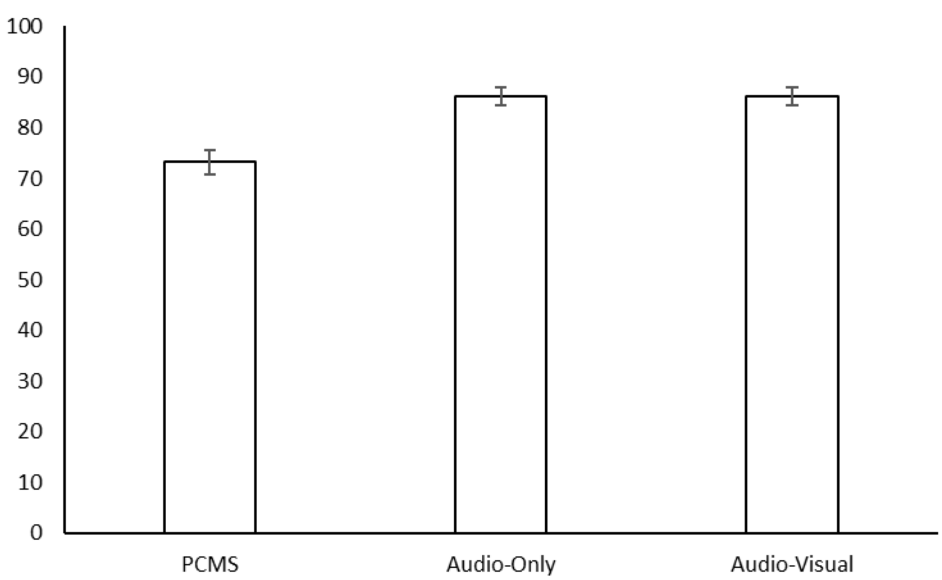

Figure 4.6 SUS scores measuring subjective system usability for each modality.

4.3.2.4 Situational Awareness

To assess participants' situational awareness of the work zone environment during each drive, researchers examined the Situational Awareness Inventory (Appendix C). The work zone event recall proportion correct scores were treated as the dependent variable. There was a main effect of message modality, F (1.635, 73.597) = 26.733, p < .001, η^2 = .367. Post-hoc examinations found the recall score for the PCMS condition (M = .407, SE =.035) was significantly lower than those of the audio-only condition (M =.509, SE = .033), t (46) = 2.856, p = .007. No statistical differences were found between the PCMS and audio-visual, or audio-only and audio-visual messaging modalities. There was a significant three-way modality × route × placement interaction, F (2,88) = 4.035, p = .021, η^2 = .080. Further analysis uncovered a simple interaction for the passenger seat placement condition for message modality and route, F (2,44) = 4.001, p = .024, η^2 = .150. The northbound route had no effect of modality, F (2,46) = .318, p = .729, η^2 = .014, but the southbound (lane closure) route had an effect of modality, F (2,46) = 6.365, p = .004, η^2 = .217. The recall scores for the PCMS condition (M = .348, SE = .067) was significantly less than the audio-only condition (M = .530, SE = .056), t (22) = 2.970, p = .007, and the audio-visual condition (M = .522, SE = .057), t (22) = 2.600, p = .016. There was no difference between the audio-only and audio-visual conditions, t (22) = .165, p = .870.

4.3.3 Visual Attention Results

Using the MAPPS software, the total number of fixations on the PCMS roadside signage for each drive was obtained by adding up the fixation numbers for each work zone event throughout one drive. Because of the mounting location, the scene camera was not able to capture the in-vehicle messaging system (i.e., Koolertron screen which simulated the cell phone delivery of the audio and visual icons) into the Smart Recorder videos, therefore MAPPS software was not readily available to use for analyzing the fixation data on the in-vehicle messaging interfaces. In the final analysis, the total number of fixations on the in-vehicle messaging interfaces were calculated and extracted from the Smart Eye eye-tracking data using the MATLAB software (Version 2016a, The MathWorks, Inc., Natick, Massachusetts). Due to the limitation of the eye tracking systems (e.g., poor eye tracking quality, calibration biases, equipment collapses, etc.) and other data losses, a final total of 136 data sets were included in the statistical analysis.

4.3.3.1 Number of Fixations on Messaging Interfaces

A 3 × 2 × 2 (Modality, Position, Route) mixed factorial ANOVA was conducted with the total number of fixations on the messaging interfaces (i.e., standard PCMS roadside signage, in-vehicle audio-visual interface, in-vehicle audio-only interface) as the dependent variable. A significant main effect of message modality was observed F (2, 48) = 40.54, p < .001, η^2 = .628. Post-hoc follow up analyses found that the total number of fixations for the PCMS condition (M = 56.311, SE = 5.786) was significantly greater than the audio-visual condition (M = 7.652, SE = 2.147), t (55.9) = 7.88, p < .001, and the audio-only condition (M = 4.956, SE = 1.356), t (44) = 8.20, p < .001 (see Figure 4.7). There was no significant difference between the audio-only and audio-visual conditions, t (75.7) = 1.06, p = .291.

