Examining the Impact of ASE (Automated Speed Enforcement) in Work Zones on Driver Attention

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16. Abstract (Limit: 250 words)

Each year, there are over 500 fatal crashes in work zones in the U.S., with over 100 road construction workers killed on work sites (NSC, 2011; FARS, 2011). Speed and distraction are among the top contributing factors to work zone crashes (Garber & Zhao, 2002; Mountain, Hirst, & Maher, 2005; Wilson, Willis, Hendrikz, Le Brocque, & Bellamy, 2006). The purpose of this study was to investigate the impact of different types of speed enforcement methods on driver attention in work zones. The investigation not only examined enforcement methods currently used in Minnesota, but also examined how implementing automated speed enforcement (ASE), which is not currently used in Minnesota, may influence driver attention and behavior in simulated work zones. Overall, the results do not appear to support the hypothesis that ASE without dynamic speed display sign (DSDS) improves driver attention in work zones. There is some evidence, however, that drivers did heighten their visual attention in work zones with ASE+DSDS enforcement. Drivers fixated on the secondary task display less frequently in the ASE+DSDS condition compared to other enforcement types while they traveled in the downstream portion of the work zone. The largest effects of the study were found among the age groups, with younger and older drivers exceeding the speed limit most often and varying their speed slightly depending on the type of enforcement present. Middle-aged drivers exhibited the greatest speed control and tended to abide by the speed limit to the same extent regardless of the type of enforcement present.

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Final Report

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EXECUTIVE SUMMARY

Work zones are a vital component of our transportation infrastructure; however, they pose a threat to motorists, workers, and law enforcement due to a wide range of complex issues. Each year, over 100 road construction workers in the U.S. are killed in work zones (NSC, 2011). Furthermore, in 2013, there were 579 work zone, fatal motor vehicle crashes in the U.S. (FARS, 2013). Driver inattention contributes to approximately half of all work zone crashes and worker strikes (NSC, 2011). More work can be done to develop countermeasures against work zone crashes, especially those resulting from inattention.

Experts from the Minnesota Departments of Transportation, Department of Public Safety, and State Patrol were surveyed to examine which aspects of work zones present the most concern for safety. Respondents reported that factors that drivers may not expect such as lane closures, maintenance work zones, and high traffic volumes present the most external threats to safety in work zones. The experts also indicated that distraction, speeding, and aggressive driving are the most risky driving behaviors, with older and younger drivers being the driving groups that most often threaten safety in work zones. When asked about which interventions have the greatest short- and long-term influence on speed reductions in work zones, respondents overwhelmingly reported traditional law enforcement was the most effective, and automated speed enforcement (ASE) was the least perceived effective method. A comprehensive examination of research conducted in other states and countries with ASE, however, clearly indicate a strong effect of ASE in reducing speed, serious injury and fatal crashes.

The purpose of this study was to investigate the impact of different types of speed enforcement methods on driver attention in work zones. The investigation not only examined enforcement methods currently used in Minnesota, but also examined how implementing ASE, which is not currently used in Minnesota, may influence driver attention and behavior in work zones. While a substantial body of work exists regarding the efficacy of ASE in work zones and other roadways, it is unknown how ASE compares with other speed limit enhancements (e.g. speed display signs, high visibility traditional law enforcement, etc.) in terms of its impact on driver attention and distraction. Overall, the proposed research plan examines how drivers respond to four types of enforcement at work zones: control (no enforcement), police car present, dynamic "your speed" signs, and ASE. The experiment uses a simulated work zone on a realistic rural divided Minnesota roadway, Hwy 169 between Jordan, MN and Belle Plaine, Minn. The aim of this study was to determine whether drivers respond to various types of speed limit enhancements differently with regard to speed limit compliance, safe following distances, crash rates, lane control, visual attention, and distraction seeking.

Overall, the results do not strongly support the hypothesis that ASE without dynamic speed display sign (DSDS) improves driver attention in work zones. There is some evidence, however, that drivers heighten their visual attention in work zones with ASE+DSDS Enforcement. Drivers fixated on the secondary task display less frequently in the ASE+DSDS condition compared to other enforcement types while they traveled in the downstream portion of the work zone. This may suggest a time and distance halo of visual attention to the primary task of driving when drivers are monitored with ASE+DSDS. Finally, drivers do engage in more glances to their speedometer in the ASE+DSDS work zones compared to ASE only, but they do not appear to be overly occupied with this monitoring since they do not monitor their speedometer significantly more often compared to when police are present or under no enforcement conditions.

The largest effects of the study were found among the age groups, with Young and Older Drivers exceeding the speed limit most often and varying their speed slightly depending on the type of enforcement present. Middle-aged drivers exhibited the greatest speed control and tended to abide by the speed limit to the same extend regardless of the type of enforcement present. Exerting this control may have contributed to their higher reported mental effort. Young and Older drivers are the most at-risk age groups in work zones, and they appear to be most positively influenced by ASE+DSDS.

CHAPTER 1: INTRODUCTION

1.1 Work Zone Crashes: Magnitude of the Problem

Work zones are a vital component of our transportation infrastructure; however, they pose a threat to motorists, workers, and law enforcement due to a wide range of complex issues. Each year, over 100 road construction workers in the U.S. are killed in work zones (National Safety Council (NSC), 2011). Furthermore, there were 87,606 crashes in U.S. work zones in 2010; 525 of those crashes were fatal (FARS, 2011).Driver inattention contributes to approximately half of all work zone crashes and worker strikes (NSC, 2011). More work can be done to develop countermeasures against work zone crashes, especially those resulting from inattention.

Work zones are hazardous because they introduce disruption to the layout of the roadway and traffic patterns. These environmental factors are compounded by some motorists engaging in risky driving behaviors which impose a threat to themselves and others. Among the many risky driving behaviors associated with work zone crashes, speeding (Garber & Zhao, 2002; Mountain, Hirst, & Maher, 2005; Wilson, Willis, Hendrikz, Le Brocque, & Bellamy, 2006) and driver inattention (Li & Bai, 2009; Dissanayake & Akepati, 2009; et al.) are two of the more prevalent behaviors reported as contributing crash factors. This project aims to examine the relationship between driver attention and speed enforcement methods, including existing Minnesota speed enforcement methods and a potential future method, automated speed enforcement (ASE).

1.2 Work Zone Crash Factors

1.2.1 <u>Driver Characteristics</u>

While certain characteristics of drivers 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 different 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 amount that each group typically travels. Second, crash rates can be examined by a group's average vehicle miles travels (VMT). This method considers the frequency and amount that each group tends to travel on the road, but VMT is an imprecise measure since it is typically determined by self-reported miles driven. Additionally, VMT is rarely included as a variable in examinations of certain groups, e.g. gender differences.

While teen drivers are often considered the most risky driver, older 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 (FARS, 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 counterparts (Li & Bai, 2009; Weng & Meng, 2011). Older drivers, 65 and older, 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 to be most likely involved in a fatal work zone crash between the hours of 8:00 pm and 6:00 am (Li & Bai, 2007), 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).

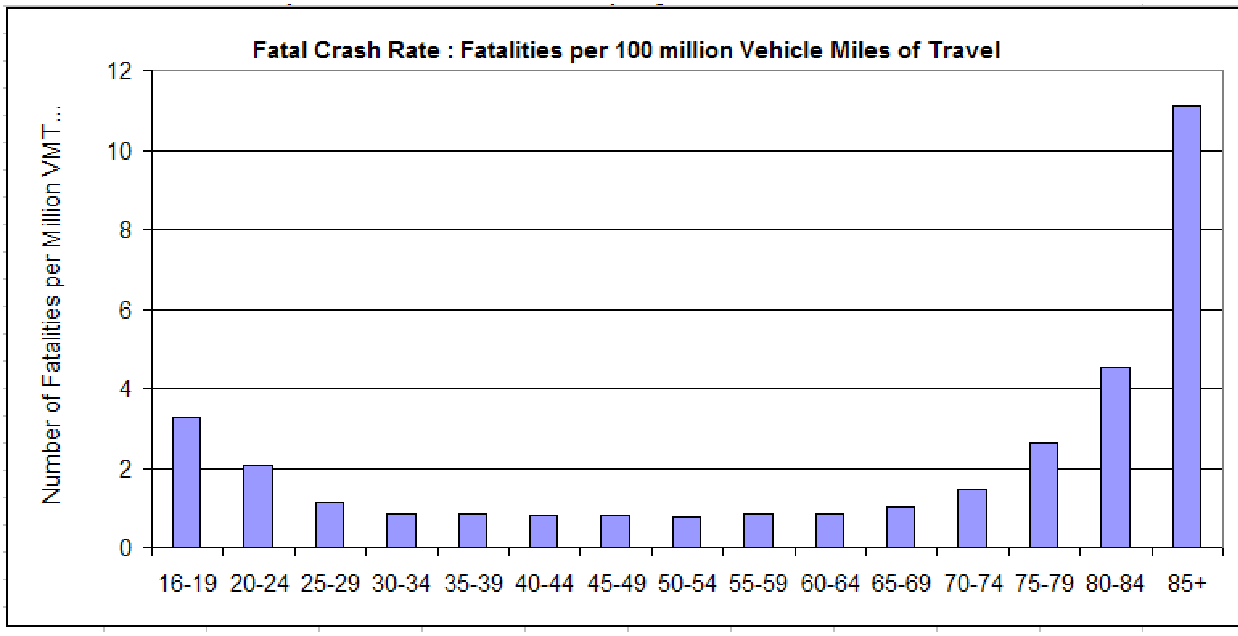

Figure 1.1 National fatal passenger vehicle driver crash involvements per 100 million vehicle miles traveled by age group, 2007. Based on National Household Travel Survey VMT by Age and NHTSA FARS (Cicchino & McCartt, 2014).

Male drivers have been found to pose a greater fatal crash risk than female drivers (Li & Bai, 2009). Just as males made up 70% of those involved in 2014 fatal work zone crashes in Minnesota (MnDPS, 2015), crash data examined 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 and often revealed that male occupants were also more likely to be involved work zone crashes (Dissanayake & Akepati, 2009). The type of work zone could be a factor in examining gender differences since 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.

Socioeconomic status has also been linked to crash risk, which would extend to work zone crash risk. Drivers with limited education (i.e. no high school diploma) are at a 2-3 fold increase of fatal crash risk compared to those with post-secondary education (Braver, 2003). These rates are in part due to findings that those with limited education, especially men, are less likely to wear their seatbelt (19%) than those with an education beyond high school (42%). Furthermore, they are attributed to higher BAC rates of those less educated. Lower income tends to be strongly associated with increased fatal crash rates with the possible exception to teens. Teens from more affluent families are more likely to have access to their own car which increases their early driving exposure rate, leading to increased fatal crash rate (Williams, Leaf, Simons-Morton, & Hartos, 2006).

Vehicle type has been found to impact 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 overwhelmingly large proportion of overall work zone crashes involve passenger vehicles, trucks and busses have been shown to have anywhere between a 4 (Li & Bai, 2009) to 10 times (Weng & Meng, 2011) increase in fatal work zone crash risk compared to other vehicles. Moreover, compared to non-work zones, the crashes in work zones are disproportionally more likely to involve trucks than other vehicles (Daniel, Dixon, & Jared, 2000).

1.2.2 Driver Behavior

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 do not lack 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 Crash Facts, 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 the given environmental and traffic conditions.

1.2.2.1 Driver Risk Taking

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 are alcohol related (Minnesota Crash Facts, 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, as well (Harb, Radwan, Yan, Pande, & Abdel-Aty, 2008; Dissanayake & Akepati, 2009).

Impairment of any kind (alcohol, drugs, fatigue, etc.), however, are 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 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 since traveling speeds and speed differentials are lower. Additionally, impairment may cause drivers to be less likely to follow traffic controls, a behavior that makes driver three times more likely to be involved in a fatal crash (Li & Bai, 2009).

Next to impairment, speeding or traveling too fast for conditions is at the forefront of hazardous behaviors that increase crash risk. Speeding was cited as the cause of 20% of fatal work zone crashes in 2014 in Minnesota (MnDPS, 2015). Both crash risk and crash severity increase with speed (Mountain et al., 2005; Wilson et al., 2006). NHTSA estimates that speeding contributes to approximately 30% of all serious injury and fatal crashes (McAvoy, Duffy, & Whiting, 2011). Drivers often underestimate the necessary time and distance required to safely stop if a lead vehicle suddenly brakes. This is especially true when drivers are traveling at higher speeds, which contributes 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 mph require 23 meters and 36 meters, respectively, to safely stop

(Mountain et al., 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 two vehicle crashes (Daniel et al., 2000; Wilson et al., 2006; McAvoy et al., 2011).

1.2.2.2 Driver Attention and Distraction

Following speeding, inattention or distraction is typically the next commonly cited contributing factor 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 Crash Facts, 2013). A proper understanding of driver attention is prudent to determine the influence of distraction on safety travel in work zones. This is no easy feat considering 19th century, famous psychologist William James said "Everyone knows what attention is" and conversely contemporary, renowned psychologist Harold Pashler said "No one knows what attention is, and…there may not even be an "it" there to be known about (although of course there might be)" (Pashler, 1998). What is hardly disputable is that attention is not an unlimited resource and drivers must choose where and when is it needed most (Wickens & Hollands, 2000). Cognitive or internal attention processing is difficult to measure directly, so often surrogate measures of attention are used in driving research, such as response times and recall accuracy. Visual attention, measured through eye tracking can help to indicate how drivers allocate their attention. Experience can play an important role in visual fixations and eye movements. While all drivers tend to predictably place more than half of their fixations on the far road ahead on highways, novice drivers have been found to scan the roadway less than experienced drivers when hazards are present (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). Typical scanning patterns, such as checking mirrors when changing lanes, have been shown to be disrupted when drivers are distracted by cell phone-type tasks in work zones (Muttart, Fisher, Knodler, & Pollatsek, 2007).

Distraction as a causal factor of driver error 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. According to NHTSA, however, "lost in thought" is the most prevalent form of distraction; accounting for approximately 18% of fatal crashes, while "conversing with passengers" accounts for approximately 15% of all internally distracted crashes (FARS, 2010). Distraction caused by cell phone use (e.g. calling, texting, or dialing) accounts for approximately 11% of distraction related fatal crashes (FARS, 2010). Similar to impairment, distraction may lead drivers to engage in other risky driving behaviors such as disregarding traffic, monitoring mirrors, roadway or speed less often, engaging in "looked-but-did-not-see" errors, and having 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, e.g. failure to notice slowing or stopping traffic, are likely to lead to rear-end crashes, which comprise a majority of work zone crashes (Wang, Hughes, Council, & Paniati, 1996; McAvoy et al., 2011; Dissanayake & Akepati, 2009). Interestingly, rear-end and sideswipe crashes are more likely to occur in work zones than non-work zones (Khattak, Khattak, & Council, 2002).

1.2.3 Driver Behaviors within Areas of the Work Zone

When precise data about crashes within a work zone are made available, researchers are allowed to examine how crash risks and rates change within select sections. The federal Manual on Uniform Traffic Control Devices (MUTCD) divides work zones into 4 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), the federally guided methodology for documenting crashes, 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 be in part due to inaccurate or incomplete crash reporting on the part of responding law enforcement. Garber and Zhao (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 & Zhao, 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, then, that the drivers were less likely to abide by the posted reduced speed limit if the work zone did not appear to necessitate it, which deemed the signage 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 et al., 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) since drivers are less likely to feel compelled to abide by speed limits and signage when no workers or activity is present. Moreover, this indicates the potentially counterintuitive outcome when states attempt to improve safety by reducing work zone speed. While a majority of drivers will reject low speeds they deem unreasonable, some drivers will comply, thus creating dangerous speed differentials worsening overall safety conditions.

1.2.4 Environmental Factors in Work Zone Crashes

Most work zone crashes, approximately 78%, in Minnesota occur during the day (Minnesota Crash Facts, 2013); however, this may be attributed to the higher traffic volumes during the day. A comparison of work zone types found that fatal crash risks in maintenance work zones was greatest under dark conditions, while construction and utility work zone fatal crashes were 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 of high summer temperatures (Arditi, Lee, & Polat, 2007). Conversely, work zones operating at night not only leads to poor visibility for drivers and higher incidences of fatigue and distraction (McAvoy, Schattler, & Datta, 2007), but poor visibility for workers, as well, subsequently decreasing productivity and prolonging work zone durations.

Infrastructural elements are important for safe travel in work zones, especially under reduced visibility conditions. Poor lighting conditions (i.e. limited or no street lighting) have been associated with increased fatal crash risks (Li & Bai, 2007), 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, dents and tears in the retro-reflective sheeting over time reduce visibility (McAvoy et al., 2007).

1.2.5 Road Conditions

Inclement weather and hazardous road conditions are obvious elements that increase crash risk, especially in work zones (Garber & Woo, 1990). Most crashes, however, occur during clear conditions on dry road surfaces (Dissanayake & Akepati, 2009; Weng & Meng, 2011). The typical roadway factors that are associated with increased fatal crash risk are: local roads and arterials (rather than interstate highways or freeways), asphalt paved roads, roadways that are straight and on a grade, curved and level, and curve on a grade, and typically those 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 2 lane highways because the low traffic density allows for it and there is a lower likelihood of police speed enforcement (Daniel et al., 2000; Li & Bai, 2007). Perceived road safety can actually promote riskier driving behaviors. Motorists are more likely to speed on divided roadways compared to undivided roadways, likely because they feel safer doing so. As a result, mean speeds and crash rates are higher in divided roadway work zones compared to undivided (McAvoy et al., 2011).

1.2.6 Work Zone Characteristics

Work zones, by nature, disrupt the normal flow of traffic and driving behaviors which inevitably increase crash rates compared to non-work zone roadways (Venugupal & Tarko, 2000). The same roadway, once converted into a work zone, is estimated to experience a 21.5% increase in crashes compared to its normal state (Khattak et al., 2002). There are several factors which 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). A study of New York work zones found that over 20 percent of serious injury crashes involved construction equipment, construction vehicles, and workers (Bryden, Andrew, & Fortuniewicz, 1998).

Changes to the road configuration (e.g. narrowing, diversion, reduced cross sections, lane closures, and roadway changes) force drivers to perform maneuvers they may not otherwise engage in or place passing restrictions on them by which they may not abide (Venugupal & Tarko, 2000; Bella, 2005).

Increased work zone length, at first glance, appears to increase crash rates through a mere increase in exposure to the work zone environment; however, this increase plateaus after some time. Shorter work zones create more extreme speed differentials which, in turn, increase crash rates of approaching traffic (Khattak et al., 2002). This means that longer continuous work zones have a greater net safety benefit compared to multiple smaller work zones.

Inefficient traffic control has been associated with increased crashes in work zones (Ha & Nemeth, 1995; Weng & Meng, 2011). Insufficient maintenance of equipment and technologies (e.g. remotely controlled variable signs) can result in reduced safety and efficiency within the work zone (Pigman, Agent, & Weber, 1998)

1.3 Work Zone Crash Countermeasures

There are many strategies employed to improve work zone safety and decrease crash rates. The three main areas discussed in this review are: Work Zone Barriers, Signage, and Enforcement. All three work together to promote work zone safety.

1.3.1 Work Zone Barriers

Barricades are often employed to mark construction and maintenance work zones (Daniel et al., 2000) and channeling devices or drums have been demonstrated to help drivers safely navigate through a work zone, in turn, protecting workers and mitigating crash rates (McAvoy et al., 2007). Another investigation cautions, however, that while the benefits of concrete barriers are great for intrusion prevention, crashes with portable concrete barriers can result in serious crashes (Bryden et al., 1998). The study recommends that the placement of such barriers be limited and deliberate to protect motorists from more detrimental objects and areas (e.g. bridge piers, excavations).

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. Interestingly, drivers travelled at higher speeds when the edges of the work zone was marked with barrels than when it was marked with barrels mounted with lights, suggesting that work zones with increased visibility, in effect, 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 their 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) have been demonstrated to decline minor injury crashes at twice the rate seen with safety cameras and significantly decreases serious injury and fatal crashes on low speed roadways, i.e. 30 mph (Mountain et al., 2005). Horizontal deflections (e.g. pinch points, central hatching, traffic islands, roundabouts, etc.) are also more effective crash prevention tools than safety cameras on low speed roadways, but offer less safety benefit of reducing injury crashes compared to vertical deflections (Mountain et al., 2005).

1.3.2 Work Zone Signage

Traffic control signage can be used to remind motorists of traffic laws and to alert them to upcoming changes in the roadway. Speed limit signs aim to reduce speed variance by reducing the number of speeding motorists (Wilson et al., 2006). Research conducted by Fontaine, Schrock, and Ullman (2001), however, found that work zone and speed limit signs are not successful in reducing the speeds of vehicles traveling through work zones.

An alternative to speed limit signs are Variable Speed Limit (VSL) controls which respond to varying environmental conditions (e.g. congestions, 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 ultimately 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 has indeed shown that not only can VSL improve speed compliance, but it can alleviate traffic congestion prior to a traffic bottleneck formation (Lin et al., 2004; Bertini, Boice, & Bogenberger, 2006).

1.3.3 Enforcement

Enforcement in work zones can be divided into two main categories: Law enforcement personnel and ASE. Both categories have many subcategories within to describe the multiple ways enforcement can be carried out. This summary examines the pros and cons, as well as the effectiveness, of the different types of enforcement in improving safety in work zones.

Police presence can be the most effective tool to reduce speeds in work zones (Lindly, Noorjahan, & Hill, 2002; Fontaine et al., 2001). It can be advantageous because it provides a one-on-one opportunity for law enforcement to provide immediate feedback and reasoning to motorists regarding their risky driving behavior, e.g. speeding, seatbelt use, etc. (Benekohal, Hajbabaie, Medina, Wang, & Chitturi, 2010). Law enforcement is also advantageous because it can be easily set up and removed (Fontaine et al., 2001). Police enforcement, however, is limited by time, space and staffing constraints; additionally; it puts personnel at risk (Benekohal et al., 2010). Given that work zones tend to reduce the cross section of a roadway, space restraints present a greater issue for work zones (Fontaine et al., 2001). Police and emergency vehicles are at risk of being struck on the roadside (Ashton, 2004). Increasing police vehicle conspicuity (e.g. police lights on) can reduce crashes; however, unfortunately, Medina, Benekohal, Hajbabaie, Wang, and Chitturi (2009) found that motorists were more likely to speed when they saw a police vehicle with their lights on compared to lights off. This may be because motorists perceive the officer to be occupied with another offender and will not be able to respond to them. Moreover, Medina and colleagues found that motorists are likely to speed up after passing a police vehicle, creating greater speed differentials within the work zone.