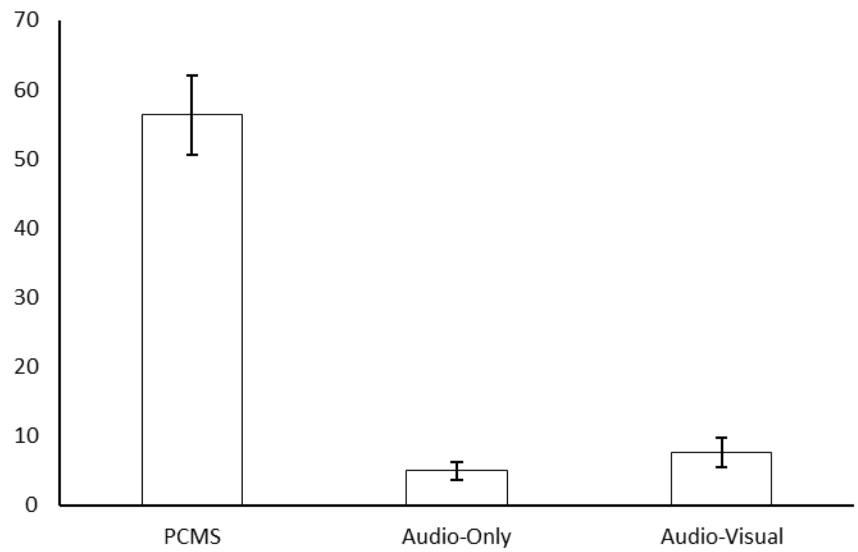

Figure 4.7 Total number of fixations on the messaging interfaces for each modality.

There was a significant modality × route interaction for the total number of fixations on the work zone messaging interfaces, F (2, 34) = 3.71, p= .035, η^2 = .179. Breaking down the interaction by modality of interface, none of the differences between northbound total fixations and southbound total fixations were significant for either modality, with t (38) = .928, p = .359 for the PCMS condition, t (38.2) = .959, p = .344 for the audio-only condition, and t (32.5) = .321, p = .750 for the audio-visual condition, respectively. While the total number of fixations was greater in northbound routes (M = 61.522, SE = 1.955) than in southbound routes (M = 50.864, SE = 3.960) for the PCMS condition, the trend was reversed for the audio-only condition (i.e., northbound M = 3.636, SE = 1.503 and southbound M = 6.217, SE = 2.233) and the audio-visual condition (i.e., northbound M = 6.957, SE= 1.955 and southbound M = 8.348, SE = 3.872, see Figure 4.8).

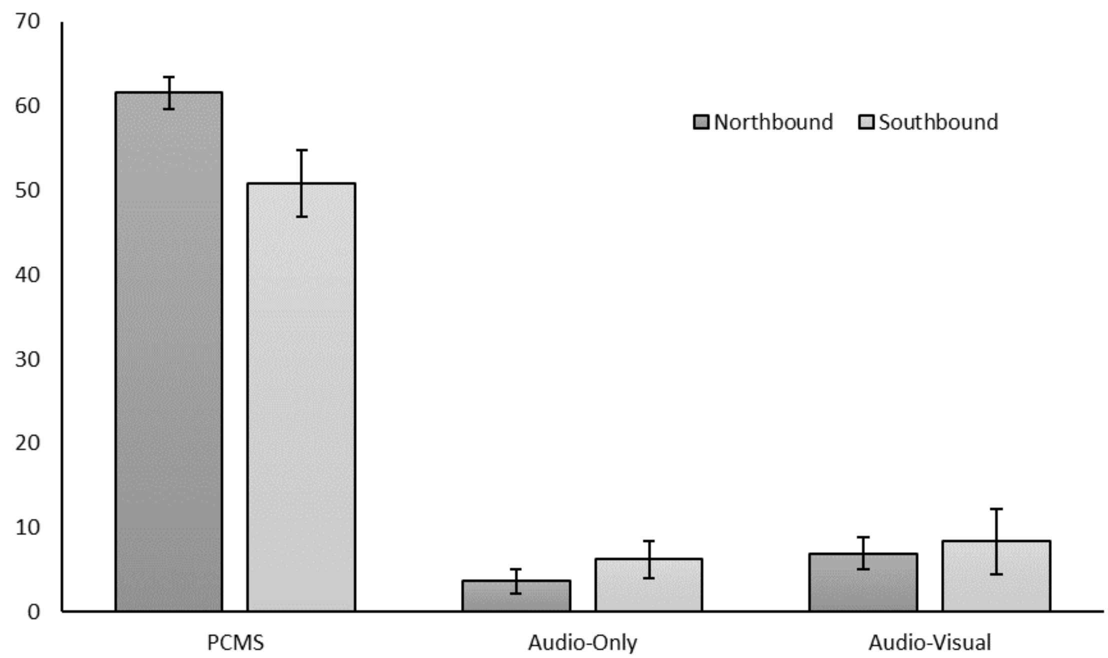

Figure 4.8 Total number of fixations on the messaging interfaces by route and modality.

The interaction effect of modality and position on number of fixations was also significant, F (2, 48) = 3.55, p = .037, η^2 = .129. When examining across different interface modalities, there were significant differences between the total number of fixations on the dashboard mounted interface and the passenger-seat interface, for the audio-only condition t (23.1) = 4.057, p < .001, and the audio-visual condition t (24.1) =3.690, p= .001. The total number of fixations on the audio-only interface was significantly greater when the smartphone was mounted on the dashboard (M = 9.167, SE = 2.222) compared to when it was placed on the passenger seat (M = .143, SE = .104). Similarly, for audio-visual modality, the total number of fixations was observed to be much greater in the dashboard mounted position (M =13.64, SE = 3.552) than in the passenger-seat position (M = 0.524, SE = 0.131). However, the total number of fixations did not significantly differ between dashboard mounted (M = 47.667, SE = 6.937) and passenger-seat placement (M = 66.191, SE = 9.243), for the PCMS condition t (38.3) = 1.603, p = .117 (see Figure 4.9).