ASE provides a solution to many of the feasibility issues faced with deploying law enforcement personnel to work zones (e.g., less danger, less need for manpower). ASE is a controversial method of enforcement, however. Many see the practice as a simple means for government agencies to make large profits off of catching speed offenders at high rates and attempt to discredit or disregard literature citing its effectiveness (Glazer, 2012). While raising revenue using ASE is an inevitable outcome of its deployment, few ASE programs actually make money and some have actually been terminated due to the high costs associated with managing them (Shaheen, Rodier, & Cavanagh, 2007). Examining systems which do profit from issuing tickets reveals a positive relationship between number tickets issued (i.e. profit collected) and an increase in safety (i.e. decrease in injury crashes) (Tay, 2010). Other arguments against ASE are that they are unconstitutional. The consensus among legal scholars, however, is that ASE programs do not violate constitutional rights (Shaheen et al., 2007) and a majority of the public in Minnesota supports their use in work zones (Douma, Munnich, & Davis, 2014).

Finally, the efficacy of ASE systems is often called into question. Wilson and colleagues (2006) reviewed overt, covert, manned, unmanned, mobile, and fixed ASE systems. All studies, but one, demonstrated an absolute reduction in mean speed, percentage of speeding, and crashes (injury and fatal) following the implementation of ASE. These effects even produced a “time halo” by which the beneficial effects were observed even after the system was removed and a “distance halo” by which speed reduction persisted 2 km downstream of the cameras. Medina et al. (2009) also observed speed reduction downstream of work zones with ASE systems which were not observed with traditional law enforcement on site. More recently, Wilson, Willis, Hendrikz, Brocque, & Bellamy (2010) conducted a meta-analysis of 35 ASE studies. The results found that all studies reported a reduction in the percentage of all speeders and a reduction of top end speeders. Most studies found a 10-35% reduction in the proportion of speeders and the 28 studies that measured crash reduction found a 14-25% reduction in crashes and a 30-40% in serious or fatal crashes.

Mountain and colleagues (2005) found that speed cameras were only successful in reducing speed deviation, but not overall speed. According to Raub, Sawaya, Schofer, and Ziliaskopoulos (2001), this would not be problematic since only 5% of work zone crashes indicate *excessive speeding* as a contributing factor. Instead, the pre-crash maneuver of stopping or slowing leading to rear-end crashes is the most prevalent concern in work zones. Reducing speed deviation is the most effective way to reduce rear-end crashes.

There are many deployment methods available for ASE. Systems can be designed to issue warnings (via mail) only or they can be designed to issue warnings for first time offenses and fines thereafter. Additionally, there are autonomous systems, by which only a computer system is on site to detect and record the offense and the offenders identity (via vehicle tag or driver photo), and staffed systems, in which officers are aided by the ASE system to detect offenders, but the officer pulls over the driver and subsequently issues the ticket. Staffed systems are beneficial since they allow officers to provide immediate positive punishment which discourages future instances of speeding, provide educational opportunities for motorists, and allow for officers to exert leniency or further police action when necessary (Tay, 2009; Shaheen et al., 2007). This may allow for potential discriminatory practices on police officers’ end which would not be an issue for unmanned ASE (Tay, 2009)

Staffed ASE enforcement cannot permanently deter people from speeding--it’s a continuous cycle: drivers will speed if there is no enforcement. This would increase enforcement which in turn would discourage drivers from speeding, and in effect, reduce enforcement. This will then again encourage the drivers the speed. (Bjornskau & Elvik, 1992). Finally, fixed/autonomous

ASE systems have been demonstrated to take up less space, less personnel time and cost, and results in the greatest reduction in speed-related crashes (by up to 65%) compared to mobile ASE systems (Shaheen et al., 2007).

1.4 Work Zone Crash Summary

Driver and roadway factors can often influence safe travel and crash rates on typical roadways; however, these factors often become magnified in work zones because the margins for error are much smaller. These factors include reduced lane widths, poor visibility (e.g. night or poorly marked barriers and objects), slow or stopped traffic (e.g. advanced warning and transition zone), and merging vehicles. In general, focusing on high risk populations of drivers (e.g. young and older drivers, and male drivers) can have the most impact of reducing crashes in work zones. Moreover, influencing drivers to refrain from risky driving in work zones (e.g. speeding, impaired driving, distraction) can result in large safety gains, but the limitations of improperly placed attention by novice drivers is important to holistically understand attention and distraction issues. Changing behavior can be targeted through awareness campaigns or through enforcement. It is important to determine how traditional and automated speed enforcement not only influences speeding at enforcement sites and downstream, but also how it may influence drivers attention and distraction seeking in work zones.

CHAPTER 2: WORK ZONE SURVEY

2.1 Survey Purpose

The overall purpose of the work zone survey was to gather information from Minnesota stakeholders regarding their experiences and perceptions of work zone safety. The design of the simulation study allows for limited inclusion of work zone variables in order to maximize statistical power, so it is important to identify which elements of work zones are of most concern and should be included. Additionally, it is interesting to compare perceived work zone risks compared to crash data in Minnesota. Both perceived and actual risks are important to address not only to improve safety, but to foster better understanding across state agencies and institutions.

2.2 Survey Design

2.1.1 Survey Participants

The three agencies recruited for this survey were Minnesota Department of Transportation, Minnesota Department of Public Safety, and Minnesota State Patrol. While those with knowledge and experience related to work zones were specifically sought for this survey, it was left open to any individuals within the agencies to provide input if they desired. A total of 32 individuals responded from the three agencies; however, only 29 completed the survey (see Table 2.1).

Table 2.1 Survey Participants

Agency	***N***	**Avg. Years Exp.** *(SD)*
DPS (Office of Traffic Safety)	8	16 (*13.3*)
MnDOT (Construction & Maintenance)	16	16 (*11.1*)
State Patrol	5	23 (*5.5*)
Total	**29**	**17.4 (*11.1*)**

2.2.1 Survey Method

Survey respondents were provided an internet link which routed them to the University of Minnesota online survey tool, Qualtrics from August 19-September 2, 2014. Participants were provided a brief description of the purpose of the survey and were notified that their participation was completely voluntary. Those who wished to proceed with the survey where presented with 10 total questions. Two questions briefly assessed the division of state government and the years of experience the responded held in their field. The remaining questions assessed their perceptions of work zone safety and risk relating to drivers and environmental factors.

2.2.2 Survey Results

Survey respondents appeared to be open and candid with their responses regarding their perceptions of work zone safety and risks. An average of 85% of participants answered each question presented. Each question was analyzed independently and the general consensus was then compared to the literature and crash statistics to determine the extent of agreement.

2.2.2.1 Greatest Perceived Work Zone Threat

Respondents were asked: *What types of work zones, in your experience, present the greatest threat to safety of motorists, workers, and law enforcement?*

The overall theme of responses tended to center around factors which change the roadway for motorists in unexpected ways (see Figure 2.1). This included lane closures, maintenance work zones, and high volume traffic as the top three perceived threats to safety. Respondents reported that divided highways, multi-lane high speed zones, and ramps present the least amount of threat to safety.

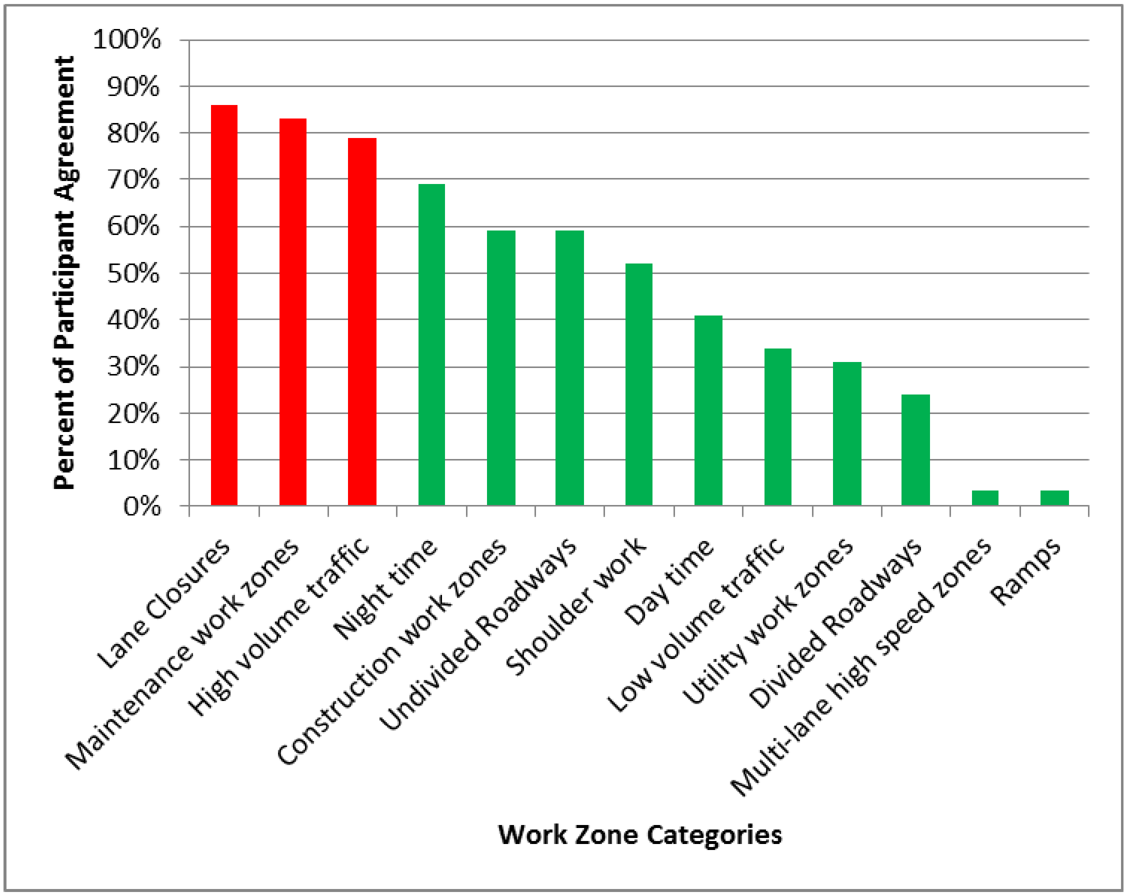

Figure 2.1. Average ranking of work zone attributes threat to safety. Threats which had 70% agreement among respondents are color-coded red and those under 70% agreement are color coded green.

The results of this question match closely with our literature review of the most hazardous work zone types or elements in relation to safety. Some discrepancies lie with respect to traffic volume. Our review found that low volume traffic allows for higher speeds and more severe crashes as a result (Li & Bai, 2009). The frequency of property damage, rear-end crashes, however, are higher in high volumes of traffic due to chain reaction events (Ulfarsson, Wang, & Kim, 2006). These property damage crashes in high traffic volume conditions are more severe compared to low volume crashes because the spacing prevents high speed differentials between vehicles. Additionally, while day time crashes make up a large majority of work zone crashes (Minnesota Crash Facts, 2013), proportionally, crashes and risk is increased in night time conditions (Arditi et al., 2007).

The question was posed in a way that may have left too much interpretation for respondents, however. The "greatest threat to safety" may have been perceived to be attributes which most frequently lead to all types of crashes or which most frequently lead to serious injury and fatal crashes. Attributes which lead to frequent property damage only crashes may be more salient, but should not be weighted equally with less frequent injury and fatal crashes. Availability bias in recalling incidents for making a judgement like this one is likely to result in interference and overrepresentation of attributes causing frequent property damage crashes (Tversky & Kahneman, 1974).

2.2.2.2 Greatest Perceived Short-term Influencers for Speed Control

Respondents were asked: *Please rank the types of speed enforcement, in your experience, which have the greatest short-term impact in getting motorists to reduce their speed in work zones?*

A large majority, 87.5%, of respondents reported that traditional law enforcement has the greatest short-term impact on speed control in work zones. All but one respondent perceived automated speed enforcement to have any pronounced short-term impacts on speed control (see Table 2.2).

Table 2.2 Ranking of greatest short-term impacts for speed control in work zones

Speed Enforcement Method	**Ranking**
Law Enforcement	1st
"Your Speed" Sign	2nd
Flagger	3rd
Signage	4th
Reduced Lane Widths	5th
Automated Speed Enforcement	6th

The results of this question do not closely match our literature review. It is not surprising, however, that ASE was ranked last since respondents were asked to rank the enforcement methods in terms of their experience. Since ASE has not been deployed in Minnesota, it is unlikely that respondents would have personally observed any safety benefit from the method or be informed about ASE's measured impact in other states (e.g. Wilson et al., 2006; Wilson et al., 2011). Reduced lane widths were rated as largely ineffective; however, motorists are less likely to speed when they feel uneasy on a roadway with reduced lane widths (Bella, 2005; Godley, Triggs, & Fildes, 2004). This effect may be difficult to personally observe, however.

2.2.2.3 Greatest Perceived Long-term Influencers for Speed Control

Respondents were asked: *Please rank the types of speed enforcement, in your experience, which have the greatest long-term impact in getting motorists to reduce their speed in work zones?*

While the confidence in traditional law enforcement's impact on long-term speed control in work zones lowered slightly, 82% of respondents still perceive it to be the superior method for effective speed enforcement. The only pronounced difference observed was that signage was reported to be less effective long-term for speed reduction compared to reduced lane widths (see Table 2.3).

Table 2.3 Ranking of greatest long-term impacts for speed control in work zones

Speed Enforcement Method	**Ranking**
Law Enforcement	1st
"Your Speed" Sign	2nd
Flagger	3rd
Reduced Lane Widths	4th
Signage	5th
Automated Speed Enforcement	6th

Comparisons of the results examining long-term perceptions to literature findings (Wilson et al. 2006; Medina et al., 2009; Wilson et al., 2010) are similar to the previous question regarding short-term efficacy. Respondents communicated that they felt that signage offers some short-term benefits, but lacks the benefits of long term speed reduction. Based on behavioral adaptation research examining behavior around signs, respondents are correct that motorists will begin to disregard signage over time. Law enforcement presence, unless always present at a work zone, offers little long term reduction in speed compliance once the enforcement is absent (even downstream within the same work zone) (Fontaine et al., 2002)

2.2.2.4 Greatest Perceived External Feature Noticed by Motorists

Respondents were asked: *Please rank the types of external features of a work zone, in your experience, that tend to be noticed most by motorists?*

Respondents reported that law enforcement has the highest tendency to capture motorists' attention in work zones. Surprisingly, they report they perceive workers to get noticed least by motorists (see Table 2.4). This perception may stem from nervousness regarding the safety and risk workers face by distracted drivers in work zones.

Table 2.4 Ranking of most noticed features in work zones

Speed Enforcement Method	**Ranking**
Law Enforcement	1st
Flagger	2nd
Barrels	3rd
Signage	4th
Workers	5th

The results of this questions are difficult to compare to the literature because few studies (e.g., Muttart et al., 2007) have been conducted which have examined eye tracking or driver attention to external features within a work zone. One aim of this investigation is to determine which of these features are most noticed by motorists. Survey respondents were asked to report which signs in particular they felt are most noticed by motorists. They reported: "Construction ahead", "Right lane closed", Advance warning signs, Electronic signs, Flashing or Flagged signs, Message boards, Arrow boards, and Black and white speed signs. One participant noted that motorists are often inundated with many signs and hypothesized that they see them all as a "blur" within a work zone.

2.2.2.5 Greatest Perceived Threat Imposing Driver Behavior

Respondents were asked: *Please rank the types of driver behaviors, in your experience, that present the greatest threat to safety of motorists, workers, and law enforcement in work zones.*

A majority of respondents reported that distraction is the greatest perceived threat to safety in work zones (see Table 2.5). This was not an overwhelming agreement for all respondents; however, 61% reported that distraction is the greatest threat of work zone safety, but 33% countered that speeding presents the greatest threat to work zone safety.

Table 2.5 Ranking of greatest threat to work zone safety

Speed Enforcement Method	Ranking
Distraction	1st
Speeding	2nd
Aggressive Driving	3rd
Impairment	4th
Fatigue	5th
Failure to Yield	6th

These results moderately match with the results of our literature review of the police reported crash data in Minnesota (Crash Facts, 2013). While distraction is not often cited as a leading contributing factor for all fatal crashes in Minnesota or in the US, it is frequently indicated as a first or second contributing factor for all types of work zone crashes. Failure to Yield, however, is cited with much greater frequency than fatigue, impairment, or aggressive driving. While aggressive driving is not commonly included in Minnesota crash reports, following too closely (which can be considered aggressive) was cited in 14% of work zone crashes (nearly as often as inattentive driving) in 2013. It should be noted, that following too closely can be compounded by driver distraction, fatigue, or impairment making the required stopping time unattainable by the driver.

2.2.2.6 Greatest Perceived Risky Driving Group in Work Zones

Respondents were asked: *Do you see a difference in behavior across different groups of people (e.g. age, gender, location, etc.)? If so, what are they?*

This question was not completed by all survey participants, as 38% of participants either did not see any differences across groups or did not know how differences might exist. Many respondents reported that young drivers overall were riskier; however, some were more specific in citing that young males, due to speeding behavior, or young females, due to distraction, specifically are riskier drivers in work zones (see Table 2.6). Several reported that all drivers, regardless of age or gender, are too distracted in work zones. Finally, older drivers were commonly listed as presenting a specific risk to work zones due to overall confusion or being overwhelmed.

Table 2.6 Rating of riskiest driving groups in work zones

Risky Driving Groups	# of Responses	Explanation
Young Drivers	4	Unsafe Speed, Distraction
Older Drivers	4	Tend to be lost or confused. Especially by flagging operations
Middle Aged Drivers	3	Distraction
Young Males	2	Risk taking behaviors
Young Females	1	Aggressive driving, speeding, distraction
Metro Drivers	1	Speeding
All Drivers	3	Distraction, illegal maneuvers

This question was left open-ended, so the qualitative data was generalized and reduced to be presented in a quantitative manner. These results match fairly closely with the literature and state crash statistics that indicate that young and older drivers are both disproportionally involved in work zone crashes (Crash Facts, 2013). Drivers aged 15-29 and those 65 years and older both accounted for 23.5% of fatal crashes in Minnesota work zones in 2014 (DPS, 2015). Perhaps the greatest take away message from these results is that it is fairly well understood that all drivers influence the safety of work zones and risky driving behaviors (e.g. distraction) are not limited to one group. This study plans to include both young and older drivers. Perhaps, the results may be able to shed some light on why older drivers seem to be confused in work zones and help to identify which features are most helpful for their safe navigation.

2.3 Conclusions

The survey provided insightful information regarding how stakeholders and those who work most closely with work zones perceive the factors that influence risk and safety. This information aided to direct the scope and focus of the simulation experiment to examine speeding and attention behavior with young and older drivers. The results also indicated how automated speed enforcement may be initially perceived if introduced in Minnesota. Respondents reported little faith in ASE's ability, in both short and long-term measures, to reduce speed in work zones. Key stakeholders will likely need to be presented with sound research findings regarding ASE in other states and countries.

CHAPTER 3: SIMULATED EXPERIMENT

3.1 Methods

The purpose of this study was to investigate the impact of different types of speed enforcement methods on driver attention in work zones. The investigation examined how existing enforcement methods currently used in Minnesota may impact driver attention and behavior as well as how the presence of ASE may influence these factors. A substantial body of work exists regarding the efficacy of ASE in work zones and other roadways; however, it is unknown how ASE impacts driver attention and distraction when compared to other forms of enforcement.

The current research examined changes in the driver's situational awareness and attention in work zones as a function of the type of enforcement (i.e., ASE, ASE + "Your Speed", and police presence) to which they are exposed. Additionally, a control condition with no speed enforcement was included as baseline measure of situation awareness and speed throughout work zones. The aim of this study was to determine if drivers respond to various types of speed enforcement differently with regard to speed limit compliance, safe following distances, crash rates, lane control, visual attention, and distraction seeking.

To investigate the effects of various speed enforcement methods in work zones, a controlled simulator study was conducted at the University of Minnesota's HumanFIRST Laboratory. We were specifically interested measuring the changes in attention throughout the upstream and downstream work zone areas as a function of speed enforcement, and observing where drivers naturally place their attention in the visual environment while navigating through a work zone.

These research questions were approached by examining driving performance measures on speed compliance throughout the work zone and following behavior from a lead vehicle. Additionally, eye-tracking was used to measure driver's observation of hazards (e.g., workers on site, machinery) and engagement in a secondary task (i.e., distraction). All measures were compared between speed enforcement type to understand any differences in behavior, attention, and distraction based on the speed enforcement present in the work zone.

3.1.1 Participants

Researchers recruited equal numbers of participants for the 18-30, 41-53, and 63-77 age groups. In total, 60 participants were included in the data collection process. Table 3.1 depicts the mean ages and group totals for each subset. Participant age group recruitment goals by age ranges and target recruitment numbers (*N*) and Task 4 participant progress by mean age and standard deviation (*M* and *SD*, respectively).

Table 3.1 Recruitment Goals and Progress

Participant Age Groups	***Recruitment Goals***		***Task 4 Progress***	
	Ages	***N***	***Ages***	***N***
Younger Drivers	18-30	20 (10 M/10 F)	*M* = 23.8, *SD* = 3.2	20 (10 M/10 F)
Middle-Aged Drivers	41-53	20 (10 M/10 F)	*M* = 45.4, *SD* = 3.5	20 (10 M/10 F)
Older Drivers	63-77	20 (10 M/10 F)	*M* = 67.9, *SD* = 3.7	20 (11 M/9 F)

Participants were screened through recruitment using the HumanFIRST Pre-Screening Questionnaire to ensure they had no cognitive or physical constraints that might limit their performance (see Appendix A). Participants had at least two years of licensed driving experience, a minimum of 4,000 miles driven each year, normal or corrected-to-normal vision (20/40 or better, normal color vision), normal hearing function, and normal cognitive function. Visual correction was allowed, but only included those who wore contacts, not glasses, due to constraints of the eye tracking glasses. Participants were excluded from the study if they had history of hearing loss that inhibits every day conversation, health problems that effect driving, inner ear or balance problems, history of motion sickness, lingering effects of stroke, tumor, head trauma, or infection, and history of migraines or epileptic seizures.