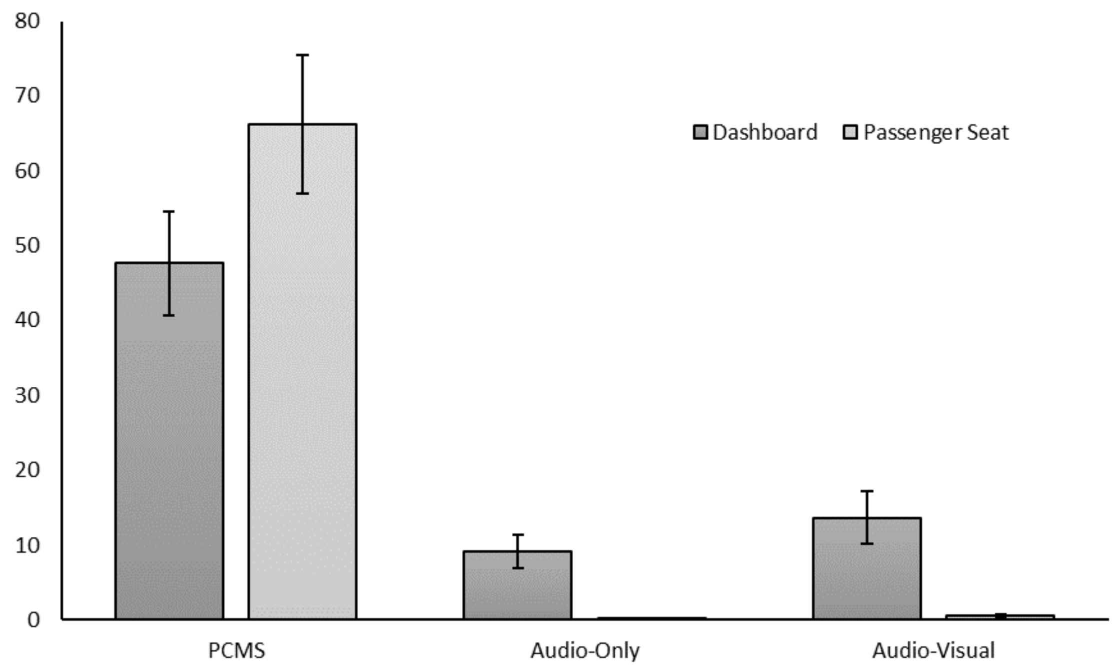

Figure 4.9 Total number of fixations on the messaging interfaces by position and modality.

4.3.4 Eye Tracking Limitations

4.3.4.1 Eye Tracking Error

The current study experienced technical errors with the SmartEye eye tracking system during data collection. Out of the 288 total drives, for 24 drives, 28 drive data sets for the forward-facing video capture and four in-cabin eye tracking data sets were lost during data collection. An additional 85 data sets were excluded from the remaining 221 data sets during statistical analyses for data quality reasons after collection, for a final total of 136 data sets. Additionally, some participant physical features such as height, cranial size, pupil size and distance, and facial features negatively impacted the data quality and acquisition using the SmartEye system, which is typical of head-tracking based eye tracking systems in the literature. The most frequent cause for data loss was related to the SmartRecorder forward-facing eye tracker participant eye calibration. This calibration step in the experimental protocol was the most error prone, due to the 9-step procedure that required participants to fixate their eyes on a 1" dot that was located on the forward projection screen.

4.3.4.2 Equipment Failure

Two drives experienced technical errors with the Koolertron screen which simulated the cell phone delivery of work zone messages, resulting in the inability for participants to receive the audio-visual message alerts. These two trials also experienced eye tracking error, further justifying researcher exclusion of these data in analysis.

4.4 DISCUSSION

4.4.1 Driving Performance Discussion

The southbound route involves a lane closure work zone and was likely the more challenging route to drive, which is reflected in the slower average driving speeds for the southbound route relative to the northbound route that had shoulder work with open lanes. Following this theme of southbound route difficulty, there were slower average speeds during event messages relative to the northbound route.

Participants were more likely to vary their driving speed in the southbound route, suggesting that the mental effort required to drive on this route left participants less able to maintain a consistent speed. Furthermore, there was greater speed deviation for participants in the PCMS condition relative to the speed deviations for the audio-visual modality. This suggests that the effort required to continuously scan the external environment for the roadside work zone messages made it less likely that the participant could maintain speed throughout the routes, at least relative to the audio-visual condition.

The southbound route and PCMS modality conditions reflected smaller speed deviations during work zone message events, relative to the other conditions. While this appears to be a reverse of the overall speed deviation analysis presented beforehand, what is likely happening is that while higher overall speed deviation may reflect less ability to maintain consistent speed over an entire route, a lower speed deviation during specific messaging events reflects less mental resources available to notice and quickly adjust or vary speed in response to immediate events. Both speed deviation patterns may emerge from the increased mental effort required of the southbound route and the PCMS modality condition.

While the proposed higher mental demand in the southbound route may contribute somewhat to higher lane deviation scores relative to the northbound route, this statistical difference in lane deviation is likely mostly due to participants being required to change lanes in the southbound lane closure route.

While there were no overall differences for lane deviation while work zone messages were being presented, lane deviation while driving the southbound route when being presented with PCMS messages was particularly high relative to the other conditions. This suggests that under higher levels of mental workload such as the southbound lane closure route, the mental focus of the driver was being significantly disrupted when presented work zone messages via roadside PCMS signage.

4.4.2 Subjective Measures Discussion

Most participants preferred the audio-only modality. Participants may be sensitive to the danger of visual distraction while driving and prefer the mode that least presents this distraction.