3.1.2 Simulator

The experiment was conducted in the HumanFIRST Portable Driving Environment Simulator (see Figure 3.1) that was manufactured by Realtime Technologies Incorporated. The driving environment simulator consisted of a driver's seat, vehicle controls (acceleration, steering, and brake), and vehicle gauges on a custom-fabricated chassis. Three 32-inch high-definition displays provided an 88.2 and 18.4 degree total forward field of view horizontally and vertically, respectfully. Rear-view mirror displays were inset on the forward display. The dashboard was presented on an LCD panel in a normal dashboard location. An eight-inch touch screen LCD display was located to the right of the driver and approximately 25 degrees down from the participant's horizontal line of sight (i.e., center stack HVAC area) and was used to display the secondary task. The position was selected because it required a head movement from participants to focus on the screen and engage in the secondary task thus emulating the physical and perceptual activities of normally occurring distraction tasks.

Figure 3.1. HumanFIRST portable driving environment simulator set up.

3.1.3 Work Zone Simulation Roadway

The simulated world consisted of a work zone on a Minnesota highway, namely, US-169 between Jordan and Belle Plaine, MN with a speed limit of 65 mph under normal conditions. The simulation reflected a rural, relatively uncluttered environment that bears the characteristics of realistic roadways such as straight segments, wooded areas, and shoulders. The roadway segment in Figure 3.2 was selected for use in this study because it matches the criterion of a roadway of interest for this study. The length of the roadway allowed for acceptable route duration (~10 minutes duration for ~9 miles of roadway) with few curves to minimize the effect of simulation sickness. It featured a divided 4-lane roadway which was simulated to include shoulder work and additional traffic in the left lane. Participants were able to drive in both directions on each roadway thus creating two driving routes for the study.

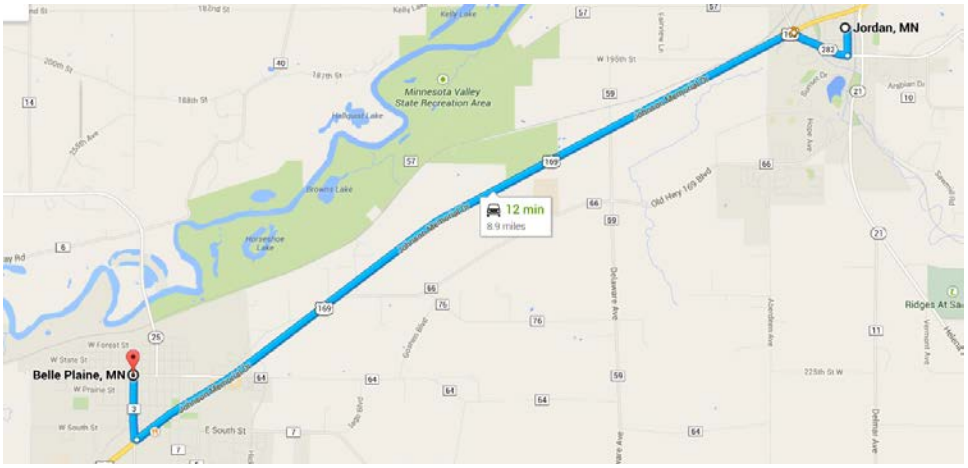

Figure 3.2. Map view of US-169 roadway between Jordan, MN and Belle Plaine, MN

The simulated work zone was structured based on MN MUTCD standards and TAP committee guidance. The test road included a total of 9.2 miles (14746 m) of roadway in each direction (see Figure 3.3). Participants first drove an introductory section of roadway for 2 miles (3219 m). Next, they entered the Transition/Warning section of the work zone which occurred for 1.2 miles (1871 m). This area presented MnDOT's most up-to-date work zone signage (e.g. work zone placard, $300 fine, etc.) and was spaced according to MN MUTCD standards. At the conclusion of the Transition/Warning section, barrels began to close off the right shoulder over a 195 ft. section of roadway. The following section was the Activity Area which featured a shoulder closure for 5 miles (8047 m) and included drums which encroached into the lane by 1 ft., reducing the participants' lane width to 11 ft. The shoulder work featured 3 work crews including work zone vehicles (see Figure 3.4) and workers on foot. Participants were presented with an End Road Work sign at the end of the 5 mile stretch and finished their route with a 1 mile conclusion drive.

Figure 3.3. Work zone vehicles within a work zone crew. Pick-up truck (left) and single backhoe (right)

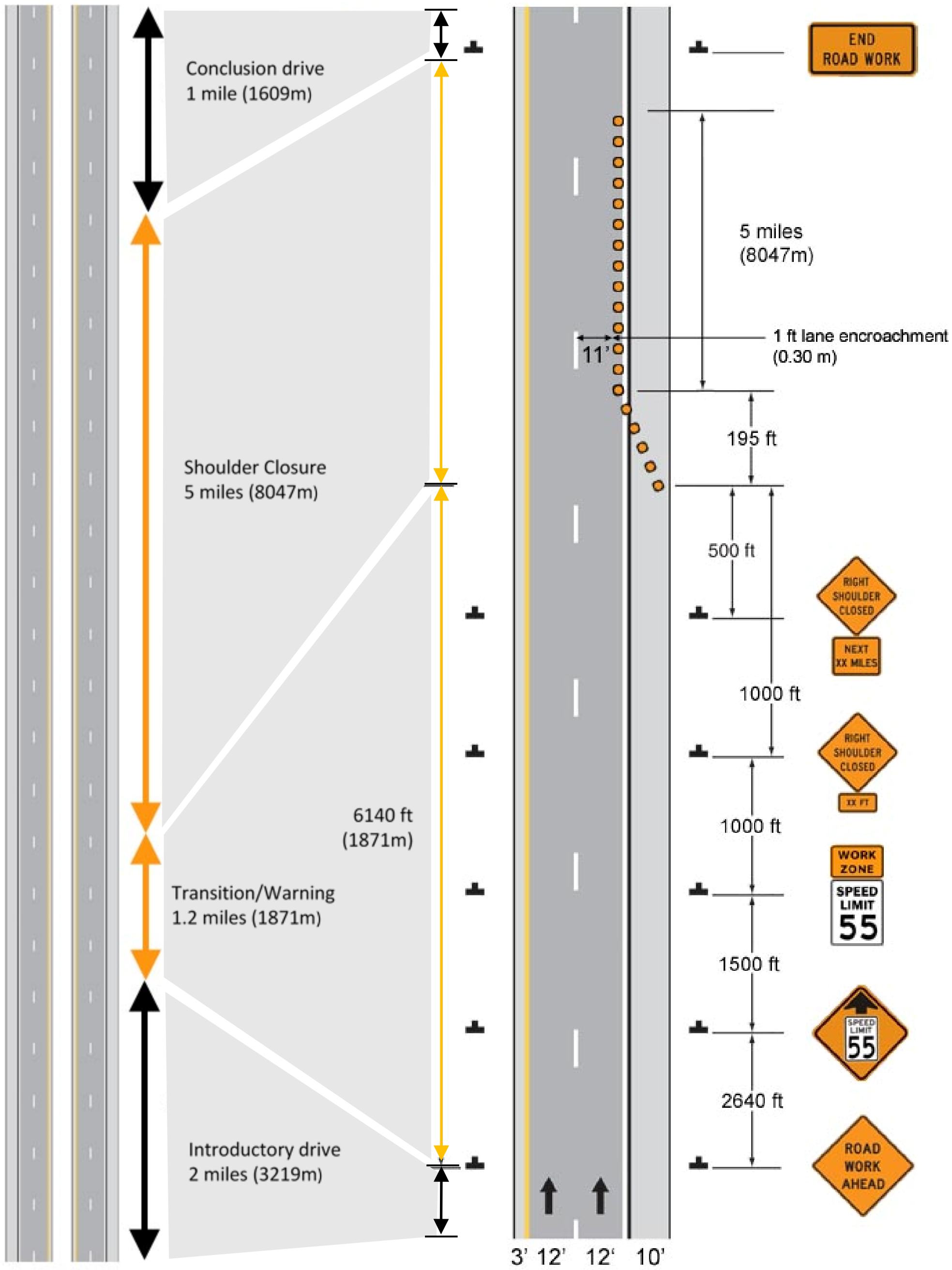

Figure 3.4. Work zone diagram of the simulated shoulder work on US-169 roadway between Jordan, MN and Belle Plaine, MN. The overall diagram (left) demonstrates the main segments of the route and detailed diagram (right) demonstrates the signage spacing within the work zone.

3.1.4 Speed Enforcement Conditions

Speed enforcement was presented to participants within the Activity area (5 miles) of the work zone. Participants either experienced no speed enforcement (Control), police presence (State Trooper vehicle with lights off, Figure 3.4), ASE, or dynamic speed display sign (DSDS, see

Figure 3.5) combined with ASE. Signage notified participants, upon entering the Transition/Warning Area, that they are entering an ASE work zone; however, the signage did not indicate if the ASE featured DSDS or not. ASE work zones featured a van marked with automated speed enforcement capabilities and a large post with camera facing downstream.

Figure 3.5. Simulated police presence, State Patrol car.

Figure 3.6. Simulated automated speed enforcement van (left) and ASE van with Dynamic Speed Display Sign (DSDS, right).

3.1.5 Eye Tracking Glasses

Visual attention was captured with the Tobii Glasses, a wearable eye tracking unit that can be used in multiple research settings (see Figure 3.6). The system comes with analysis software to assess gaze locations, glance durations. This equipment was used to capture visual attention within the simulated work zone and within the simulator apparatus to determine allocation of attention to different areas of interest (e.g. workers on site, signs, speedometer, center stack screen, etc.).

Figure 3.7. Tobii 2 Eye Tracking Glasses

The data output from the Tobii eye tracking glasses did not allow for any automated coding to determine when participants fixated on certain Areas of Interest (AOIs). Instead, the eye tracker hardware and software recorded a video of the view of the participant throughout the experiment and superimposed a red circle onto the video image to indicate their point of fixation or eye movements (see Figure 3.8). Each video was reviewed at 25% speed by two separate coders. The coders manually recorded, through key strokes, when the participant moved their gaze onto an AOI (e.g., speedometer) and then recorded when their gaze moved away from the AOI. The manual coding allowed researchers to determine the average frequency and duration at which participants tended to look at AOIs within the work zone and simulated vehicle.

Figure 3.8. Tobii 2 Eye Tracking Glasses video recording of participant's gaze on ASE van.

3.1.6 <u>Car-Following Scenarios</u>

The car-following scenarios were designed to be analogous to the real-world driving task of maintaining a constant distance (or time headway) behind a lead vehicle in moderate-density traffic conditions within a work zone. Successful performance was dependent on the participant’s continuous engagement in the driving task. Each drive featured a road segment in which the participant followed a lead vehicle and was then passed by a vehicle that pulled directly in front of the participant. This was accompanied by an instructional warning for the participant to keep a close, but safe, following distance to prevent additional vehicles from passing. A new vehicle then took position behind the participant.

The lead vehicle drove at a constant speed of approximately 55 mph for 1 minute, and then the vehicle’s speed changed using a sine function. The mean speed was 55 mph, and the amplitude increased and decreased with the sine function. The minimum speed reached by the lead vehicle was approximately 40 mph and the maximum was 70 mph within a period of approximately 60 seconds. Participants were instructed to follow the lead vehicle as closely and safely as possible, and not exceed the posted speed limit of 55mph. A tracking vehicle lagged behind the lead vehicle in the left lane and matched the lead vehicle’s sine wave speed profile (see Figure 3.9). This vehicle’s movements were designed to encourage the participant to continue to match the lead vehicle’s speed after it began to exceed 55 mph.

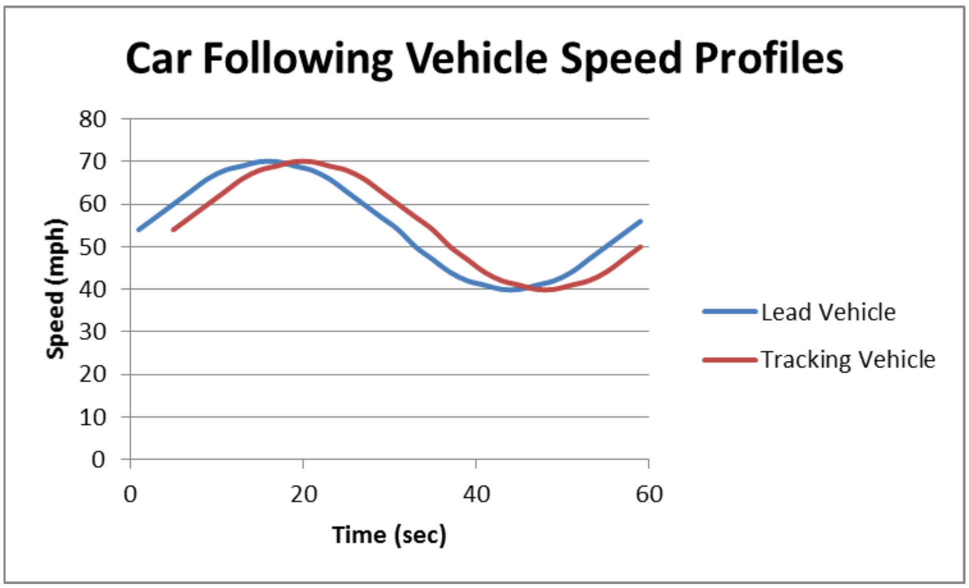

Figure 3.9. Car following sine wave travel speed example for Lead Vehicle and Tracking Vehicle.

3.1.7 Speed Monitoring

The speed limit was reduced from 65 mph to 55 mph in the work zone. Participants were instructed that they should travel as closely to 55 mph as possible (without passing the lead vehicle) throughout the work zones in order to complete the simulations in the appropriate amount of time. Participants were instructed that if they are successful in completing all work zone routes in the allotted amount of time, they would receive a $10 gift card in the mail once all participants were run and the data was analyzed. They were also informed, however, that if the simulation detected speeding, defined as any cross-over, above 55 mph, within the ranges of the police car, ASE+DSDS, or ASE areas, they would be docked $2 pay, up to $10 of their gift card, for each infraction. This explanation included participant deception in that all participants actually received the full $10 gift card at the conclusion of the study, regardless of speeding infractions, with an explanation of the reason for deception. This arrangement was designed to simulate drivers' real world desire to complete driving routes in a timely fashion while avoiding financial punishment for speeding.

3.1.8 Secondary Task

The study employed a secondary task performed on an in-vehicle screen that included visual search, target matching, working memory, and response input. As shown in Figure 3.10, the task was comprised of a matrix of arrows around a central "target" arrow. The task became active when the target arrow was pressed. The button press initiated the rotation of each arrow in a different direction and at different speeds for a random time interval (up to 1.5 seconds). The participant's task was to press a button on the keypad corresponding to the number of peripheral arrows in the matrix that matched the orientation of the central target arrow. The task was 'self-paced' in that participants could choose how many of the tasks they wished to complete in a pre-defined period of time. In this manner, this secondary task represented the basic components of distraction tasks that are typical of many existing in-vehicle self-paced secondary tasks. That is, driver decides when to start the engagement in the task and also when to respond.

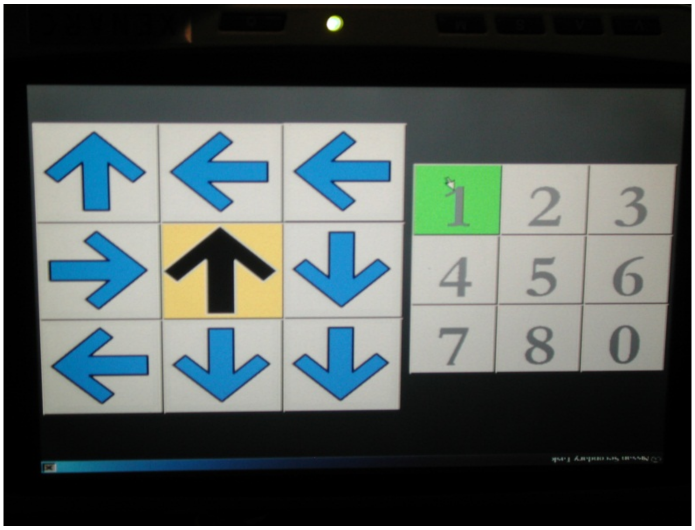

Figure 3.10. Self-paced in-vehicle secondary task that served as distraction for drivers.

3.1.9 Procedure

Participants from the three pre-designated age groups (18-30, 41-55, 62-77) came to the HumanFIRST laboratory to take part in the controlled simulator study. During the 1.5 hour study, they completed four driving routes in a simulated work zone on a realistic rural divided Minnesota roadway, Hwy 169 between Jordan, MN and Belle Plaine, MN. The experimental protocol included informed consent, vision screening, a pre-driving questionnaire, one practice drive, and four experimental driving routes with questionnaires between each drive. There was a $25 cash incentive for participation along with an additional $10 gift card that was mailed to participants after the completion of the study.

Upon entering the lab, participants were greeted by a research assistant (RA) who completed a few preliminary tasks prior to beginning the experimental portion. First, the RA asked participants for a valid driver's license and gave a verbal summary of the consent form along with a paper copy for the participant to sign. Next, the online Driving History Questionnaire (Appendix B) was then administered to capture information about years of driving experience and typical driving routes. Finally, participants had their visual acuity and color vision screened to be sure they were suitable for participation. The study required that all participants meet the minimum Minnesota regulation for driving (20/40 vision corrected or uncorrected).

After clearance from the vision screening, the RA provided participants with an overview of what they could expect during the experiment. Participants were told that they would be driving in a simulated work zone while interacting with different types of speed enforcement. Photographs of the three speed enforcement conditions were presented to participants so that they were able to familiarize themselves with what to expect in the simulation.

The RA explained that the primary task during the experiment was to follow a lead vehicle at a close, but safe distance throughout the entire route, meanwhile adhering to the speed limit of the work zone (i.e., 55 mph). Participants were told that a portion of their incentive would be deducted if they exceeded the speed limit during the experiment. The exact payment scheme was explained as follows: "Once we've analyzed the data and see that you are successful in completing all driving routes within the allotted amount of time, without exceeding the speed limit, you will receive a $10 gift card in the mail. If the simulation detected speeding within the ranges of speed enforcement, you will be docked $2 pay for each infraction, up to the total amount of the gift card." The method of deducting pay from the $10 gift card was used in order to put an extrinsic motivator on participants to both avoid speeding and avoid driving too slow. A $10 gift card was mailed to all participants, in addition to the $25 cash incentive they received the day of the study, regardless of driving performance.

Once the payment structure and the vehicle following task was explained, participants were introduced to the secondary task. The goal of the secondary task was to give participants another activity to pursue while driving. This is a common practice in driving simulation research, and the specific arrow task that researchers chose for the current study is a well-established method in driving research. Participants were told that they would see a screen to the right of the steering wheel, which contained a matrix of arrows and a number keypad. They were to press the center arrow in the matrix at which point all arrows would spin for a random amount of time (~ 2 seconds). Once the arrows stop, the participant was to count the number of arrows that match the orientation of the center arrow and press the number on the keypad that corresponds. The participants were given paper examples of the interface in order to practice the secondary task. They were also able to practice the on-screen version of the secondary task when they entered the simulator prior to beginning the experiment. Questions were encouraged during the explanation period so that all participants were comfortable upon entering the simulator.

All questions were answered prior to allowing the participant to begin the practice drive in the simulator. The experiment used eye-tracking to monitor the gaze and eye fixation of the drivers during their routes. Participants were fitted with the Tobii 2 Pro eye-tracking glasses so that they could get accustomed to the feel of the glasses during the practice drive, prior to the experimental drives. The RA pointed out all physical functions of the simulator, including how to adjust the seat and steering wheel, and where to look for the review and side view mirrors. Once participants were comfortable in the simulator, they began to practice 4-5 secondary tasks on the in-vehicle display. Next, the RA launched the practice drive and explained that participants were to stay in the right lane and follow the vehicle in front of them for the whole practice drive. If there were no further questions, the participants were instructed to put the car in "Drive" and proceed straight ahead in the right lane. Participants were also instructed to interact with the arrow tasks during the practice drive.

For the practice drive, the goal was for participants to acclimate to the simulator, such as braking and accelerating, and to have the opportunity to practice the car following task. During the practice drive, along with all consecutive experiment drives, the speed of the lead vehicle followed a sinusoidal wave formation, which required participants to adjust their speed respective of the lead vehicle's speed. The practice drive lasted approximately 5 minutes and participants encountered a sign at the end of the drive to indicate that the route was finished. Participants were encouraged to ask questions after they completed the practice drive, but were asked not to interact with the RA during any of the driving routes.

The order of the four experimental drives was counterbalanced in order to eliminate order or learning effects. Each participant from within its respective age group was randomly assigned to an order of work zone speed enforced routes (see Table 3.2).

Table 3.2. An example of the counterbalance randomization.

Participant Groups	Work Zone Route 1	Work Zone Route 2	Work Zone Route 3	Work Zone Route 4
Young Drivers	Control	ASE	Police	ASE+DSDS
Middle-aged Drivers	Police	Control	ASE	ASE+DSDS
Older Drivers	ASE+DSDS	Police	Control	ASE

Participants remained seated in the simulator for the duration of the experiment. All four experimental drives were administered consecutively, using a counterbalance spreadsheet to determine the order of the drives. The eye-tracking glasses were calibrated between each drive in order to capture the highest accuracy in fixation measures. Prior to starting the first drive, participants were reminded that they would complete four driving routes and were told that they would have two surveys administered between each drive. The Rating Scale Mental Effort (RSME) (Appendix C) was administered to capture the subjective mental workload of participants. A Situational Awareness questionnaire (Appendix D) was designed specifically for this study to investigate any differences in situational awareness between speed enforcement conditions and age groups. Participants were reminded of the payment scheme for the speed infractions and were encouraged to ask questions prior to starting the experimental drives. Upon starting each simulation, drivers were to follow the vehicle in front of them, as instructed by the RA. After about one minute, drivers were passed by another vehicle, which was to become the lead vehicle for the remainder of the drive. At the point where the lead vehicle overtook the driver, the RA stated: "Note that you have been overtaken by a car. This car is now the leader. Follow this car at all times. Please maintain close, but safe, following distance to prevent additional vehicles from passing." Upon completing each drive, the surveys were administered and the eye-tracking glasses were calibrated. This procedure was repeated for each of the four experimental drives.

CHAPTER 4: RESULTS

4.1 Dependent Variables

Dependent variables for the routes were grouped into the constructs of Driving Performance, Distraction, and Attention to better understand the extent to which the presence of speed enforcement affects safety improvements or behavioral adaptations. A summary of the dependent variables are presented in Table 4.1.

Table 4.1. Car Following dependent variables for each measurement construct.

Measure	Description
Driving Performance	
Speeding Frequency	Count of instances in which participant exceeded 55 mph.
Coherence	Assess the correlation between lead and following vehicle speed profiles. Crest and trough components of the sine wave were assessed separately.
Modulus	Measure of the magnitude of participants' over-shot and under-shot speed compared to lead vehicle. Crest and trough components of the sine wave were assessed separately.
Median Time-Headway	50^{th} percentile time-headway between lead and participant vehicle.
85^{th} Percentile Time-Headway	The 85^{th} percentile ranking of Time-Headway scores between the lead and participant vehicle.
Distraction	
Productivity	Measure of the number of self-paced distraction tasks attempted.
Eyes Off Road: Speedometer	Frequency and duration of eye glances off road to speedometer.
Eyes Off Road: Center Stack	Frequency and duration of eye glances off road to center stack touchscreen.
Attention	
Hazard Detection	Fixation on hazards within the work zone (e.g. workers, trucks, signs, etc.)
RSME	Rating Scale Mental Effort is a standardized Likert scale method to quickly assess mental workload (Appendix C).
Situational Awareness	Recall of hazards within the work zone

4.1.1 Design and Analysis

The analyses of the driving performance, distraction and attention measures were carried out within 3 x 4 mixed model ANOVA with age group (Young Drivers, Middle-aged Drivers, and Older Drivers) as a between-subjects measure and speed enforcement type (control, ASE, ASE+DSDS, and police presence) as a within-subjects measure. Driving performance and eye tracking results were analyzed and are described by work zone segment: Transition zone, Upstream, Enforcement, and Downstream. Manual eye tracking data recorded by each coder was compared for interrater reliability. Any data set which did not receive Subjective measures of workload and situational awareness were analyzed using survey tools and descriptive results are explained.

Eye tracking was coded using the Tobii Glasses Analysis Software. The top 50% of videos recorded, as measured by tracker quality, for each age group were used in this analysis (i.e. 10 for each age group, 30 overall). Overall, tracker quality decreased with age. For each participant, fixations on the speedometer and the center console (which housed the secondary task) were manual coded by the observers. On videos that did not have high tracker quality (particularly older drivers), fixations were more difficult to identify, and therefore may have resulted in slightly less accurate data. Both frequency of fixations and total length of durations on the two areas for each zone in the drive. Two independent observers manually coded each trial. Inter-rated reliability was relatively high, with r = .75 for speedometer and r = .94 for center console in frequency counts, and r = .76 and r = .88 for total duration. For both frequency and total duration, the results of the two coders were averaged before analysis.

4.2 Transition Zone

The Transition/Warning zone occurred for 1.2 miles (1871 m). This area presented MnDOT's most up-to-date work zone signage (e.g. work zone placard, $300 fine, etc.) and was spaced according to MN MUTCD standards. At the conclusion of the Transition/Warning section, barrels began to close off the right shoulder over a 195 ft section of roadway.

4.2.1 Driving Performance

4.2.1.1 Speeding "Ticket" Frequency

Count data was collected to determine the number of instances in which participants exceeded the 55 mph speed limit. Middle-aged drivers were least likely to speed and Older drivers were most likely to speed in this zone, see Figure 4.1. The ANOVA analysis using the multivariate criterion of Huynh-Feldt revealed no significant main effect of enforcement type ($p = 0.37$) for number of "tickets", but indicated a significant main effect of age group ($F(2, 57) = 3.70$, $p < .05$, $\eta_p^2 = .11$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, revealed that Middle-aged drivers sped significantly less often ($M = 0.64$, $SD = 0.49$) than Older drivers ($M = 1.06$, $SD = 0.60$) in the Transition zone ($p < .05$). Differences between Young and Middle-aged drivers and between Young and Older drivers was not statistically significant, ($p = 0.07$) and ($p = 0.32$), respectively.

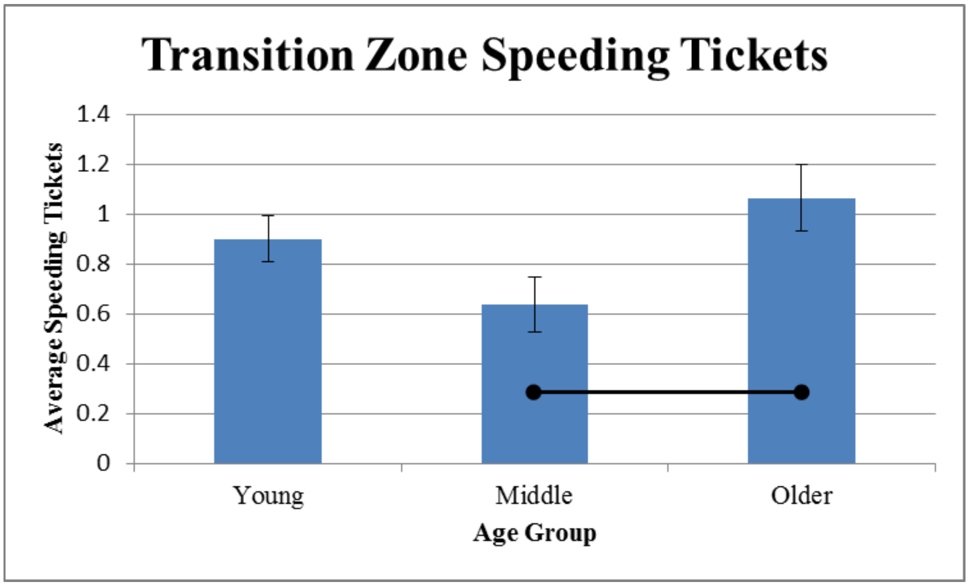

Figure 4.1. Average number of times participants in each age group (across all enforcement conditions) exceeded the 55 mph speed limit in the Transition zone. The connected dots indicate differences that are significant. *All error bars display standard error.

4.2.1.2 Coherence

Coherence was measured to assess the correlation between lead and following vehicle speed profiles. Crest and trough components of the sine wave were assessed separately to parse out car following that could have included speeding. This allows for a measure of how well participants are able to car follow when the lead vehicle traveled at 55 mph and under. Since participants were discouraged from speeding, any car following above 55 mph is not considered good performance and is not examined here. Values close to 1 indicate near perfect car following and values near 0 indicate very poor car following.

Younger drivers were the most successful at matching their speed to the lead vehicle's speed and Older drivers were the least successful, see Figure 4.2. The ANOVA analysis using the multivariate criterion of Huynh-Feldt revealed no significant main effect of enforcement type ($p = 0.41$) for ability to engage in car-following, but indicated a significant main effect of age group ($F(2, 57) = 7.71$, $p < .01$, $\eta_p^2 = .21$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, revealed that Young drivers were significantly better at matching speeds with the lead vehicle ($M = 0.90$, $SD = 0.09$) than Older drivers ($M = 0.67$, $SD = 0.27$) in the Transition zone ($p < .01$). Differences between Young and Middle-aged drivers ($M = 0.79$, $SD = 0.04$) and between Middle-aged and Older drivers was not statistically significant, ($p = 0.23$) and ($p = 0.12$), respectively.

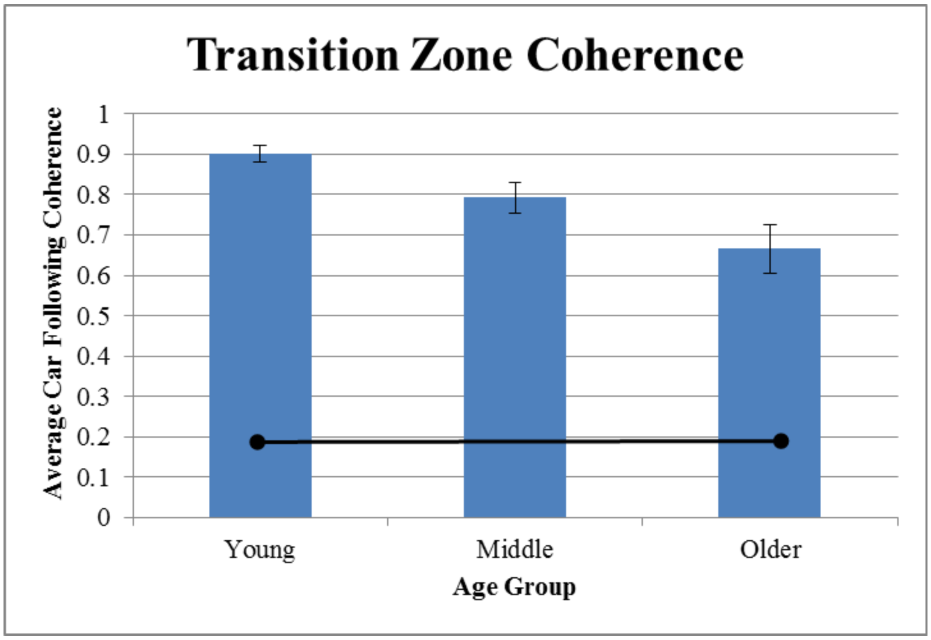

Figure 4.2. Average coherence to speed changes by lead vehicle in each age group (across all enforcement conditions) in the Transition zone. The connected dots indicate differences that are significant.

4.2.1.3 Modulus

Modulus (Mod) is a measure representing the amplification of the participant speed signal with respect to the lead vehicle. It can be interpreted as the magnitude of overshoot (Mod > 1) or undershoot (Mod < 1) in the participant speed signal. Values closest to 1 indicate the participant was able to closely match their minimum and maximum speeds according to the lead vehicle. Since the maximum speeds of the lead vehicle exceeded the speed limit and matching the speed above 55 was not considered safe driving behavior, Mod was measured for the minimum speeds reached on deceleration portions only. There were some significant outliers in the data set not typical of other dependent variable data in this study. The extreme outliers were replaced with the 95th percentile value for the entire participant group. This allowed for individual variability for more extreme values without violating normality assumptions.

Young and Middle-aged drivers responded appropriately in braking to the lead vehicle (M = 1.10, SD = 0.19; M = 1.11, SD = 0.22, respectively); however, Older drivers overreacted to the lead vehicle braking patterns (M = 1.41, SD = 1.01), see Figure 4.3. The ANOVA analysis using the multivariate criterion of Huynh-Feldt revealed no significant main effect of enforcement type (p = 0.14) for ability to match minimum speed braking patterns, but indicated a significant main effect of Age Group ($F(2, 55) = 4.95$, $p < .05$, $\eta_p^2 = .15$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, verified that Young and Middle-aged drivers were significantly better at matching minimum speeds with the lead vehicle compared to Older drivers in the Transition zone ($p < .01$ and $p < .01$, respectively). Differences between Young and Middle-aged drivers was not statistically significant, (p = 0.94).

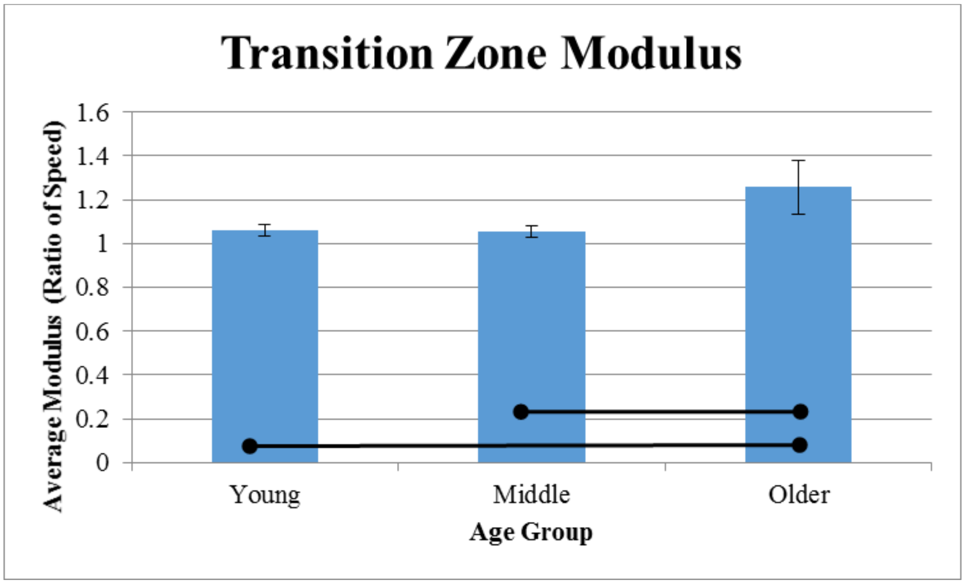

Figure 4.3. Average modulus, or ratio, of participant matching minimum speeds of lead vehicle in each age group (across all enforcement conditions) in the Transition zone. The connected dots indicate differences that are significant.

4.2.1.4 Median Time Headway (MTH)

Median time headway was measured to assess the safe traveling distance participants engaged in a majority of the time. Values one second or less are deemed to be unsafe following distances. The Transition zone is highlighted because it is the area where rear-end crashes occur most frequently.

As expected, Younger drivers' median following distance was the closest of the group and Older drivers followed behind with the largest gap, see Figure 4.4. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type (p = 0.62) for car-following for Median Time Headway, but indicated a significant main effect of Age Group ($F(2, 57) = 5.80$, $p < .01$, $\eta_p^2 = .17$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, revealed that Young drivers followed significantly closer to the lead vehicle (M = 1.77, SD = 0.49) than Older drivers (M = 4.06, SD = 0.58) in the Transition zone ($p < .01$). Differences between Young and Middle-aged drivers (M = 2.63, SD = 0.34) and between Middle-aged and Older drivers was not statistically significant, (p = 0.64) and (p = 0.12), respectively.

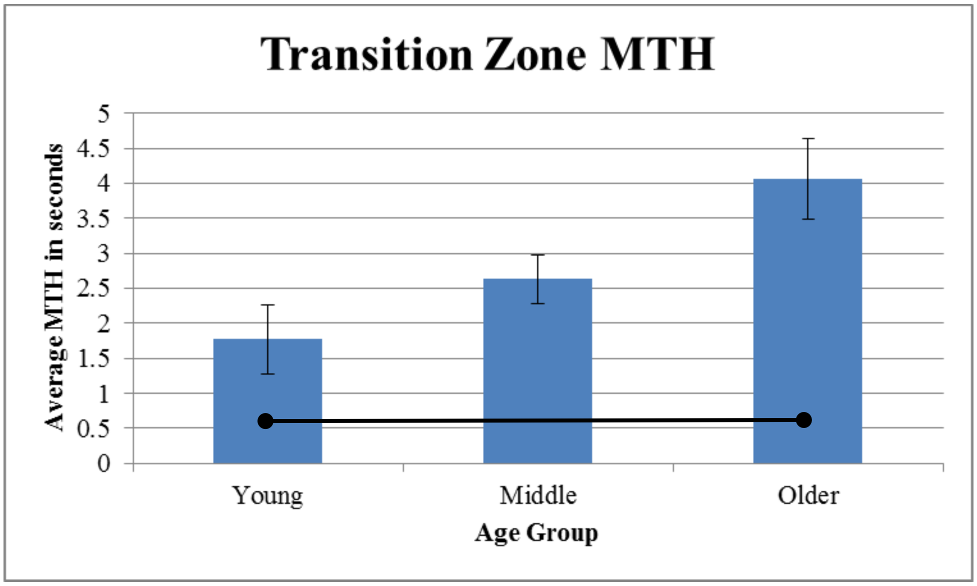

Figure 4.4. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in each age group (across all enforcement conditions) in the Transition zone. The connected dots indicate differences that are significant.

4.2.1.5 85th Percentile Time Headway (85th MTH)

The 85th percentile time headway was measured to assess the nearest (with a margin for error) participants followed behind the lead vehicle. Because rear-end collisions were unlikely in the study, the 85thMTH is a surrogate for crash risk and "close calls". Values one second or less are deemed to be unsafe following distances. The Transition area is highlighted because it is the area where rear-end crashes occur most frequently.

Similar to MTH, Younger drivers' closest following distance was the smallest of the group and Older drivers followed behind with the largest gap, see Figure 4.5. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type ($p = 0.39$) for car-following for 85th Percentile Time Headway, but indicated a significant main effect of Age Group ($F(2, 57) = 5.0$, $p < .05$, $\eta_p^2 = .15$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, revealed that Young drivers' 85th Percentile Time Headway was significantly closer to the lead vehicle (M = 1.3, SD = 0.43) than Older drivers (M = 3.1, SD = 0.54) in the Transition zone ($p < .05$). Differences between Young and Middle-aged drivers (M = 1.74, SD = 0.26) and between Middle-aged and Older drivers was not statistically significant, ($p = 1.0$) and ($p = 0.09$), respectively.

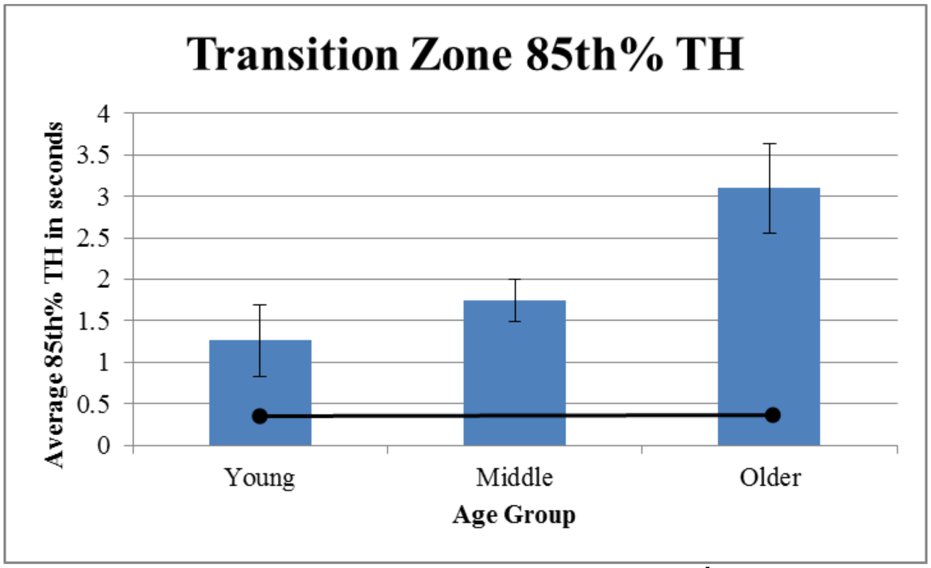

Figure 4.5. Average closest following distance, measured as 85th Percentile Time Headway (85th%TH), to lead vehicle in each age group (across all enforcement conditions) in the Transition zone. The connected dots indicate differences that are significant.

4.2.2 Distraction Engagement

Distraction engagement was measured as the number of self-paced secondary attempted by the participant during each zone of the simulated drive. This measure accounts only for the times that the secondary task was initiated, not accounting for correct answers or delay in response. There was a significant effect of age found for the Transition zone ($F(2,59) = 1.02$, $p < .005$, $\eta_p^2 = .20$). Pairwise comparisons using the Bonferroni correction to control for type I error showed a significant difference between younger and older drivers and between middle age and older drivers. Figure 4.6 shows the differences in means for the age groups.

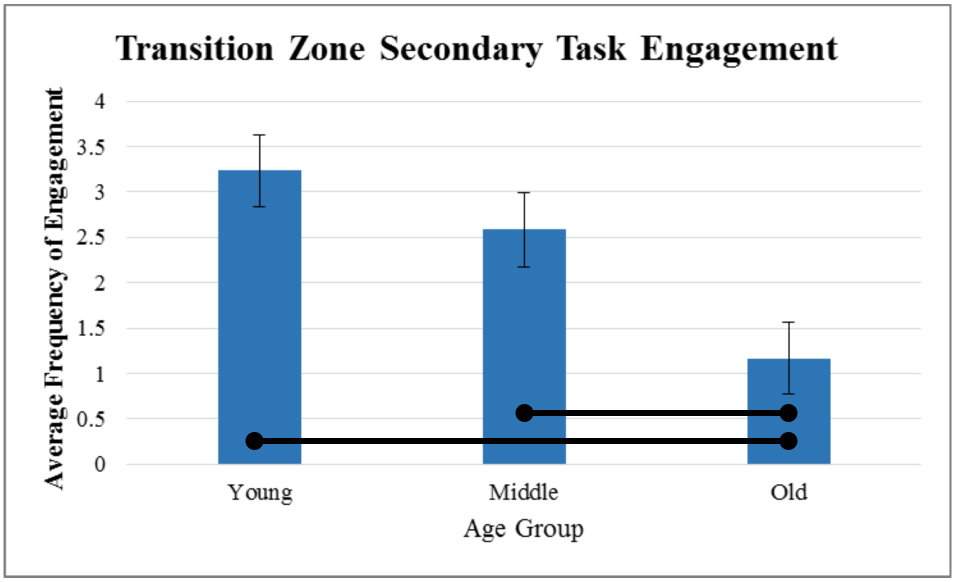

Figure 4.6. Average number of times participants in each age group (across all enforcement conditions) engaged the secondary task in the Transition zone. The connected dots indicate differences that are significant differences between young and old, and middle and old age groups.

4.3 Upstream Activity Zone

Following the Transition zone was the activity area which featured a shoulder closure for 5 miles (8047 m) and included barrels which encroached into the lane by 1 ft, reducing the participants' lane width to 11 ft. The activity area was divided into four sections, each approximately 2012 m. The first was the Upstream Activity zone which was "upstream" from speed enforcement. This section contained no work crews or enforcement.

4.3.1 <u>Driving Performance</u>

4.3.1.1 Speeding "Ticket" Frequency

Similar to the Transition zone, Middle-aged drivers sped the least number of times ($M = 0.44$, $SD = 0.09$) and Older drivers sped the most ($M = 0.99$, $SD = 0.15$) in the Upstream Activity zone, see Figure 4.7. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type ($p = 0.99$) for number of "tickets", but indicated a significant main effect of age group ($F(2, 57) = 3.18$, $p < .05$, $\eta_p^2 = .10$). Follow up comparisons, using Bonferroni control, revealed that Middle-aged drivers sped significantly less often than Older drivers in the Upstream Activity zone ($p < .05$). Differences between Young ($M = 0.70$, $SD = 0.20$) and Middle-aged drivers and between Young and Older drivers was not statistically significant, ($p = 0.72$) and ($p = 0.65$), respectively.