Driving on routes with PCMS signs for work zone messages presentation was rated by participants as being significantly higher in mental effort to perform relative to the routes driven with the smartphone messages as the primary modality in which work zone messages were communicated. PCMS signs were also rated by participants as being significantly less usable to drive with, compared to the routes driven with the smartphone messages.

Participants remembered less of the work zone events when driving on routes with PCMS signs compared to the routes driven with the smartphone messages, suggesting that being reliant on external signs on the road yields less driving situation awareness than providing work zone messages in the vehicle. Furthermore, for drivers with a smartphone in the passenger seat, recall scores were poor for the PCMS condition when driving the southbound lane closure route, relative to the other conditions.

4.4.3 Visual Attention Discussion

Overall, participants appeared to look less frequently at the in-vehicle messaging interfaces than the PCMS roadside signage. Combined with the subjective results of their metal workload and recall of the work zone events, the significant main effect of modality on total number of fixations further suggests that driving on routes with PCMS signs for work zone presentation required significantly higher visual demands for drivers and was more distracting to drivers, compared to routes in which work zone messages were communicated via in-vehicle smartphone.

The results suggest that when the work zone messages were presented with in-vehicle alerting systems, participants paid significantly less visual attention to the smartphone when it was positioned on the passenger seat for both audio-only and audio-visual conditions. As expected, the participants' total number of fixations on the roadside PCMS signage was not affected by the placement of the in-vehicle work zone messaging system.

4.4.4 Experimental Results Conclusion

Participants performed multiple drives on two routes in the HumanFIRST driving simulator with various work zone event messaging interfaces and smartphone placements. The general pattern of results for driving performance, visual attention, and subjective measures suggest that audio-only and audio-visual smartphone interfaces had at least equivalent and frequently better results than the more typical roadside PCMS work zone messages. The analysis provides empirical evidence that work zone event messages through smartphones may be a promising approach for a technology intervention for safe driving through work zones.

CHAPTER 5: CONCLUSIONS

5.1 SUMMARY

The purpose of this study was to determine whether in-vehicle messages delivered by smartphones could be beneficial for motorists driving through work zones, particularly for warning about events within the work zone and promoting safer driving behavior. To this end, the present research summarized the risk inherent in work zones, conducted a safety survey on both smartphone and work zone attitudes and behaviors, designed potential warning messages for delivery inside the vehicle, and conducted a simulator study to investigate the viability of this method of message delivery.

5.1.1 Work Zone Behavior and Crash Risk

The placement of a work zone elevates the risk of crashes on a road relative to that road's normal state (Khattake et al., 2002). For work zones, most accidents occur during daytime and clear weather conditions, meaning the cause of these crashes are less likely to be driven by the weather (Dissanayake & Akepati, 2009). However, lighting conditions appear to significantly matter, with low lighting contributing to a higher crash rate (Li & Bai, 2009). Furthermore, longer lengths, more complex road geometries, and more components in work zones such as machinery and construction barriers contribute to higher crash rates in work zones (Khattake et al., 2002; Li & Bai, 2009). Certain driving behaviors contribute to higher crash rates in work zones, such as speeding and inattention (NHTSA, 2010; Wilson, 2006). Therefore, barring new developments in work zone structures, delivering timely messages about work zones and events within work zones will help drivers anticipate and attend to these elements in the road, helping to mitigate the driving risk.

5.1.2 Safety Culture Survey

The safety culture survey was used to understand public perception about work zones along with certain habits related to smartphones to anticipate how smartphones were used and how to best test the delivery of in-vehicle messages. The primary finding of the survey was that there was general trust in Minnesota work zones and their signage, although there was greater trust in electronically delivered messages, perhaps because these messages would be perceived as more up-to-date. Furthermore, smartphones are frequently present in vehicles, but their placement is reported to be non-ideal, with only a small but significant number of participants stating that they mount their smartphone on their dashboard. Many other participants report placing the smartphone on the console, passenger seat, pocket, or cup holder. This implies that testing would have to make use of at least more than one placement to see if location plays a role in the utility of these in-vehicle work zone messages.

5.1.3 Experiment Results

The HumanFIRST lab tested the relative impact of the in-vehicle messaging system on visual attention, driving performance, mental workload, and user-technology opinions while performing a driving task through a simulated work zone. Ultimately, the results found that drivers responded very well to in-vehicle messaging for work zone hazards and information. They highly preferred audio-only messaging (i.e., allowing designers to push the message through any platform), but their performance or visual distraction was not affected by the presence of visual icons accompanying the message, nor was the placement of the phone a factor in safety or performance. The PCMS sign was the poorest way to receive this information. Not only did it decrease driving performance (i.e., vehicle control), but it also took far more visual attention without improving situational awareness. Drivers had a much harder time recalling messages they received this way. Overall, these findings support a very promising and inexpensive way to effectively alert drivers to hazards or changing conditions in work zones through in-vehicle messaging.

5.2 CONCLUSIONS

5.2.1 Theoretical Implications

While there is a heightened risk of driving through work zones, there is also a known risk of using in-vehicle messaging during driving, due to the possibility of increased workload and distraction (Strayer & Johnson, 2001). The results suggest in-vehicle messaging via smartphones can lead to lower mental workload and improved usability. Besides the practical potential intervention to minimize accident risk within work zones, there are generalizable possible rules of thumb one can take from these findings. First, task-relevant messages are less distracting to the overall task compared to task-irrelevant messages (Czerwinski, Cutrell, & Horvitz, 2000), suggesting that if so-called distracting technologies present information relevant to the overall task, these messages can be effectively integrated into task performance. However, if the messages from devices like smartphones present task irrelevant information, such as social gossip, the human must switch mental sets, resulting in difficulty switching back to the original task and a cost to reaction time (Jersild, 1927; Monsell, 2003). This opens an avenue for further theory-driven applied research on the impact of environmental stimuli with varying levels of task-relatedness and its corresponding relationship with distraction and mental workload.