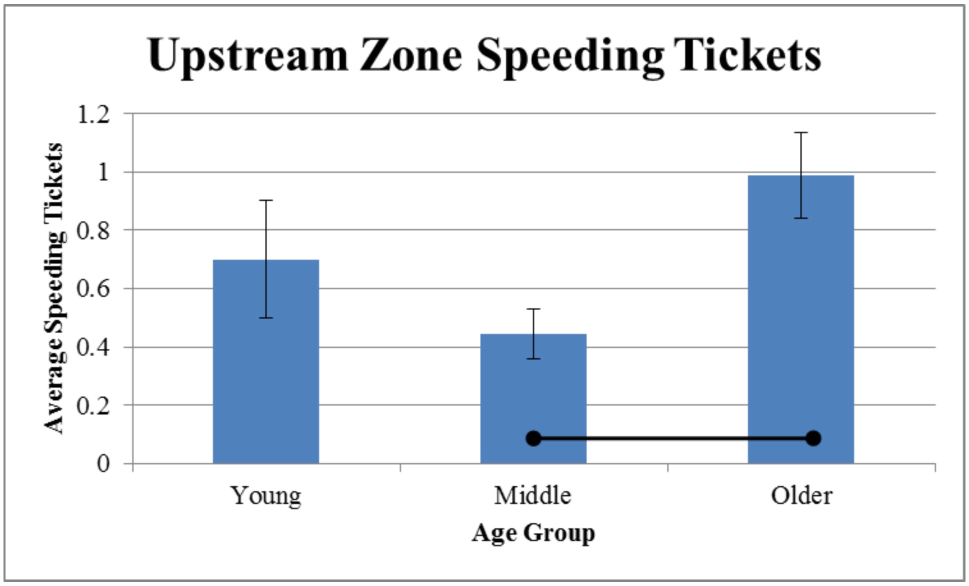

Figure 4.7. Average number of times participants in each age group (across all enforcement conditions) exceeded the 55 mph speed limit in the Upstream Activity zone. The connected dots indicate differences that are significant.

4.3.1.2 Coherence

Younger drivers were the better at matching their speed to the lead vehicle's speed compared to Middle-aged and Older Drivers, see Figure 4.8; however, all age groups began experiencing difficulty matching the lead vehicle's speed once they entered the Activity zone. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type ($p = 0.41$) for ability to engage in car-following and a near significant main effect of age group ($p = 0.054$).

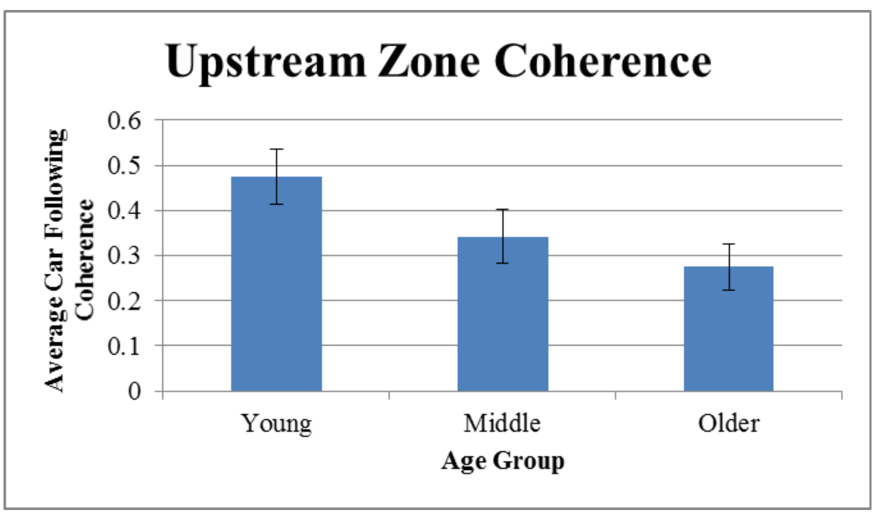

Figure 4.8. Average coherence to speed changes by lead vehicle in each age group (across all enforcement conditions) in the Upstream Activity zone. Differences are not significant.

4.3.2 Distraction Engagement

There was a significant effect of age on spin number ($F(2,59) = 8.46$, $p < .001$, $\eta_p^2 = .22$) for the Upstream Activity zone. Pairwise comparisons using the Bonferroni method to control for type I error showed a significant difference only between Young and Older drivers ($p < .05$). As shown in Figure 4.9, Young drivers engaged in the task more than Older drivers. Middle-aged drivers were not significantly different from Older drivers or Young drivers.

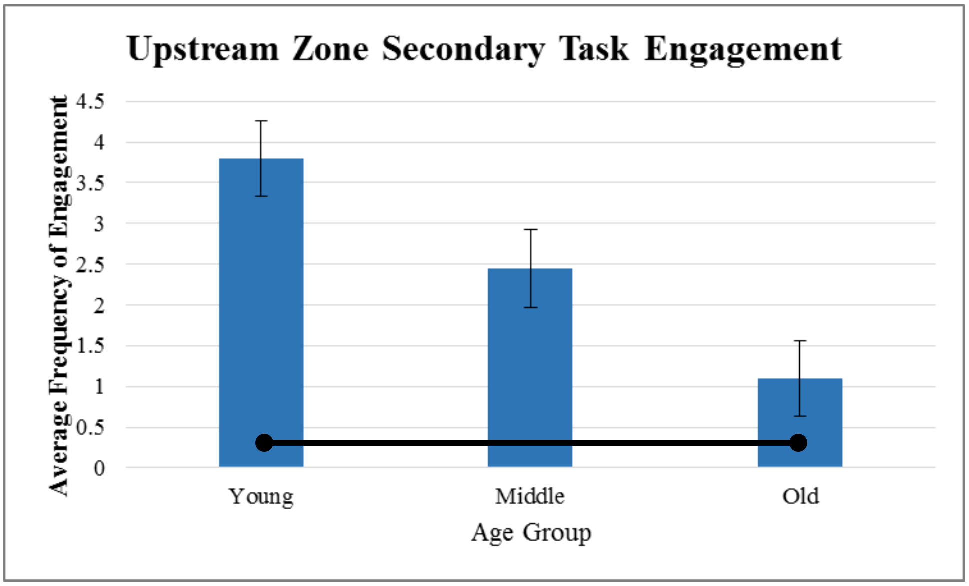

Figure 4.9. Average number of times participants in each age group (across all enforcement conditions) engaged the secondary task in the Upstream zone. The connected dots indicate differences that are significant differences between Young and Older drivers.

4.3.3 Eye Tracking

There was a significant difference between conditions for glace frequency at the speedometer ($F(3,42) = 2.96$, $p < .05$, $\eta_p^2 = .17$). Using the Bonferroni correction to account for type I error, there was an approaching-significant difference ($p = .055$) between control and police. As can be seen on Figure 4.10, participants looked at their speedometer more during the police condition than the control condition. Both ASE and ASE+DSDS conditions were not significant different from any of the other conditions ($p > .05$).

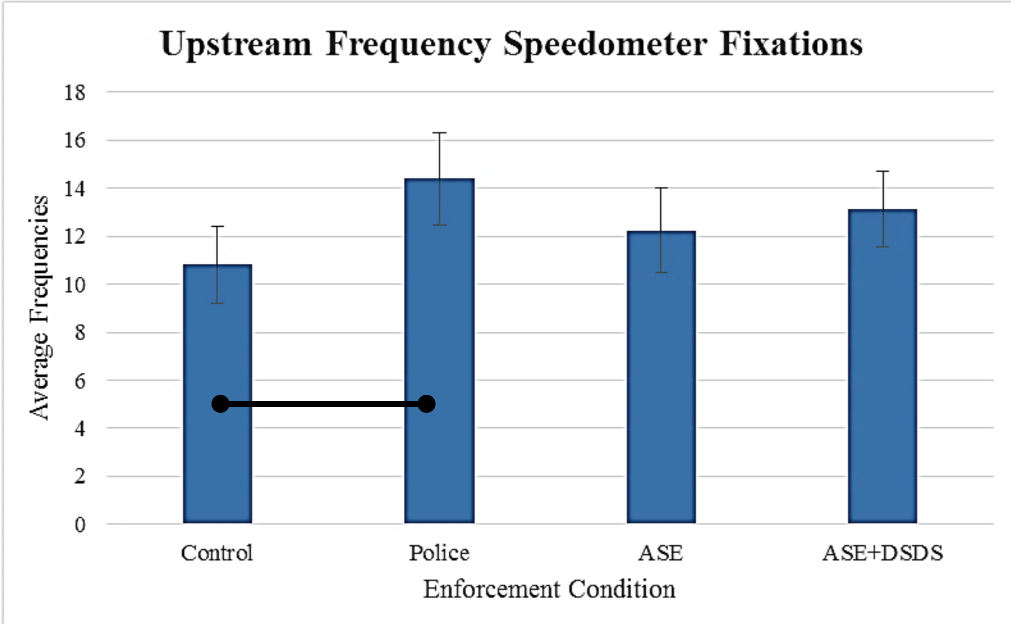

Figure 4.10. Average fixations on speedometer for different enforcement zones (across all age groups) in the Upstream zone. Differences between control and police are approaching significance.

4.4 Enforcement Activity Zone

Following the Upstream Activity zone was the Enforcement Activity zone which contained speed enforcement (exception for the control condition) and one work crew.

4.4.1 <u>Driving Performance</u>

4.4.1.1 Speeding "Ticket" Frequency

Speeding behavior across the three age groups was similar in the Enforcement zone as measured in previous zones; however, interesting patterns across age and condition were found in this zone, see Figure 4.11. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type ($p = 0.49$) for number of "tickets" and no significant main effect of age group ($p = 0.08$), but found a significant interaction between enforcement type and age group ($F(6, 171) = 2.59$, $p < .05$, $\eta_p^2 = .08$). Middle-aged drivers exhibited the most speed control in this section of the work zone, while Young and Older drivers demonstrated much less control. Furthermore, Older drivers responded differently depending on the enforcement present.

Follow-up one-way between-subjects ANOVAs, controlled with Bonferroni correction, were conducted. Two conditions were found to have a significant main effect of age. The first was the police enforcement condition, $F(2, 57) = 3.72$, $p < .05$, $\eta_p^2 = .12$. Pairwise comparisons of age groups, with Bonferroni correction, within the police condition found Middle-aged drivers sped significantly less than Older drivers ($p < .05$). Differences between Middle-aged and Young drivers did not meet significance after correction ($p = 0.22$) and no significant difference was found between Young and Older drivers ($p = 1.0$).

The second enforcement condition with a significant main effect of age was the ASE enforcement condition, $F(2, 57) = 3.68$, $p < .05$, $\eta_p^2 = .11$. Pairwise comparisons of age groups, with Bonferroni correction, within the ASE condition again found Middle-aged drivers sped significantly less than Older drivers ($p < .05$). Differences between Middle-aged and Young drivers and between Young and Older drivers were not significant ($p = 0.50$ and $p = 0.59$, respectively).

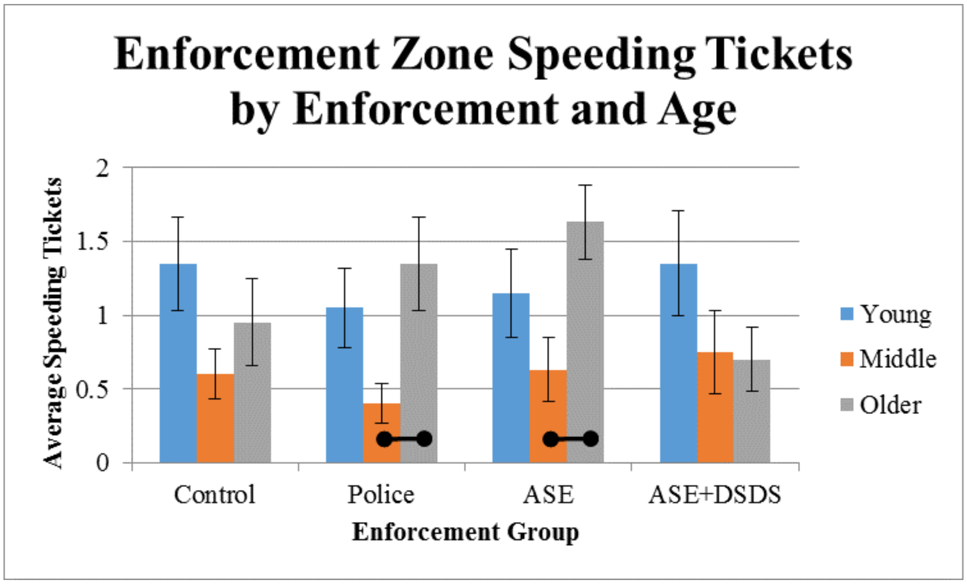

Figure 4.11. Average number of times participants by age group and enforcement exceeded the 55 mph speed limit in the Enforcement zone. The connected dots indicate differences that are significant.

A final one-way within-subjects ANOVA was conducted using the multivariate criterion of Greenhouse-Geisser and revealed a significant main effect of Enforcement for Older drivers, $F(3, 57) = 3.46$, $p < .05$, $\eta_p^2 = .16$ (see Figure 4.12). Pairwise comparisons of enforcement type, with Bonferroni correction, for Older drivers they sped significantly less than in the ASE+DSDS condition compared to the ASE condition ($p < .05$). Differences between other enforcement types were not found to be significant.

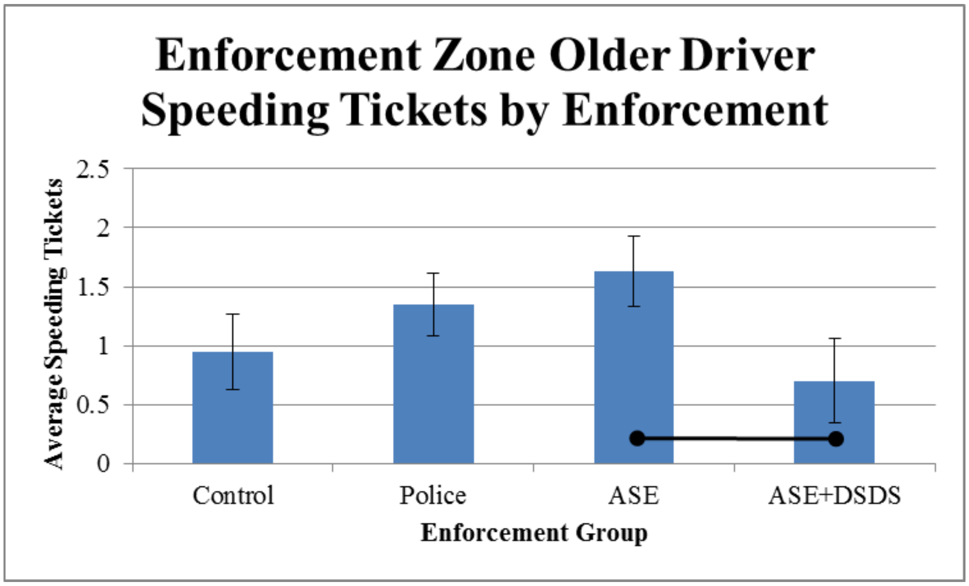

Figure 4.12. Average number of times Older drivers exceeded the 55 mph speed limit in the Enforcement zone by enforcement type. The connected dots indicate differences that are significant.

4.4.1.2 Median Time Headway (MTH)

Following distances continued to increase by the time participants reached the Enforcement zone. The age trends remained consistent with Older drivers following with the largest MTH, followed by Middle-aged drivers, and with Younger drivers following most closely, see Figure 4.13. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser demonstrated no significant main effect of enforcement type ($p = 0.71$) for Median Time Headway, but indicated a significant main effect of age group ($F(2, 57) = 3.23$, $p < .05$, $\eta_p^2 = .10$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, revealed that Young drivers followed significantly closer to the lead vehicle ($M = 7.30$, $SD = 3.21$) than Older drivers ($M = 11.08$, $SD = 6.38$) in the Enforcement zone ($p < .05$). Differences between Young and Middle-aged drivers ($M = 9.10$, $SD = 3.94$) and between Middle-aged and Older drivers was not statistically significant, ($p = 0.69$) and ($p = 0.57$), respectively.

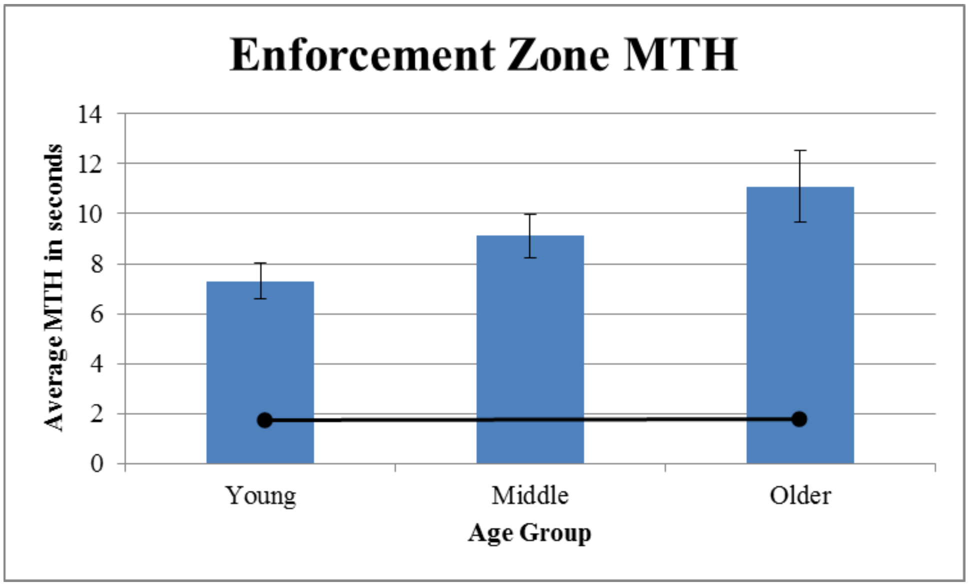

Figure 4.13. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in each age group (across all enforcement conditions) in the Enforcement zone. The connected dots indicate differences that are significant.

4.4.1.3 85th Percentile Time Headway (85th MTH)

Consistent with earlier sections of the work zone, Younger drivers' closest following distances were the shortest and Older drivers' closest following distance had largest gap of any age group, see Figure 4.14. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type ($p = 0.30$) for car-following for 85th Percentile Time Headway, but indicated a significant main effect of age group ($F(2, 57) = 3.79$, $p < .05$, $\eta_p^2 = .12$). Follow up comparisons, using Holm's sequential Bonferroni to control for familywise error, revealed that Young drivers' 85th Percentile Time Headway was significantly closer to the lead vehicle ($M = 3.57$, $SD = 2.56$) than Older drivers ($M = 7.10$, $SD = 5.83$) in the Enforcement zone ($p < .05$). Differences between Young and Middle-aged drivers ($M = 5.26$, $SD = 2.99$) and between Middle-aged and Older drivers was not statistically significant, ($p = 0.57$) and ($p = 0.47$), respectively.

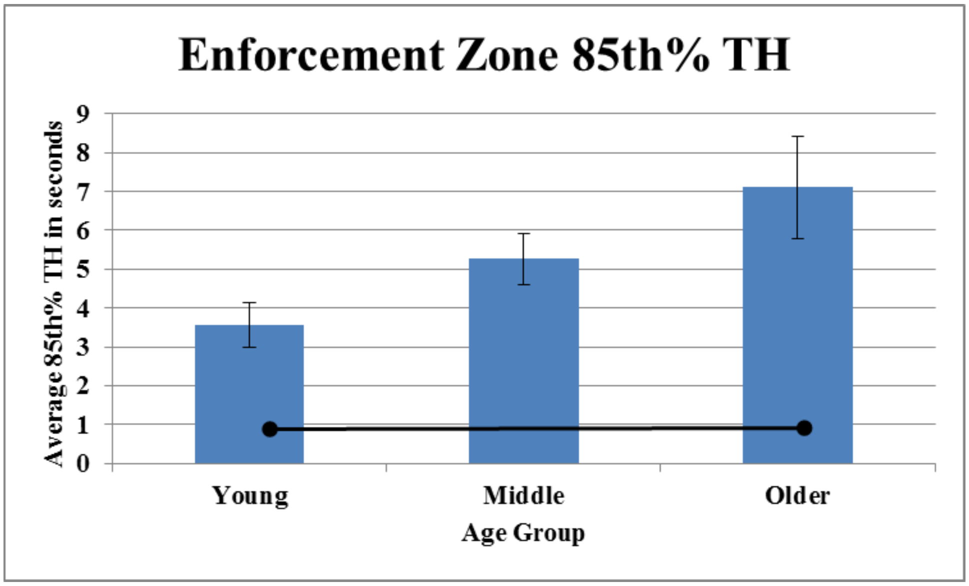

Figure 4.14. Average closest following distance, measured as 85th Percentile Time Headway (85th%TH), to lead vehicle in each age group (across all enforcement conditions) in the Enforcement zone. The connected dots indicate differences that are significant.

4.4.2 Distraction Engagement

There was a significant effect of age on spin number ($F(2,59) = 7.79$, $p < .001$, $\eta_p^2 = .21$) for the Enforcement zone. Pairwise comparisons using the Bonferroni method to control for type I error showed a significant difference only between Younger and Older drivers ($p < .05$). As shown in Figure 4.15,Younger drivers engage in the secondary task more than Older drivers. There were no other significant pairwise comparisons ($p > .05$).

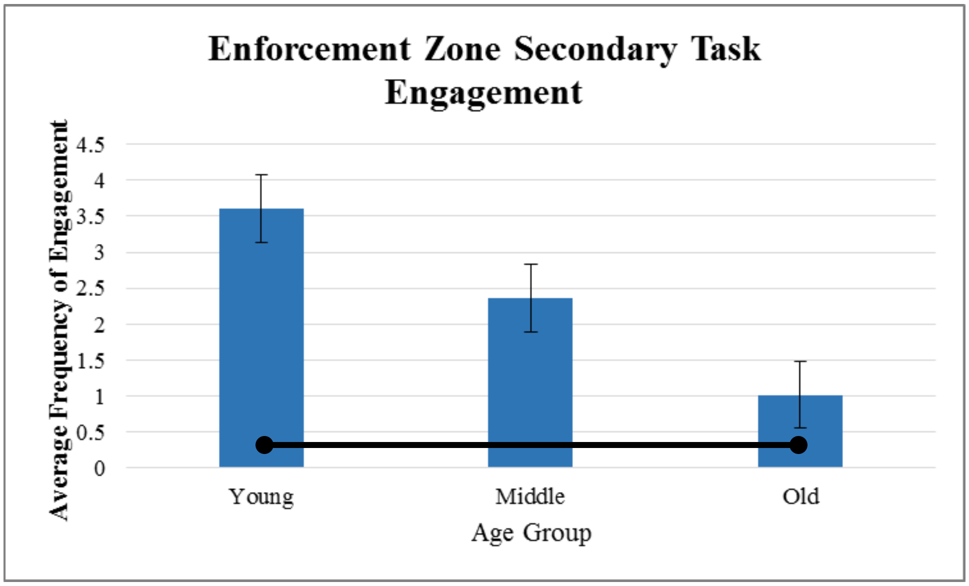

Figure 4.15. Average number of times participants in each age group (across all enforcement conditions) engaged the secondary task in the Enforcement zone. The connected dots indicate differences that are significant differences between Young and Old drivers.

4.4.3 <u>Eye Tracking</u>

There was an approaching-significant difference between enforcement conditions for glace frequency at the speedometer (F(3,42) = 2.51, p = .071, η_p^2 = .15). Using the Bonferroni correction to account for type I error, there was an approaching-significant difference (p =.085) between control and police (see Figure 4.16). The result indicates that participants looked at their speedometer more during the police condition than the control condition. Both ASE and ASE+DSDS conditions were not significant different from any of the other conditions (p > .05).

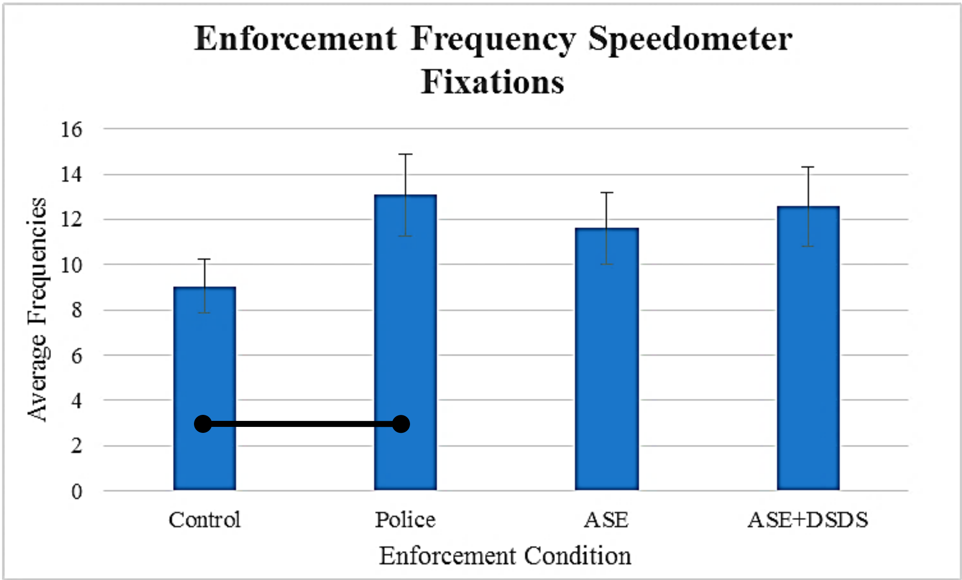

Figure 4.16. Average fixations on speedometer for different enforcement zones (across all age groups) in the Enforcement zone. The connected dots indicate differences that are significant differences between control and police are approaching significance.

Specific eye tracking coding was done for areas of simulation where the enforcement was visible, measuring fixations on the enforcement itself (i.e. police car, ASE, or ASE+DSDS) for the top 50% of videos, as described above. There was an effect of age ($F(2,38) = 8.02$, $p < .005$, $\eta_p^2 = .30$). Pairwise comparisons using the Bonferroni method to control for type I error showed significant differences ($p < .05$) between ASE and ASE+DSDS (see Figure 4.17).

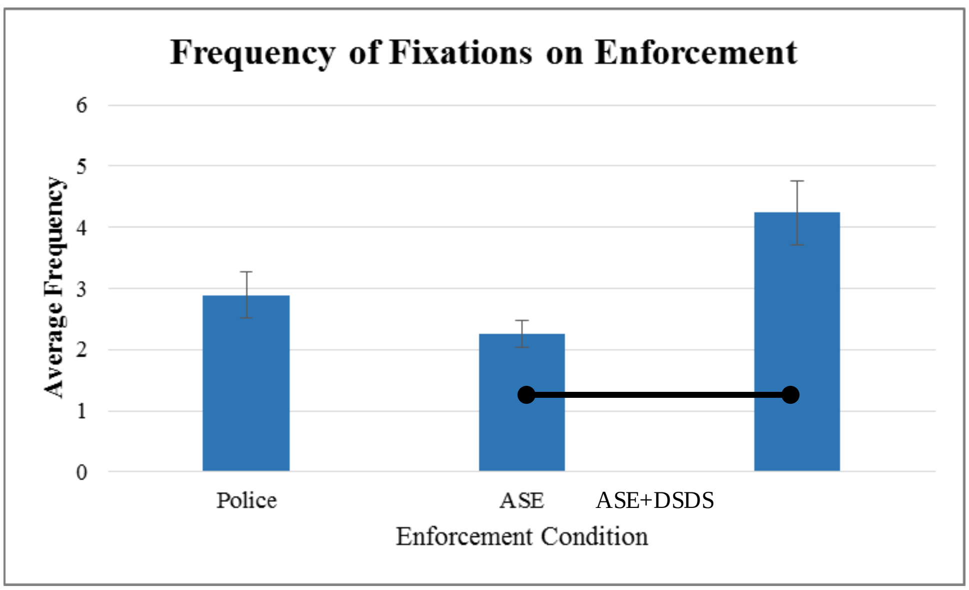

Figure 4.17. Average frequency of fixations on enforcement. Significant differences indicated by the solid line show differences between ASE and ASE+DSDS

4.5 Downstream 1 Activity Zone

Following the Enforcement Activity zone was the first Downstream Activity zone which contained one work crew. This and the next downstream section are of importance to examine the time and distance halo effect of enforcement on driving behavior and attention.

4.5.1 Driving Performance

4.5.1.1 Median Time Headway (MTH)

Following distances closed slightly for Young and Middle-Aged drivers in the first Downstream zone compared to the Enforcement zone; however, Older drivers steadily increased their following distance, see Figure 4.18. The age trends remained consistent with Older drivers following with the largest MTH, followed by Middle-aged drivers, and with Younger drivers following most closely, see Figure 4.19. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser demonstrated no significant main effect of enforcement type (p = 0.51) for Median Time Headway, but indicated a significant main effect of age group ($F(2, 57) = 5.56$, $p < .01$, $\eta_p^2 = .16$). Follow up comparisons, using Bonferroni control, demonstrated that Young drivers followed significantly closer to the lead vehicle (M = 5.46, SD = 3.54) than Older drivers (M = 12.97, SD = 10.99) in the first Downstream zone ($p < .01$). Differences between Young and Middle-aged drivers (M = 8.22, SD = 1.06) and between Middle-aged and Older drivers was not statistically significant, (p = 0.69) and (p = 0.13), respectively.

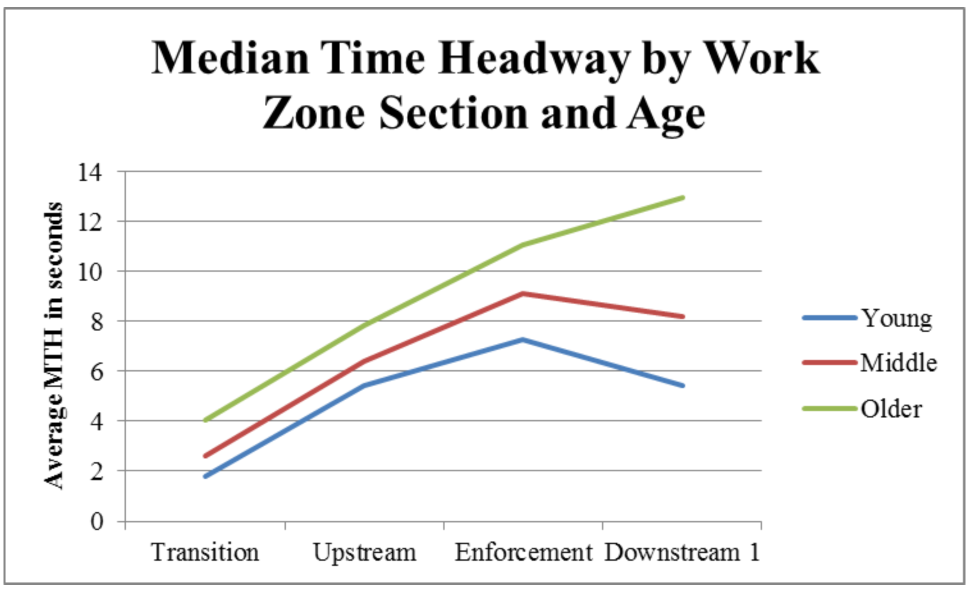

Figure 4.18. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in each age group (across all enforcement conditions) from the Transition zone to the first Downstream zone.

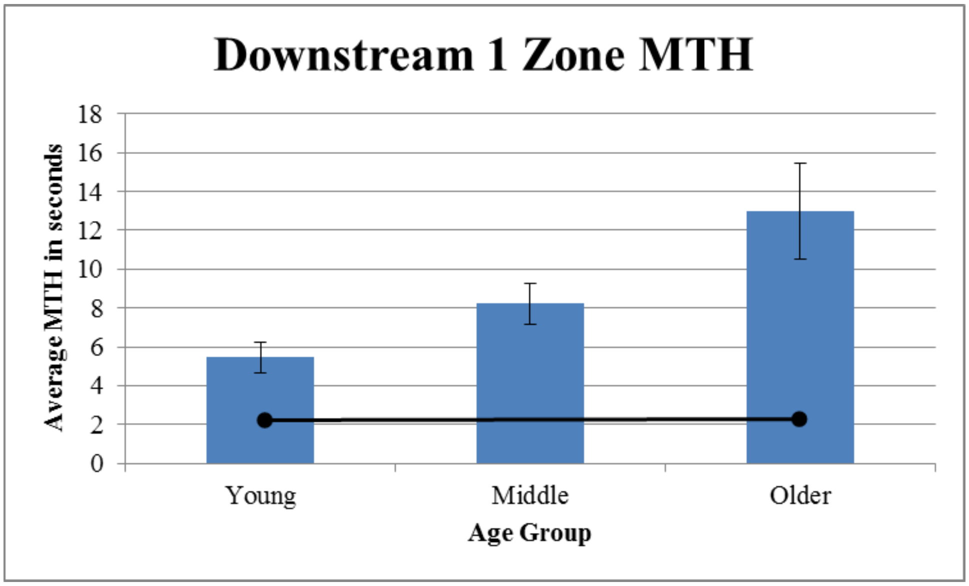

Figure 4.19. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in each age group (across all enforcement conditions) in the first Downstream zone. The connected dots indicate differences that are significant.

4.5.1.2 85th Percentile Time Headway (85th MTH)

Younger and Middle-aged drivers began to level out in their 85th Percentile Time Headway (i.e. did not increase in time distance from the lead vehicle), but Older drivers continued to fall further behind. Younger drivers still demonstrated the closest following distances and Older drivers' demonstrated the largest following distance, see Figure 4.20. The ANOVA analysis using the multivariate criterion of Huynh-Feldt revealed no significant main effect of enforcement type (p = 0.61) for car-following for 85th Percentile Time Headway, but indicated a significant main effect of age group ($F(2, 57) = 5.28$, $p < .01$, $\eta_p^2 = .17$). Follow up comparisons, using Bonferroni control, revealed that Young drivers' 85th Percentile Time Headway was significantly closer to the lead vehicle (M = 3.99, SD = 2.43) than Older drivers (M = 8.76, SD = 8.23) in the first Downstream zone ($p < .01$). Differences between Young and Middle-aged drivers (M = 5.11, SD = 4.07) and between Middle-aged and Older drivers was not statistically significant, (p = 0.59 and (p = 0.18), respectively.

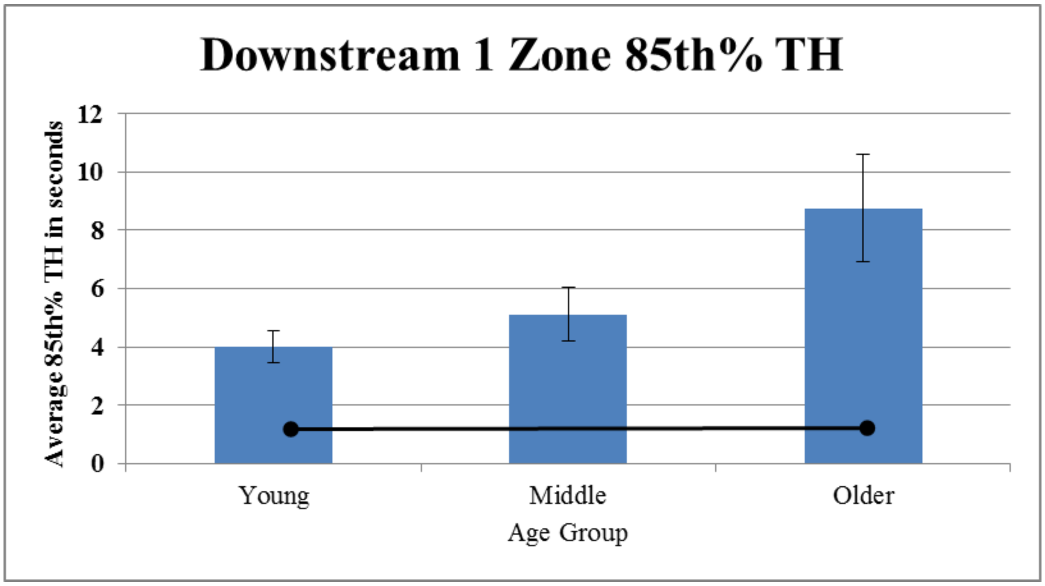

Figure 4.20. Average closest following distance, measured as 85th Percentile Time Headway (85th%TH), to lead vehicle in each age group (across all enforcement conditions) in the first Downstream zone. The connected dots indicate differences that are significant.

4.5.2 Distraction Engagement

There was a significant effect of age on engagement frequency ($F(2,59) = 5.51$ $p < .05$, $\eta_p^2 = .16$) for the first Downstream zone. Pairwise comparisons using the Bonferroni method to control for type I error showed a significant difference ($p < .05$) only between Younger and Older drivers; no other pairwise comparisons were significant ($p > .05$). As shown in Figure 4.21, Younger drivers engage in the secondary task more than Older drivers.

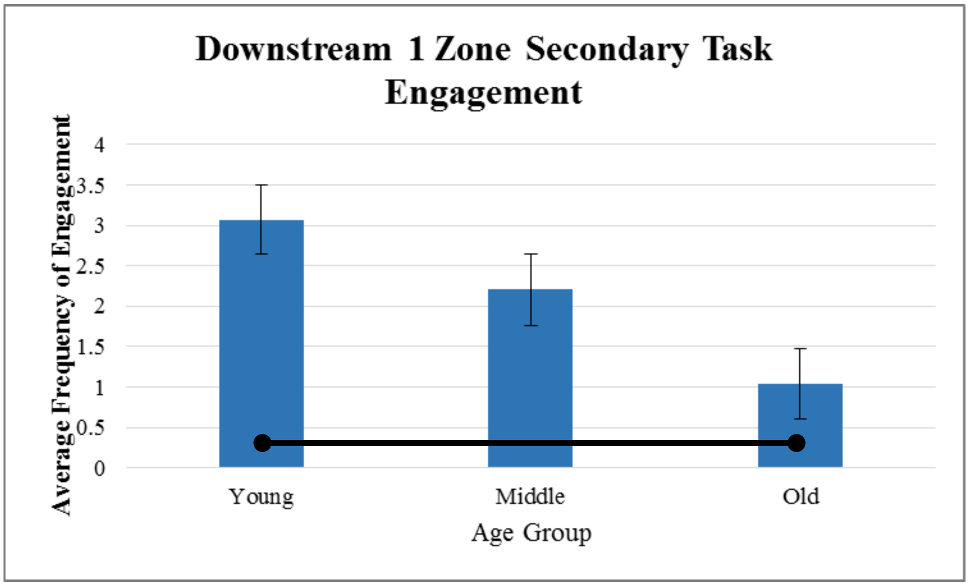

Figure 4.21. Average number of times participants in each age group (across all enforcement conditions) engaged the secondary task in the first Downstream zone. The connected dots indicate differences that are significant differences between Young and Older drivers.

In addition to an age effect, there was also an effect of condition in the first Downstream zone that was approaching significant ($F(2,59) = 5.51$ $p < .05$, $\eta_p^2 = .16$). However, the Bonferroni correction to control for type I error showed no significant pairwise comparisons between the conditions.

4.6 Downstream 2 Activity Zone

The final Activity zone segment was the second Downstream Activity zone which contained the final work crew.

4.6.1 Driving Performance

4.6.1.1 Median Time Headway (MTH)

Following distances increased all ages from the first to the second Downstream zones. Unsurprisingly, Older drivers followed the lead vehicle with the largest MTH and Middle-aged and Young drivers each successively followed more closely, see Figure 4.22. The ANOVA analysis using the multivariate criterion of Huynh-Fledt demonstrated no significant main effect of enforcement type ($p = 0.60$) for Median Time Headway, but indicated a significant main effect of age group ($F(2, 57) = 3.81$, $p < .05$, $\eta_p^2 = .12$). Follow up comparisons, using Bonferroni control, demonstrated that Young drivers followed significantly closer to the lead vehicle ($M = 6.79$, $SD = 3.76$) than Older drivers ($M = 15.67$, $SD = 15.75$) in the first Downstream zone ($p < .05$). Differences between Young and Middle-aged drivers ($M = 9.34$, $SD = 5.90$) and between Middle-aged and Older drivers was not statistically significant, ($p = 1.0$) and ($p = 0.23$), respectively.

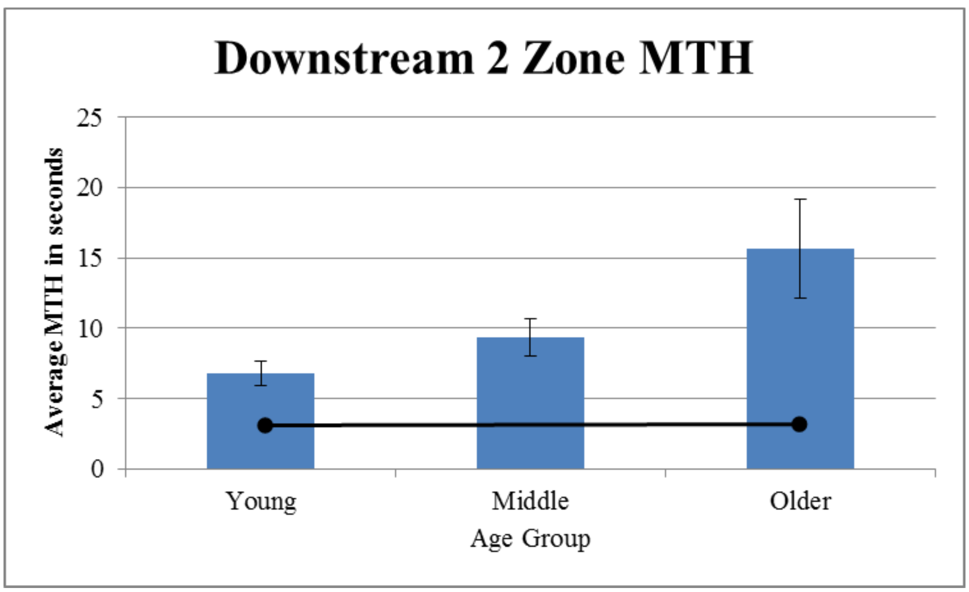

Figure 4.22. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in each age group (across all enforcement conditions) in the second Downstream zone. The connected dots indicate differences that are significant.

4.6.1.2 85th Percentile Time Headway (85th MTH)

Just as MTH increased in the second Downstream zone, the 85th Percentile Time Headway also increased for all age groups, see Figure 4.23. All drivers appeared to be fatigued by the end of each work zone and failed to engage in car following as they did at the beginning of the work zone. The ANOVA analysis using the multivariate criterion of Greenhouse-Geisser revealed no significant main effect of enforcement type (p = 0.60) for car-following for 85th Percentile Time Headway, but indicated a significant main effect of age group ($F(2, 57) = 4.27$, $p < .05$, η_p^2 = .13). Follow up comparisons, using Bonferroni control, revealed that Young drivers' 85th Percentile Time Headway was significantly closer to the lead vehicle (M = 4.86, SD = 3.06) than older drivers (M = 11.07, SD = 12.03) in the first Downstream zone ($p < .05$). Differences between Young and Middle-aged drivers (M = 6.61, SD = 5.53) and between Middle-aged and Older drivers was not statistically significant, (p = 0.59) and (p = 0.18), respectively.

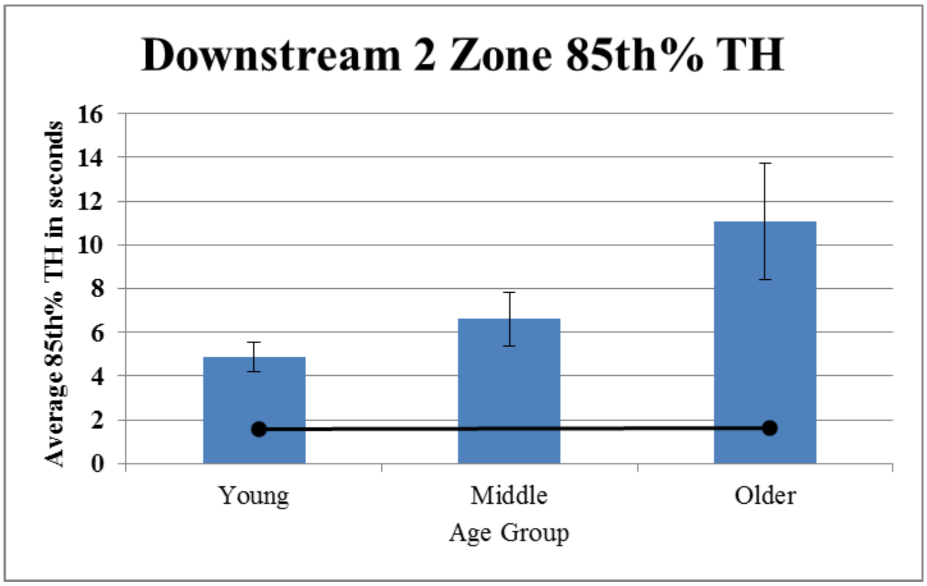

Figure 4.23. Average closest following distance, measured as 85th Percentile Time Headway (85th%TH), to lead vehicle in each age group (across all enforcement conditions) in the second Downstream zone. The connected dots indicate differences that are significant.