Work zone event recall was better and visual attention more directed toward the road than the messaging interface for the in-vehicle smartphone conditions. This pattern was notably salient for the audio-only interface but occurred for the audio-visual interface as well. There is an implication that there is efficient attentional allocation toward relevant information for driving safely in work zones without needing visual content that competes with the similarly visual driving task (Wickens, 2008). For example, Parkes and Coleman (1990) found when participants performed a primary navigation task with a secondary information source for guidance (visual and auditory), the auditory condition had the best performance, lowest workload, and most gaze time on visual navigation. Therefore, further consideration of in-vehicle messages should consider (1) the task-relevant information properties of messages that limit task-switching and distraction and (2) the structural properties of the information sources that define the attentional channel or type by which the information will be processed, be it visual or auditory, and whether the primary modality of the task will compete with the modality of the messages. These two considerations set up an interesting scenario for future research in this area: highly task-relevant and non-competing secondary messages are helpful for task performance, while highly task-irrelevant and modality competing secondary messages are significantly detrimental for task performance, with levels of helpfulness and hindrance in between those extremes and varying with primary task demand.

5.2.2 Practical Implications and Benefits

Design guidance (e.g., UMTRI, 1994) clearly prescribes where within the vehicle in-vehicle messages should be positioned (i.e., just outside of the driver’s direct view of the roadway); however, deploying messaging via smartphones makes it nearly impossible to control where users will place such devices. People report they usually place their smartphones in non-dashboard areas (Achtemeier & Morris, 2016), raising concerns about safety implications; however, the results of this study appear to assuage such concerns. Recall was higher for events in the in-vehicle conditions compared with the control condition on the southbound lane closure route, particularly when the phones were located on the passenger seat. The southbound route restricted participants to one lane through the work zone. The northbound route did not impose this demand on participants. Therefore, relative to the northbound route, the southbound route could be more stressful. This may push participants' visual attention away from the roadside signage. All considered, placement of in-vehicle message systems may be less concerning than modality and task relevance. Furthermore, many participants preferred the audio-only design. Participants may be aware of the risk of visual distraction when driving and thus want the audio modality to prevent this visual distraction. Future research may compare these two modalities in more detail.

The primary practical implication and benefit, outside of placement and perceptual modalities, is the finding that these in-vehicle messaging systems may improve awareness and safe driving in work zones. Work zones are sections of the roadway that present significant risk to drivers and work zone crew (Khattake et al., 2002). Far from just being a distraction risk as suggested in the cell phone literature, the use of in-vehicle messaging systems could allow drivers to anticipate events ahead of time and reduce mental demand, giving the drivers the mental resources to respond to adverse events and other potential driving scenarios. This idea is supported by other research, demonstrating that mental workload can be reduced by in-vehicle messages, and drivers transfer the visual task demand of scanning for hazards in the work zone to the smartphone, moving their freed attentional responsibilities to the primary driving task (Jamson & Merat, 2005).

5.2.3 Next Steps and Specific Recommendations

Other practical avenues to test, besides the aforementioned future research possibilities on task relevance, task demand, and perceptual modalities, would be to (1) field test in-vehicle messaging systems outside of the simulator, and (2) test the usability and practicality of using smart phones versus other potential in-vehicle systems, such as the electronic interface or dashboard utilized by modern vehicles. The latter is not standardized but does have at least the audio-visual capabilities to potentially act as a broadly accessible in-vehicle messaging system.

5.2.3.1 Recommendations

The researchers suggest that future work using an in-vehicle messaging system places the smartphone device on top of the dashboard using a sturdy phone mount. The phone should be located within a 15° window to the left or right in relation to the center of the steering wheel when placed on the dashboard, preferably on a mount that provides a clear front view of the roadway for the driver. In agreement with the current results, previous work on in-vehicle technology systems have also demonstrated the effectiveness and safety benefits of placing these devices within this area on the forward dashboard (United Nations, 2010).

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APPENDIX A: SAFETY CULTURE QUESTIONS

Gender:

- ❍ Male
- ❍ Female
- ❍ I'd prefer not to say
- ❍ Other ____________________

Age:

Highest level of education:

- ❍ High School/ Vocational School
- ❍ Associates Degree
- ❍ Bachelors of Art/ Bachelor of Science
- ❍ Masters
- ❍ Doctorate
- ❍ Other ____________________

Occupation:

Please state the year you received your driver's license (or best estimation):

Please list your state of residence:

If you do not live in the state of Minnesota, do you do a majority of your driving in Minnesota?

- ❍ Yes
- ❍ No

About how often do you drive?

- ❑ Never
- ❑ Hardly Ever
- ❑ Sometimes
- ❑ Most Days
- ❑ Every Day

Estimate roughly how many miles you personally have driven in the past year:

- ❍ Less than 5000 miles
- ❍ 5000-10,000 miles
- ❍ 10,000-15,000 miles
- ❍ 15,000-20,000 miles
- ❍ Over 20,000 miles

Do you drive frequently on:

	Response	
	Yes	No
Highway/Interstate	❍	❍
Main roads (not freeway)	❍	❍
Urban roads	❍	❍
Country roads	❍	❍

During the last three years, have you ever been convicted of:

	Response	
	Yes	No
Speeding	❍	❍
Careless or dangerous driving	❍	❍
Driving under the influence of alcohol/drugs	❍	❍
Involvement in a collison	❍	❍

What type of vehicle do you drive most often?

❍ Motorcycle
❍ Passenger car
❍ Commercial Motor Vehicle
❍ Other: ____________________

Are you now or have you ever been a commercial motor vehicle operator?

❍ Yes
❍ No

Do you own or have you in the past used a cell phone?

❍ Yes, I currently own one
❍ Yes, but I don't currently own one
❍ No, I've never owned one

If yes: Describe the most recent cell phone (select all that apply)

❑ Basic phone (camera equipped or not)
❑ Android Smartphone
❑ iPhone Smartphone
❑ Windows Smartphone
❑ Blackberry Smartphone
❑ I do not have a cell phone

How frequently do you use your cell phone? (select one)

- ❍ Hourly
- ❍ Many times throughout the day
- ❍ Less than once a day

What do you primarily use your cell phone for? (select all that apply)

- ❑ Calling
- ❑ Text/ Picture/ Messaging Apps
- ❑ Timekeeping (calendar, alarm clock)
- ❑ Taking pictures
- ❑ Email
- ❑ Web browsing
- ❑ Shopping
- ❑ Social networking
- ❑ Navigation/GPS
- ❑ Gaming
- ❑ Other applications (Pandora, weather, stocks, etc)

How many cell phone calls do you make/receive in a given day? (select one)

- ❍ 0-1 calls per day
- ❍ 2-5 calls per day
- ❍ 6-10 calls per day
- ❍ 11-25 calls per day
- ❍ 25+ calls per day

How many text messages do you send/receive in a given day?

- ❍ 0-10 texts per day
- ❍ 11-50 texts per day
- ❍ 51-99 texts per day
- ❍ 100-150 texts per day
- ❍ 150+ texts per day

Are you willing in some circumstances to make or answer a phone call while you are driving?

- ❍ Yes
- ❍ No

Under what circumstances might you make or receive a phone call while you are driving a vehicle? (check all that apply)

- ❑ Never
- ❑ When alone on roadway
- ❑ When stopped at a stoplight or stop sign
- ❑ Stopped in traffic
- ❑ Cruising down the highway
- ❑ Traveling on low speed roads (e.g. residential or side roads)
- ❑ At any time while driving

Are you willing in some circumstances to make or read a text message while you are driving?

- ❍ Yes
- ❍ No

How often do you make or receive text messages while you are driving a vehicle? (select all that apply)

- ❑ Never
- ❑ When alone on roadway
- ❑ When stopped at a stoplight or stop sign
- ❑ Stopped in traffic
- ❑ Cruising down the highway
- ❑ Traveling on low speed roads (e.g. residential or side roads)
- ❑ At any time while driving

Please select the type of navigation system you have used. (select all that apply)

- ❑ Built-in vehicle navigation system
- ❑ Portable navigation system (Garmin, TomTom)
- ❑ Smart phone application (Apple, Google maps)
- ❑ Other:_______

How frequently do you use a GPS or navigation system? (select one)

- ❍ Never
- ❍ A few times per month
- ❍ A few times per week
- ❍ Nearly every day
- ❍ Nearly every trip

What are the primary uses for the navigation system? (select all that apply)

- ❑ Driving in unfamiliar cities/neighborhoods
- ❑ Determining the best route to my destination
- ❑ Determining alternate route (i.e. in case of road construction or traffic)
- ❑ Determining my arrival time or trip time to my destination
- ❑ Getting directions to recent destinations
- ❑ Driving in familiar cities/neighborhoods
- ❑ Finding direction to return home
- ❑ Finding gas stations/restaurants/shopping locations etc.
- ❑ Fitness or exercise tracking
- ❑ Biking or walking directions
- ❑ Other

Are you willing in some circumstances to operate your navigation or GPS while you are driving?

- ❍ Yes
- ❍ No

How often do you operate your navigation system while driving? (i.e. changing destination/volume/zoom/etc) (select all that apply)

- ❑ Never
- ❑ When alone on roadway
- ❑ When stopped at a stoplight or stop sign
- ❑ Stopped in traffic
- ❑ Cruising down the highway
- ❑ Traveling on low speed roads (e.g. residential or side roads)
- ❑ At any time while driving

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
I am concerned about safety when I drive through a work zone.	❍	❍	❍	❍	❍
My driving behaviour changes when I pass through an active work zone.	❍	❍	❍	❍	❍
Speed limits during live work in a work zone should be lower than an empty work zone.	❍	❍	❍	❍	❍
Work zone warning and alerting signs are safe and do their job well.	❍	❍	❍	❍	❍
I am often wishing there would be a more tech-savvy way of being notified of upcoming work areas while driving.	❍	❍	❍	❍	❍

Typically, work zone signs give enough warning for drivers.	❍	❍	❍	❍	❍
Cones and barriers are sufficient to show clear direction in a work zone, such as in a lane closure.	❍	❍	❍	❍	❍
Electronic signs do a better job at allowing me to understand what is changing or what to expect in a work zone.	❍	❍	❍	❍	❍
I am likely to use a smart phone app that would alert and inform me about upcoming hazards or conditions in a work zone.	❍	❍	❍	❍	❍
Typically, I feel uncomfortable or uneasy while driving through work zones.	❍	❍	❍	❍	❍

Automatic notifications on a phone during the approach or driving though a work zone would be distracting to my driving.	❍	❍	❍	❍	❍
An app would provide more up-to-date work zone information than conventional signage.	❍	❍	❍	❍	❍
I tend to rely on other drivers for how fast I should drive in a work zone.	❍	❍	❍	❍	❍
The amount of orange signs in a work zone are overwhelming.	❍	❍	❍	❍	❍
A phone alert would be more effective than signs in a long work zone.	❍	❍	❍	❍	❍