4.6.2 Distraction Engagement

There was a significant effect of age on engagement frequency ($F(2,58) = 7.28$ $p < .005$, η_p^2 = .20) for the second Downstream zone. Pairwise comparisons using the Bonferroni method to control for type I error showed a significant difference ($p < .05$) only between Younger and Older drivers; no other pairwise comparisons were significant ($p > .05$). As shown in Figure 4.24, Younger drivers engage in the secondary task more than Older drivers.

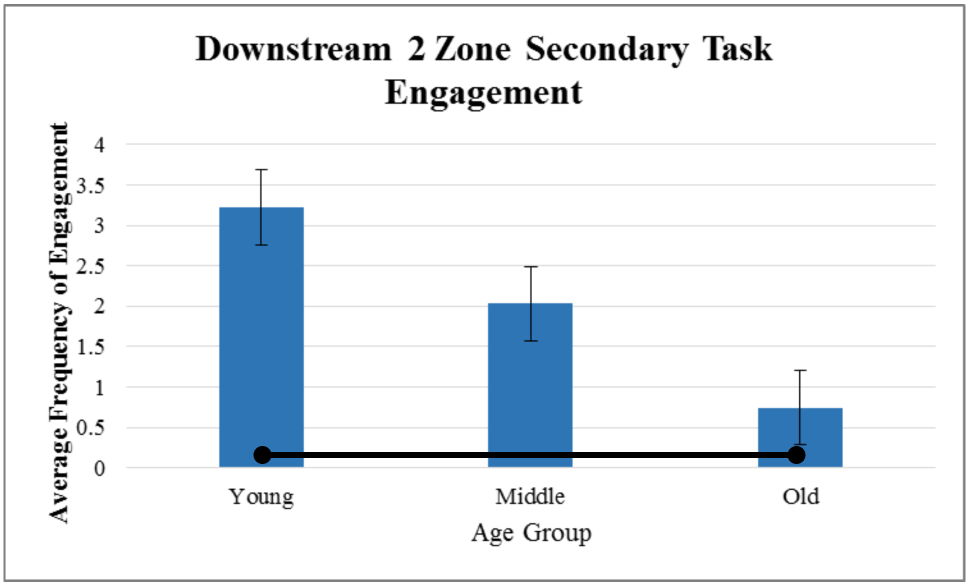

Figure 4.24. Average number of times participants in each age group (across all enforcement conditions) engaged the secondary task in the second Downstream zone. The connected dots indicate differences that are significant differences between Young and Older drivers.

4.6.3 Eye Tracking

There was a significant difference between conditions for glance frequency at the speedometer ($F(3,42) = 3.69$, $p < .05$, $\eta_p^2 = .20$) in the second Downstream zone. Using the Bonferroni correction to account for type I error, there was an approaching-significant difference (p =.095) between ASE and ASE+DSDS. As can be seen on Figure 4.25, participants looked at their speedometer more during the ASE+DSDS condition than the ASE condition. Both control and police conditions were not significant different from any of the other conditions ($p > .05$).

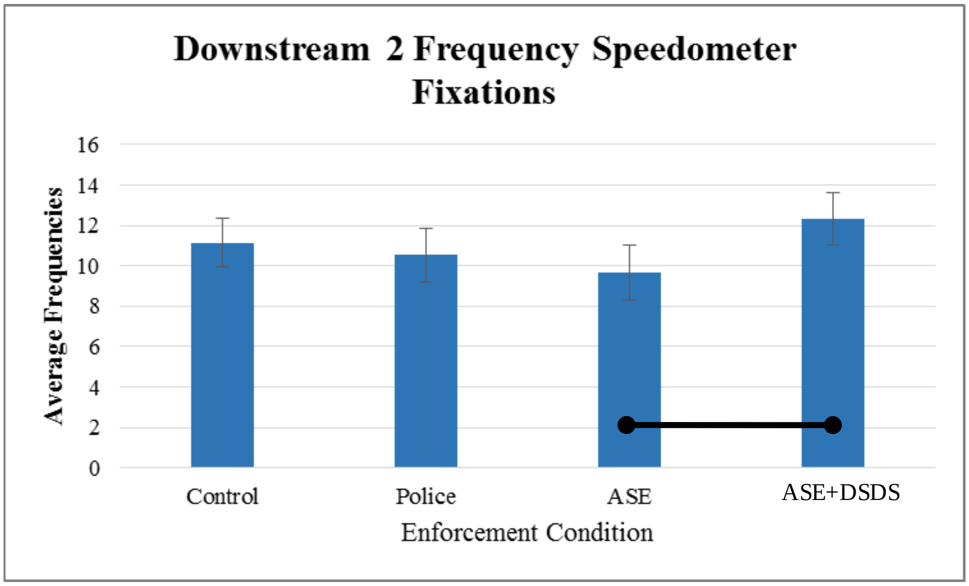

Figure 4.25. Average fixations on speedometer for different enforcement zones (across all age groups) in the second Downstream zone. Differences between ASE and ASE+DSDS are approaching significance.

There was also a significant difference between conditions for glance frequency at the secondary task ($F(3,42) = 2.83$, $p < .05$, $\eta_p^2 = .17$) in the second Downstream zone. Using the Bonferroni correction to account for type I error, there was a significant difference ($p < .05$) between ASE and ASE+DSDS. As can be seen on Figure 4.26, participants looked at the secondary task screen the least of the four conditions and this difference was significantly less than the fixations in the ASE condition. Both control and police conditions were not significant different from any of the other conditions ($p > .05$).

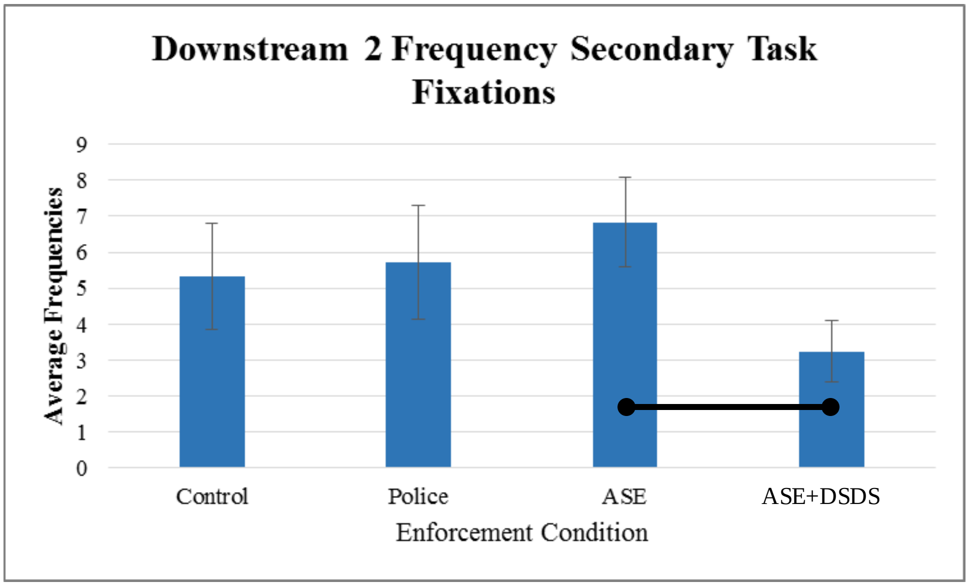

Figure 4.26. Average fixations on secondary task for different enforcement zones (across all age groups) in the second Downstream zone. Differences between ASE and ASE+DSDS are significant (p < .05).

There was an effect of age on the total duration of time fixating on speedometer ($F(3,42) = 2.83$, $p < .05$, $\eta_p^2 = .17$) in the second Downstream zone. Using the Bonferroni correction to account for type I error, there was a significant difference ($p < .05$) between Younger and Older drivers. As can be seen on Figure 4.27, middle-aged participants looked at their speedometer significantly less than Young drivers in the second Downstream section of the work zone. All other pairwise comparisons were not significant ($p > .05$).

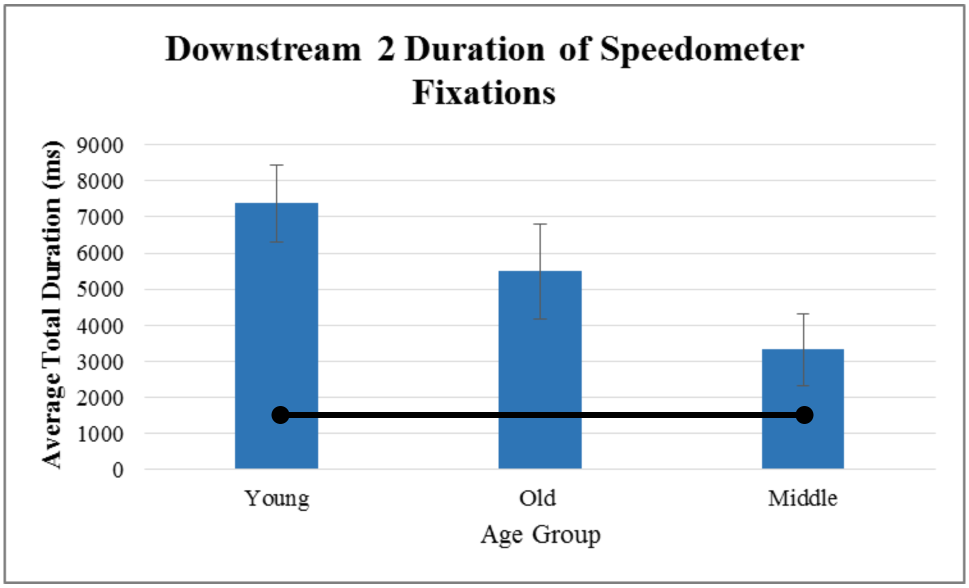

Figure 4.27. Average duration of fixations on speedometer for different age groups (across all enforcement conditions) in the second Downstream zone. Differences were found between Young and Older drivers are significant.

4.7 All Work Zones

4.7.1 Eye Tracking

Throughout the entire work zone on all conditions, there was a significant effect of time. In other words, there was a difference in the amount of fixations and total duration to both the speedometer and center console. The specific pairwise differences showed a consisted trend of differences between the transition zone and other parts of the work zone. Additionally, as shown below, these effects are quite large and therefore explain much of the variance.

Across all conditions, there was a main effect of zone for total duration of fixations on speedometer ($F(1.7,24.3) = 13.19$, $p < .001$, $\eta_p^2 = .49$). Pairwise comparisons using the Bonferroni method showed a significant difference ($p < .05$) for the Transition zone when compared to the Upstream, Enforcement, and second Downstream zone; and between the Upstream and first Downstream zone. There was an approaching significant difference ($p = .055$) between Transition zone and first Downstream zone. Figure 4.28 shows the difference between zones.

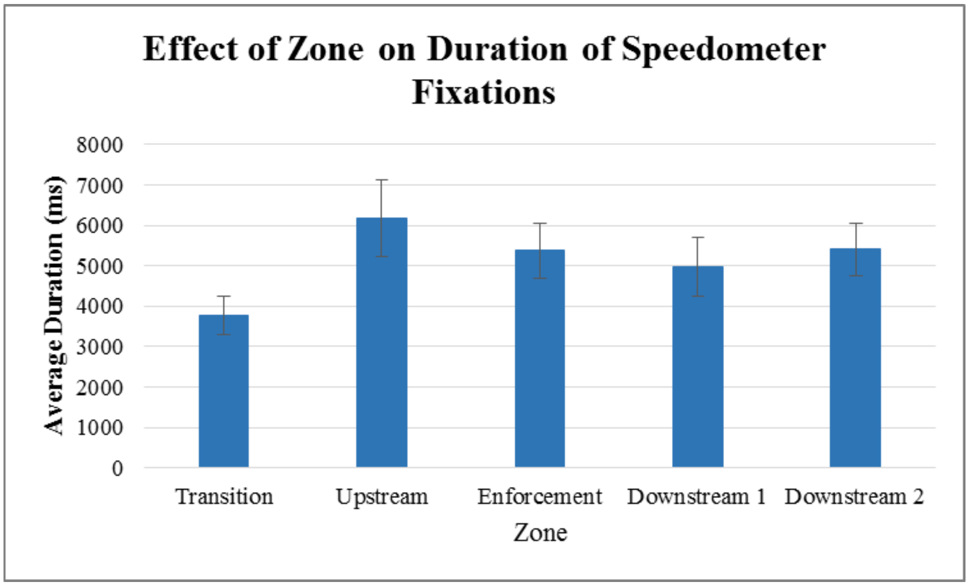

Figure 4.28. Average duration of fixations on speedometer for different zones (across all enforcement and age conditions).

Across all conditions, there was a main effect of zone for total duration of fixations on the center console ($F(4,56) = 8.89$, $p < .001$, $\eta_p^2 = .38$). Pairwise comparisons using the Bonferroni method showed a significant difference ($p < .05$) between the Transition zone and the first Downstream zone, and between the Enforcement zone and the first and second Downstream zones. Figure 4.29 shows the differences between the zones.

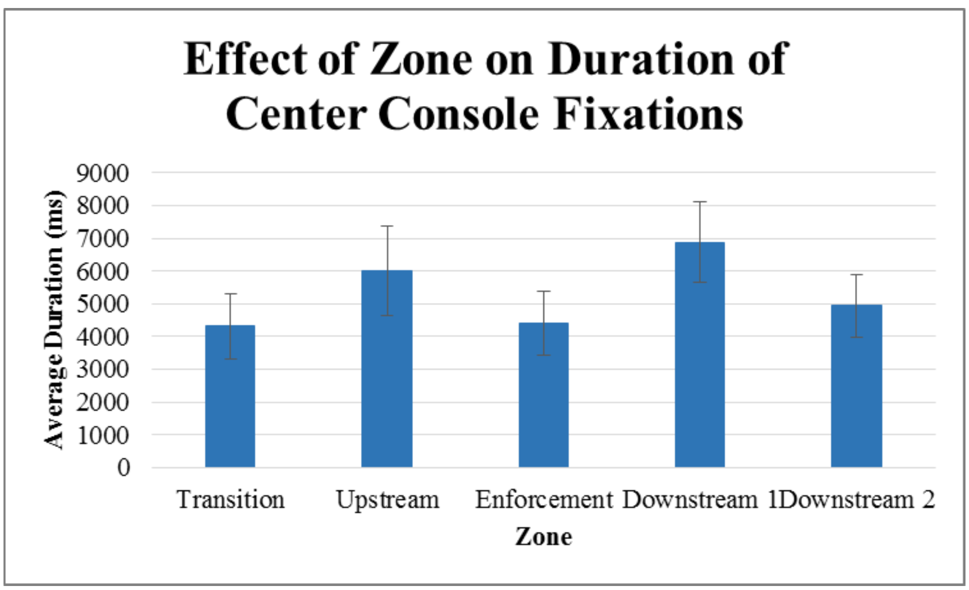

Figure 4.29. Average duration of fixations on center console for different zones (across all enforcement and age conditions).

There was also a significant main effect for zone for average frequency of fixations on the speedometer ($F(4,56) = 18.69$, $p < .001$, $\eta_p^2 = .57$). Pairwise comparisons using the Bonferroni method showed a significant difference ($p < .05$) between the Transition zone and all subsequent zones in the trial. Figure 4.30 shows the average differences between zones.

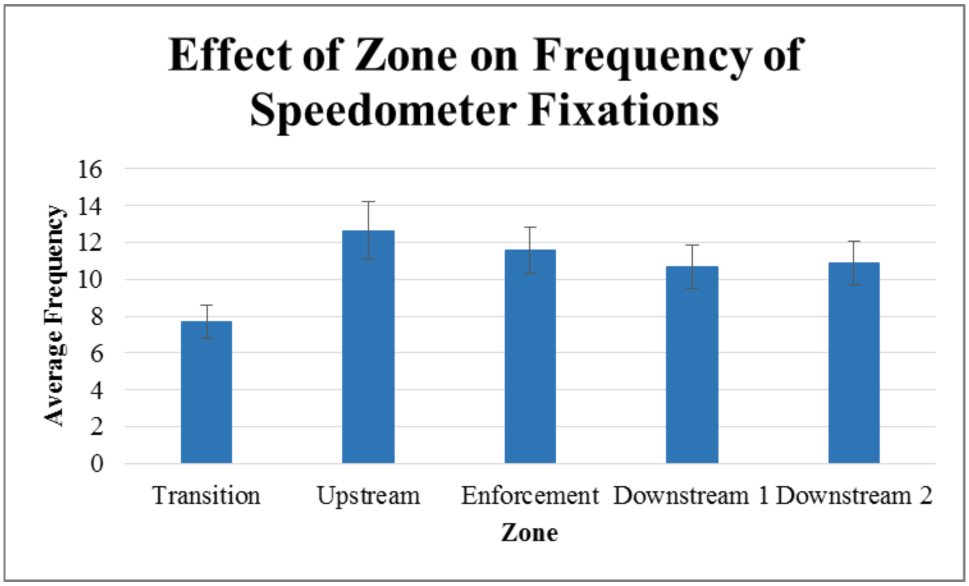

Figure 4.30. Average frequency of fixations on speedometer in different zones (across all enforcement and age conditions).

Finally, there was a main effect of zone for average frequency of fixations on the center console ($F(4,56) = 18.74$, $p < .001$, $\eta_p^2 = .38$). Pairwise comparisons using the Bonferroni method showed a significant difference ($p < .05$) between the Transition zone and the Upstream, first Downstream, and second Downstream zones, and between Enforcement and first Downstream. There was also an approaching-significant difference between Transition and Upstream ($p = .053$), Upstream and Enforcement ($p = .083$), and first Downstream and second Downstream ($p = .054$). Figure 4.31 shows the average differences between zones.

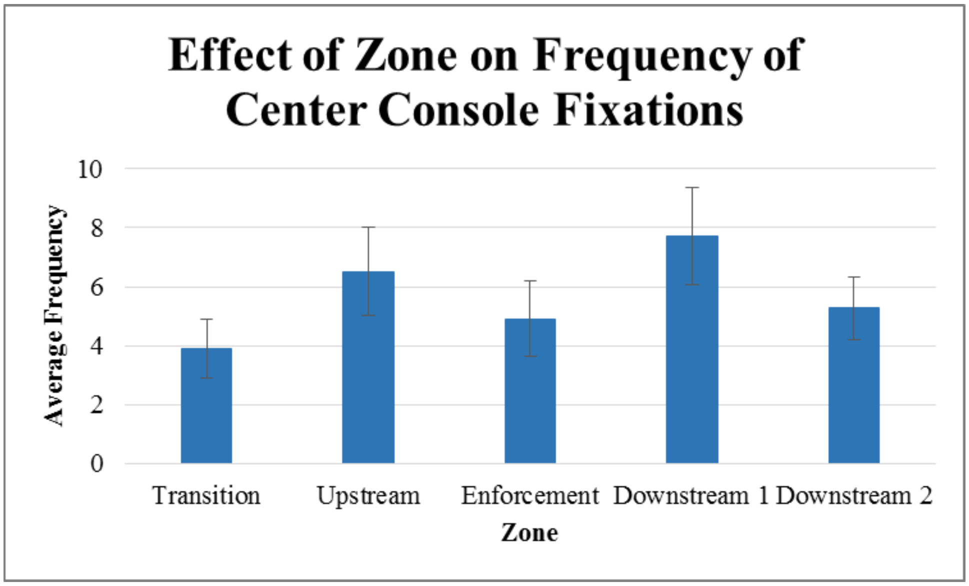

Figure 4.31. Average frequency of fixations on center console in different zones (across all enforcement and age conditions).

4.8 Subjective Ratings

Two surveys were administered between each speed enforcement condition to measure the subjective experiences of participants. The Rating Scale Mental Effort (RSME) provided a basis for understanding the average mental workload involved in the driving task. A Situational Awareness survey, which was designed by researchers to be suited for the specific characteristics of this experiment, gave insight into which elements of the drive were accurately recalled by participants. For example, recalling the specific type of speed enforcement present or the type of work machinery in work zones helped capture whether participant's attention had changed as a result of other factors (e.g., age group or enforcement type).

4.8.1 Rating Scale Mental Effort (RSME)

The results of the Rating Scale Mental Effort (RSME) revealed that there were no significant main effects for enforcement type ($F(3, 171) < 1$). A significant main effect emerged for age ($F(2, 57) = 4.071$, $p < 0.05$), indicating that there is an overall difference in RSME scores between age groups. A Tukey post-hoc test revealed that the average RSME score for the Middle age group ($M = 55.95$, $SD = 25.11$) was significantly higher compared to the Older age group ($M = 38.60$, $SD = 20.23$). This finding is consistent with driving behavior results, which describe middle age drivers as having the highest level of control over their driving performance (e.g., speed infractions). The fact that Middle age drivers display a significantly higher rating of mental workload is likely a reflection of the level of attention they gave to the driving task.

4.8.2 Situational Awareness

The results of the Situational Awareness survey question 1A ("Do you recall seeing any workers on site in the work zone") showed that 99.6% of participants remembered seeing workers on site at some point in the work zone. All work zones had three work crews randomly placed throughout the five mile shoulder closure. The results of question 1B (“If yes, how many crews do you recall seeing?”) indicate that 60.1% of participants recalled seeing three work crews, 19.4% reported seeing two work crews, 12.5% recalled seeing five or more, 6% recalled seeing four work crews and 1.2% reported seeing only one work crew. There were no significant differences captured between the age groups or enforcement types.

Question 2A (“Do you recall seeing any types of speed enforcement?”) of the Situational Awareness survey revealed that participants consistently recalled seeing speed enforcement during all non-control conditions (i.e., ASE, ASE+DSDS, Police). The control drive yielded an 84% correct response, with only 9 participants falsely remembering seeing speed enforcement in the simulation. An ANOVA revealed that there were no significant effects of age on whether participants claimed to have falsely remembered seeing the enforcement in the control condition.

The follow-up item, 2B (“If yes, what type of enforcement do you recall seeing?”), showed that, of the 82.3% of participants who recalled seeing ASE speed enforcement, only 67.7% correctly identified the type of enforcement (32.3% falsely remembered a different type of speed enforcement). The ASE+DSDS condition yielded an overall 91.9% recall rate, with 79% of those participants correctly identifying ASE+DSDS enforcement. The highest overall recall rate was in the police condition, with 98.4% of participants recalling seeing a police car, and 90.3% of those participants correctly identifying the enforcement type. Table 4.2 describes the results of Question 2A and 2B. The reason for the high recall rate and match rate of the police condition is likely due to the fact that police car are much more recognizable to all driver in comparison to ASE and ASE+DSDS equipment.