My driving abilities are better than the average driver.	❍	❍	❍	❍	❍
I would trust an app’s accuracy in keeping me alerted to current road work conditions.	❍	❍	❍	❍	❍
I comply with work zone messages, such as posted lower speed limits, even when no workers are present.	❍	❍	❍	❍	❍
I would feel at a disadvantage compared to other drivers if they had a work zone alert app on their phones and I did not.	❍	❍	❍	❍	❍
In general, motorists are very careful while driving through a work zone.	❍	❍	❍	❍	❍

Information while driving, such as lane closures, road repair, and exit closures is acceptable and safe in the state of Minnesota.	❍	❍	❍	❍	❍
Work zones are an annoyance by slowing my commute time.	❍	❍	❍	❍	❍
Restricting cell phone usage in work zones increases the safety of my driving.	❍	❍	❍	❍	❍

If you are not interested in using a smart phone application based on information about work zones, what incentives could motivate you to do so?

Where is your phone typically placed in your car when driving? Examples: on the dash, in my pocket, on my lap, in my hand, etc.

What is the most challenging aspect of a work zone? Would real-time automatic notifications on your phone providing road conditions or directions potentially be a solution to this challenge?

Where do you typically get information about the status of work zones? Examples: google, 511 app, signage, news, etc.

What additional information about a work zone could increase safety of yourself or other motorists?

APPENDIX B:
DRIVING HISTORY AND TECHNOLOGY USE QUESTIONNAIRE

This questionnaire asks you to indicate some details about your driving history and related information. Please tick one box for each question.

1. Your age: _____________ years

2. Your gender:
- ☐ Male
- ☐ Female
- ☐ I prefer not to say

3. What is your highest educational level completed?
- ☐ High School / Vocational School
- ☐ Associates Degree
- ☐ Bachelor of Arts / Bachelor of Science
- ☐ Masters
- ☐ Doctorate

4. Are you currently taking any college level classes?
- ☐ Yes
- ☐ No

5. Please state your occupation:____

6. Please state the **year** when you obtained your full driving license: ___________

7. About how often do you drive?

☐ ======= ☐ ======= ☐ ======= ☐ ======= ☐

Never	Hardly Ever	Sometimes	Most Days	Every Day
☐	☐	☐	☐	☐

8. Estimate roughly how many miles you personally have driven in the past year:
- ☐ Less than 5000 miles
- ☐ 5000-10,000 miles
- ☐ 10,000-15,000 miles
- ☐ 15,000-20,000 miles
- ☐ Over 20,000 miles

9. Do you drive frequently on:

	Yes	No
Highways?	☐	☐
Main Roads other than Highways?	☐	☐
Urban Roads?	☐	☐
Country Roads?	☐	☐

10. During the last three years, have you ever been convicted of:

	Yes	No
a. Speeding	☐	☐
b. Careless or dangerous driving	☐	☐
c. Driving under the influence of alcohol/drugs	☐	☐
d. Involvement in a collision	☐	☐

10. What type of vehicle do you drive most often?

☐ Motorcycle
☐ Passenger Car
☐ Tractor and Trailer
☐ Other:_______

11. Do you own or have you in the past used a cell phone?
    a. Yes, I currently own one
    b. Yes, but I don't currently own one
    c. No, I've never owned one

12. If yes: Describe the most recent cell phone (select all that apply)
    a. Basic phone (camera equipped or not)
    b. Android Smartphone
    c. iPhone Smartphone
    d. Windows Smartphone
    e. Blackberry Smartphone
    f. I do not have a cell phone

13. How frequently do you use your cell phone? (select one)
    a. Hourly
    b. Many times throughout the day
    c. Less than once a day

14. What do you primarily use your cell phone for? (select all that apply)
    a. Calling
    b. Text / Picture /Messaging Apps
    c. Timekeeping (Calendar/Date book reminders/Time/Alarm Clock)
    d. Taking pictures
    e. Email
    f. Web browsing
    g. Shopping
    h. Social Networking
    i. Navigation/ GPS
    j. Playing Games
    k. Other applications (Pandora, weather, stocks, etc)

15. How many cell phone calls do you make/receive in a given day? (select one)
    a. 0-1 calls per day
    b. 2-5 per day
    c. 6-10 per day
    d. 11-25 per day
16. How many text messages do you send/receive in a given day? (select one)
    a. 0-10 texts per day
    b. 11-50 texts per day
    c. 51-99 per day
    d. 100-150 texts per day

17. Have you ever used voice recognition software on a mobile phone or computer?
    a. Yes
    b. No

18. Are you willing in some circumstances to make or answer a phone call while you are driving?
    a. Yes
    b. No

19. How often do you to make or receive a phone call while you are driving a vehicle? (select one)
    a. Never
    b. Rarely (e.g. When alone on roadway)
    c. Sometimes (e.g. When stopped at a stoplight)
    d. Often (e.g. Cruising down the highway, stopped traffic)
    e. All of the time (e.g. At any time while driving)

20. Are you willing in some circumstances to make or read a text message while you are driving?
    a. Yes
    b. No

21. How often do you make or receive text messages while you are driving a vehicle? (select one)
    a. Never
    b. Rarely (e.g. When alone on roadway)
    c. Sometimes (e.g. When stopped at a stoplight)
    d. Often (e.g. Cruising down the highway, stopped traffic)
    e. All of the time (e.g. At any time while driving)

22. Please select the type of navigation system you have used. (select all that apply)
    a. Built-in vehicle navigation systems
    b. Portable navigation systems (e.g. Garmin, TomTom)
    c. Smart phone based navigation systems (Apple, Google maps)
    d. Other:_______

23. How frequently do you use a GPS or navigation system? (select one)
    a. Never
    b. Rarely (e.g. When alone on roadway)
    c. Sometimes (e.g. When stopped at a stoplight)
    d. Often (e.g. Cruising down the highway, stopped traffic)
    e. All of the time (e.g. At any time while driving)

24. What are the primary uses for the navigation system? (choose all that apply)
    a. Driving in unfamiliar cities/neighborhoods
    b. Determining the best route to my destination
    c. Determining alternate route (i.e. in case of road construction or traffic)
    d. Determining my arrival time or trip time to my destination
    e. Getting directions to recent destinations
    f. Driving in familiar cities/neighborhoods
    g. Finding direction to return home
    h. Finding gas stations/restaurants/shopping locations etc.
    i. Fitness or exercise tracking
    j. Biking or walking directions
    k. Other

25. Are you willing in some circumstances to operate your navigation or GPS while you are driving?
    a. Yes
    b. No

26. How often do you operate your navigation system while driving? (i.e. changing destination/volume/zoom/etc)
    a. Never
    b. Rarely (e.g. When alone on roadway)
    c. Sometimes (e.g. When stopped at a stoplight)
    d. Often (e.g. Cruising down the highway, stopped traffic)
    e. All of the time (e.g. At any time while driving)

Where is your phone typically placed in your car when driving? Examples:in a mount, in my pocket, on my lap, in my hand, etc.

APPENDIX C: SITUATION AWARENESS INVENTORY

Experimenter instructions: **"**Please recall as many of the messages and signs you saw in the drive as you can." If you can only remember the gist of something, include that too. There is no time limit so please take as much time as you need. Please try to recall as many details as you can.

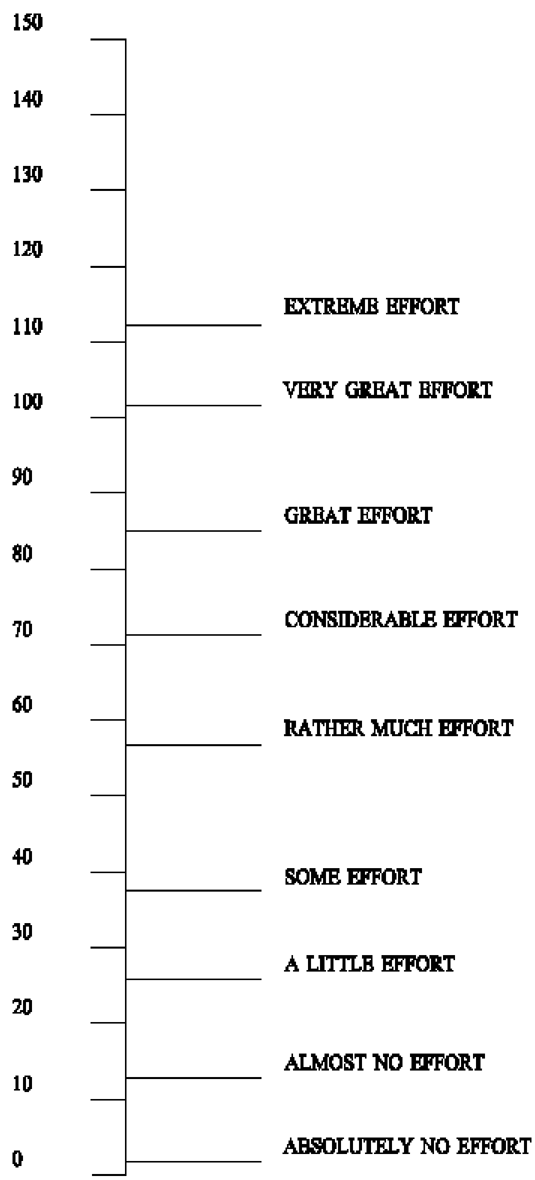
Experimenter instructions: **"**Please recall as many of the messages and signs you saw in the drive as you can." If you can only remember the gist of something, include that too. There is no time limit so please take as much time as you need. Please try to recall as many details as you can.

Experimenter instructions: **"**Please recall as many of the messages and signs you saw in the drive as you can." If you can only remember the gist of something, include that too. There is no time limit so please take as much time as you need. Please try to recall as many details as you can.

APPENDIX D: RATING SCALE MENTAL EFFORT

Rating Scale Mental Effort

Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task you've just finished



APPENDIX E: SYSTEM USABILITY SCALE

For each of the following questions, place an "X" through the one number to indicate your response.
"1" for strongly disagree, "3" for neutral- neither agree nor disagree, "5" for strongly agree.

1. I think that I would like to use this system frequently.

Strongly Disagree		Neutral		Strongly Agree
①	②	③	④	⑤

2. I found the system unnecessarily complex.

①	②	③	④	⑤

3. I thought the system was easy to use.

①	②	③	④	⑤

4. I think that I would need the support of a technical person to be able to use this system.

①	②	③	④	⑤

5. I found the various functions in this system were well integrated.

①	②	③	④	⑤

6. I thought there was too much inconsistency in this system.

①	②	③	④	⑤

7. I would imagine that most people would learn to use this system very quickly.

①	②	③	④	⑤

8. I found the system very cumbersome to use.

①	②	③	④	⑤

9. I felt very confident using the system.

①	②	③	④	⑤

10. I needed to learn a lot of things before I could get going with this system.

①	②	③	④	⑤