Table 4.2. Response rates to recalling enforcement by Enforcement Type.

Condition	Recall seeing speed enforcement?	Correctly identified the speed enforcement?
Control	16%	n/a
ASE	82.3%	67.7%
ASE+DSDS	91.9%	79%
Police	98.4%	90.3%

The results of the Situational Awareness question 3A (“Do you think you exceeded the 55 mph speed limit within the work zone?”) revealed that 56.9% of participants believed that they had exceeded the speed limit at some point during the work zone. Question 3B (“If yes, how many times do you think you might have exceeded 55 mph within the work zone?”) concluded that, of the 56.9% who claimed to have sped, 74.4% thought they exceeded the speed limit 1-2 times, 21.5% said they had exceeded it 3-4 times, and 3.5% thought they had exceeded the speed limit 5-6 times throughout the work zone. The overall percentage of participants who claimed to have sped on the Situational Awareness survey was under-representative of the observed speeding data collected from the simulation record. In the simulation, young drivers and older drivers were more inclined to speed in the work zone than middle drivers, prompting a follow up analysis on the Situational Awareness data to identify any effects of age. Of the overall positive responses to question 3A, 38.6% were accounted for by Young drivers, 36.3 by Older drivers, and only 25.5% were Middle drivers. An independent samples Kruskal-Wallis test was conducted, which found that there we no significant differences in the distribution of responses to question 3A or 3B across the independent age groups. The same test was conducted to measure the effects of enforcement type on reported speeding, and again, there were no significant findings.

Finally, the responses to question 4A ("Do you recall seeing any work vehicle in the work zone?") showed that 93.1% of participants recalled seeing some type of work vehicle in the work zone and only 6.9% did not. The simulation was set up to have a specific construction vehicle present in the northbound conditions and a different construction vehicle present in the southbound conditions. This approach created some randomness to prevent participants from memorizing the equipment from one drive to the next. Northbound drives portrayed the work crews with a yellow backhoe and southbound drives displayed a white pickup truck with the work crews. Question 4B ("If yes, which [image] do you recall seeing in the work zone?") revealed that in the northbound drives 76.4% of participants correctly identified the yellow backhoe in the Situational Awareness survey. In the southbound drives, 80.8% of participants correctly identified the white pickup truck in the survey. Participants had to choose between one of four images in the multiple choice question (see Appendix D).

CHAPTER 5: GENERAL DISCUSSION AND CONCLUSIONS

The investigation into the impact of different types of speed enforcement on driver attention in work zones yielded mixed results. Differences in driver performance and attention were most pronounced among the age groups (Young, Middle-aged, and Older drivers) and were less pronounced among the different speed enforcement conditions (no enforcement, police, ASE, and ASE+DSDS). The significant differences in driving performance data (e.g., exceeding speed limit, coherence, MTH) primarily existed between age groups, with Middle-age drivers exhibiting optimal driving behaviors. The marginal differences captured between speed enforcement conditions were found among Older drivers in select metrics (i.e., speeding tickets). The analysis additionally revealed marginal differences among the different speed enforcement conditions in which participants' tended to devote their visual gaze within the work zone and simulated vehicle.

Age plays a role in speed coherence in the real world, with teen drivers being prone to high-risk behaviors like speeding, and experienced drivers (age 30-65) having the greatest control over their speed. Older drivers (age 65-85) are a high-risk driving population due to natural declines and limitations in cognitive abilities. The simulator data replicated these real-world expectations with regard to speed coherence trends. In the study, Younger drivers and Older drivers were more likely to speed in all enforcement conditions compared to Middle-aged drivers. The difference only reached statistical significance, however, between the Middle-age and Older driver groups. Older drivers did appear to respond to speed limits best in the presence of ASE paired with DSDS since they had the fewest incidences of speeding within its proximity compared to other enforcement types (e.g. control, police, and ASE). Surprisingly, the incidences of exceeding the speed limit in the simulator were infrequent across all conditions. Regardless of age, participants appear to have been strongly motivated to avoid exceeding the speed limit in the study. It is suspected that the cause of this finding may be due to the fact that participants were inadvertently primed to avoid speeding during the introduction of the payment incentive scheme. The researcher's goal in using a monetary addition/subtraction scheme was to introduce extrinsic motivation by placing time pressure on participants while simultaneously discouraging excessive speeds during the routes. In the end, participants were more encouraged to avoid speeding than they were to finish the route on time. Post-experiment feedback confirmed this suspicion and revealed that the prospect of monetary incentive loss through the speeding penalty provided more motivation than the prospect of monetary earning through time-limit structure placed on participants.

The two Downstream zones (i.e., area after enforcement) provide a good metric for determining the efficacy of speed enforcement in terms of speed coherence; therefore, the primary behavior of interest in the study, driver attention in the work zone, was closely examined in this area. Eye tracking data were analyzed to detect eyes off-road fixations on the speedometer and the secondary task. The findings of the secondary task engagement eye tracking analysis in the second Downstream zone revealed that ASE+DSDS was the condition that had the fewest secondary task fixations, differing significantly from the number of fixations in the ASE only condition. This suggests that participants maintained their attention to the task of driving and maintaining speed control for a more extended amount of time and distance after exposure to ASE+DSDS, leaving few attentional resources available to devote to secondary distraction tasks.

All around, there was less engagement in the secondary task around speed enforcement. Additional fixation data showed that drivers in the ASE only condition had the fewest speedometer glances, which illustrates that they do not over-focus on the speedometer in the presence of the ASE van. The fixation on speedometer data was not significant, indicating that all speed enforcement conditions pose little risk for excessive eyes-off-road due to speedometer fixation.

Age also played a role in the secondary task engagement, potentially due to the fact that it was self-paced activity, creating large differentials in engagement by group. Older drivers did not engage in the secondary task nearly as much as the other two groups; however, their avoidance of the secondary task did not appear to improve their general driving behaviors, as they continued to struggle with active car-following or speed coherence. The performance of Older drivers in this study helps validate other findings, which indicate that older drivers are a safety concern in work zones because they struggle to process the complex driving environment and maintain safe speeds and following distances. The large following distances are undoubtedly a compensatory strategy employed by older drivers. These very large gaps, however, are vulnerable to be "filled in" by other drivers and may be difficult to maintain without creating additional fluctuations in their driving patterns and adding to the already dangerous speed differentials present in work zones. Young drivers engaged in the most secondary tasks, but their performance was not affected. There were no imminent collision events presented in the work zone, however, so it is unclear how well they would have navigated in a more intense driving situation while engaging in distraction at the rate observed in this study. Lastly, the sample of Middle-age drivers tended to be able to prioritize speed adherence over car-following, exhibited by their ability to consistently stay within the speed limit, and participated in secondary tasks after attending to their driving. Middle-aged drivers, more so than Young or Older drivers, appeared to maintain high levels of control in their driving performance across the work zone, as their behavior did not fluctuate at any measurable level by work zone section or speed enforcement condition. This supports the literature findings and survey results that middle-aged drivers are of least concern compared to other age groups in work zones.

The subjective data from post-drive RSME surveys corroborate the fact that Middle-age drivers have the highest level of attention. Middle-age drivers claim to experience the highest level of workload throughout the drives, reaching a level of statistical significance when compared to Older drivers' responses. In regard to situation awareness, it is not surprising that the police condition yielded the highest recollection in the post-drive surveys, due to the recognizability of the trooper vehicle.

Overall, the results do not strongly support the hypothesis that ASE without DSDS improves driver attention in work zones. There is some evidence, however, that drivers did heighten their visual attention in work zones with ASE+DSDS enforcement. Drivers fixated on the secondary task display less frequently in the ASE+DSDS condition compared to other enforcement types while they traveled in the Downstream portion of the work zone. This may suggest a time and distance halo of visual attention to the primary task of driving when drivers are monitored with ASE+DSDS. Finally, drivers do engage in more glances to their speedometer in the ASE+DSDS work zones compared to ASE only, but they do not appear to be overly occupied with this monitoring since they do not monitor their speedometer significantly more often compared to when police are present or under no enforcement conditions.

CHAPTER 6: LIMITATIONS AND FUTURE RESEARCH

The current project included a number of limitations. First, the eye tracking equipment that was used for the task of recording driver attention and distraction did not provide a data format that afforded automated examinations of fixations or perform the analysis as expected. Instead, the eye tracking videos required manual coding which spurred a significant increase in analysis hours across multiple coders and subjected the interpretation to some amount of error due to the subjective nature of video coding. Further, the eye fixation capture did not present reliability as expected. The lower reliability of gaze capture was due, in part, to the participant population of older driver whose facial characteristics around their eyes impeded the sensor's ability to consistently follow eye position. As a result, researchers excluded analysis of the videos which contained less than half gaze samples captured. This reduced the number of videos to half of the total eye tracking videos recorded. The best gaze 10 gaze samples (i.e. near 50% gaze capture or better) from each age group were analyzed in eye tracking coding to maintain equal sampling. The data analysis standards were rigorous for manual coders ensuring the results were as reliable as possible in spite of these limitations.

Another limitation included possible priming due speed monitoring being a primary focus of the experiment. It was decided that deception would not be used to hide the true nature of the study because of the additional ethics risk that deception poses when conducting a controlled experiment. Instead, researchers told participants that they would be exposed to various speed enforcements and that they were expected to follow the speed limit throughout the work zone. Despite the payment scheme that was set up to incentivize participants to complete the drive in a timely manner while simultaneously penalizing speed infractions, it appears that participants may have been overly sensitive to the speed monitoring aspect of the experiment, to avoid speeding, and weighted the financial penalty of speeding over the financial incentive to complete the drive in a timely fashion. This led to a deflated number of excessive speed occurrences across all driving conditions and subsequently less engagement in car following once the lead vehicle exceeded the speed limit.

In the future, studying the effects of ASE or ASE+DSDS in a naturalistic setting will provide an interesting focus and would make for an optimal pilot program prior to statewide deployment of ASE. The current study provided a strong foundation for the efficacy of ASE in a simulated environment and follow-up work on-road will be necessary in order for policy changes and state regulations to take effect.

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APPENDIX A: AUTOMATED SPEED ENFORCEMENT SIMULATION SCREENING QUESTIONNAIRE

This questionnaire was administered during the recruitment process to determine eligibility for participation.

1. What is your age?
    - EXCLUDE IF NOT 18-30, 41-53, or 65-77
2. Have you had a U.S. driver's license for at least two years?
    - EXCLUDE IF NO
3. Do you drive a minimum of 4,000 miles each year?
    - EXCLUDE IF NO
4. Do you have at least 20/40 visual acuity, either corrected (contact lens only) or uncorrected? (i.e. persons that use corrective contact lenses which improve their vision to 20/40 may participate)
    - EXCLUDE IF NO
    - EXCLUDE IF CORRECTION REQUIRES GLASSES
5. Do you have normal color vision?
    - EXCLUDE IF NO
6. Do you have any history of hearing loss which inhibits every day conversation?
    - EXCLUDE IF YES
7. Do you have any health problems that affect your driving?
    - EXCLUDE IF YES
8. Do you experience inner ear problems, dizziness, vertigo, or balance problems?
    - EXCLUDE IF YES
9. Do you have a history of motion sickness? (e.g., back seat of car, boats, amusement park rides, etc)
    - EXCLUDE IF YES
10. Are you suffering from any lingering effects of stroke, tumor, head trauma, or infection?
    - EXCLUDE IF YES
11. Do you or have you ever suffered from epileptic seizures?
    - EXCLUDE IF YES
12. Do you have a history of migraines?
    - EXCLUDE IF YES

APPENDIX B: DRIVING HISTORY 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 sex: ☐ Male
☐ Female

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

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 nowadays?

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

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. About how often do you drive to and from your place of work?

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

Never	Hardly Ever	Sometimes	Most Days	Every Day

Do you drive frequently on… Yes No

10. Highways? ☐ ☐
11. Main Roads other than Highways? ☐ ☐
12. Urban Roads? ☐ ☐
13. Country Roads? ☐ ☐

14. During the last three years, how many minor road accidents have you been involved in where you were at fault? A minor accident is one in which no-one required medical treatment, AND costs of damage to vehicles and property were less than $1000.

Number of minor accidents ____ (if none, write 0)

15. During the last three years, how many major road accidents have you been involved in where you were at fault? A major accident is one in which EITHER someone required medical treatment, OR costs of damage to vehicles and property were greater than $1000, or both.

Number of major accidents ____ (if none, write 0)

16. During the last three years, have you ever been convicted for:

	Yes	No
Speeding	☐	☐
Careless or dangerous driving	☐	☐
Driving under the influence of alcohol/drugs	☐	☐

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

- ☐ Motorcycle
- ☐ Passenger Car
- ☐ Pick-Up Truck
- ☐ Sport utility vehicle
- ☐ Van or Minivan
- ☐ Other, briefly describe: ______________________________

18. How frequently to do drive on Highway 52?

Never ☐—☐—☐—☐—☐ ***Every Day***

19. How frequently to do drive on County Road 9?

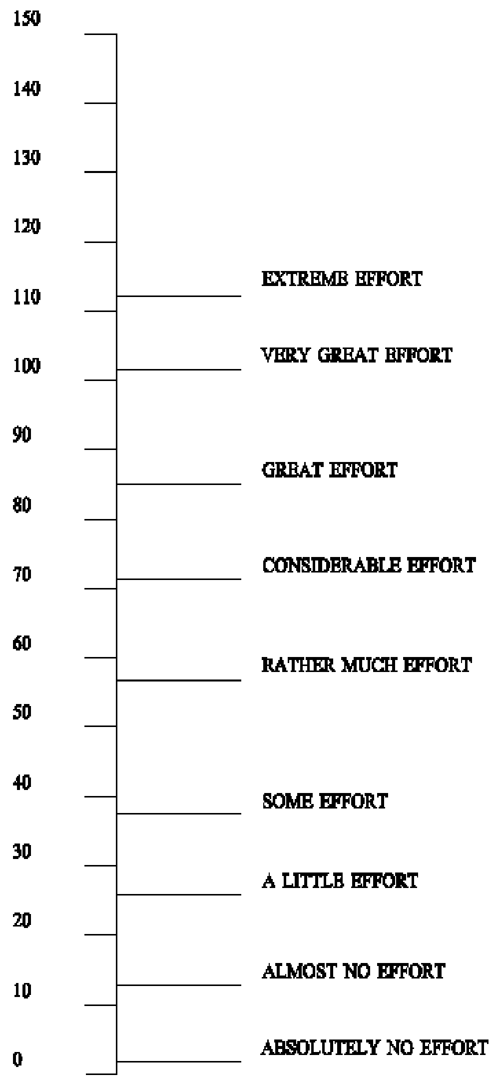
Never ☐—☐—☐—☐—☐ ***Every Day***

20. How frequently to do cross or enter Highway 52 from County Road 9?

Never ☐—☐—☐—☐—☐ ***Every Day***

APPENDIX C: RATING SCALE MENTAL EFFORT (RSME)

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



APPENDIX D: SITUATION AWARENESS QUESTIONNAIRE

1a. Do you recall seeing any workers on site in the work zone?

☐ Yes

☐ No

1b. If yes, how many crews do you recall seeing?

A. 1
B. 2
C. 3
D. 4
E. 5+

2a. Do you recall seeing any types of speed enforcement?

☐ Yes

☐ No

2b. If yes, what type of enforcement do you recall seeing?

A. Police
B. ASE
C. Your Speed + ASE
D. Other
E. Don't know

3a. Do you think you exceeded the 55 mph speed limit within the work zone?

☐ Yes
☐ No

3b. If yes, how many times do you think you might have exceeded 55 mph within the work zone?

A. 1-2 times
B. 3-4 times
C. 5-6 times
D. 7-8 times
E. 9+ times

4a. Do you recall seeing any work vehicles in the work zone?

☐ Yes
☐ No

4b. If yes, which do you recall seeing in the work zone?

i. 

ii. 

iii. 

iv. 

v. None of the above

APPENDIX E: ADDITIONAL DATA VISUALIZATION

The data availability from driving behavior recorded by the simulator is quite expansive. In order to provide a more concise analysis of the data, the subset of analyses of greatest interest were included in the main report. Extraneous data that was not analyzed together or did not reveal significant results have been plotted in the graphs below. The data has been graphed in two main formats. First, dependent variables are graphed by enforcement group and work zone section. Each enforcement group displays means and standard errors across all participants. Second, dependent variables are graphed by age group and work zone section. Each age group displays means and standard errors across all enforcement groups. While the two road sections outside of the work zone (i.e. introductory drive and conclusion drive) were not of major interest in the analyses, some of the data is displayed with them included to show the differences in driving behavior inside and outside of the work zone. These graphs are then repeated with the extraneous segments removed to make the smaller differences between groups within the work zone more visible.

E.1. Speed-Related Data

Figure E. 1Percent of miles participants drove over 55 mph by enforcement condition and simulation segment (including introductory and conclusion segments).

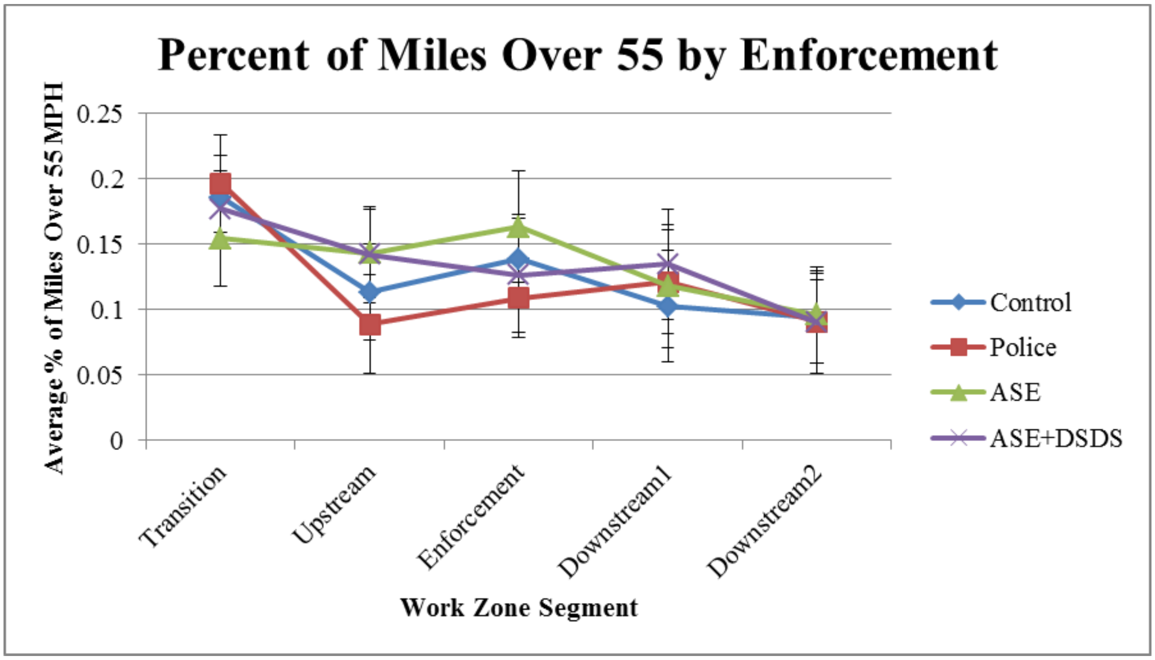


Figure E. 2. Percent of miles participants drove over 55 mph by enforcement condition and simulation segment (without introductory and conclusion segments).

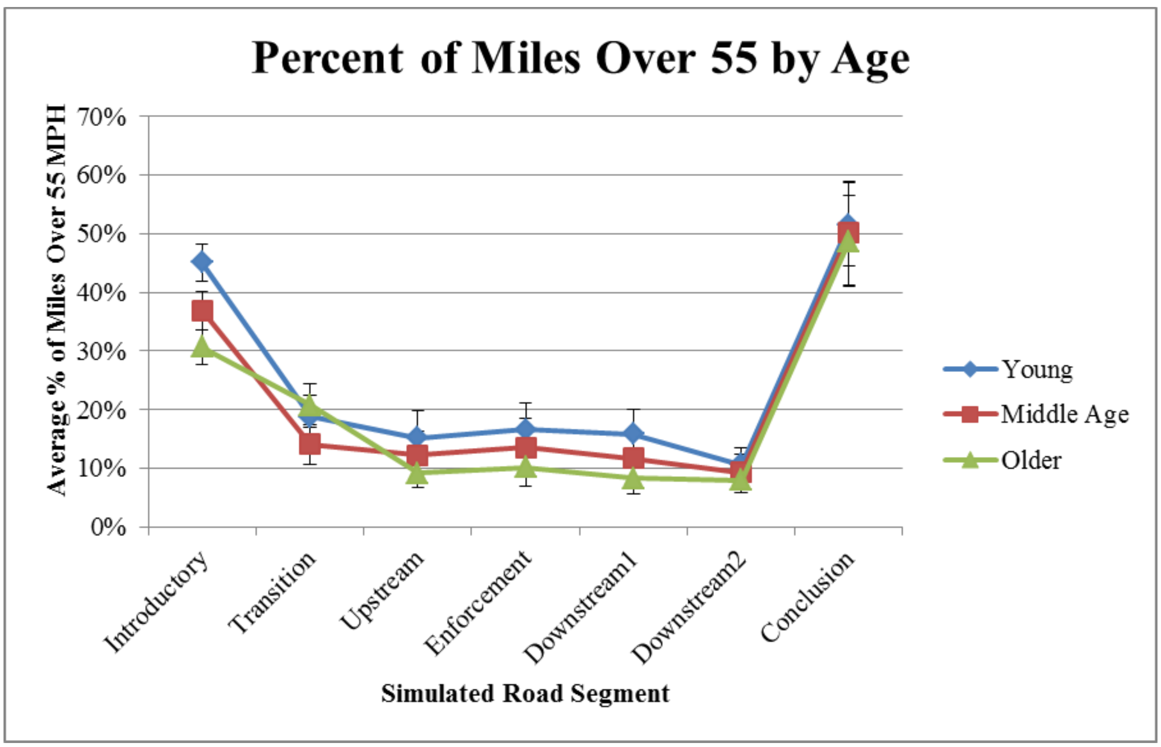


Figure E. 3. Percent of miles participants drove over 55 mph by age group and simulation segment (including introductory and conclusion segments).

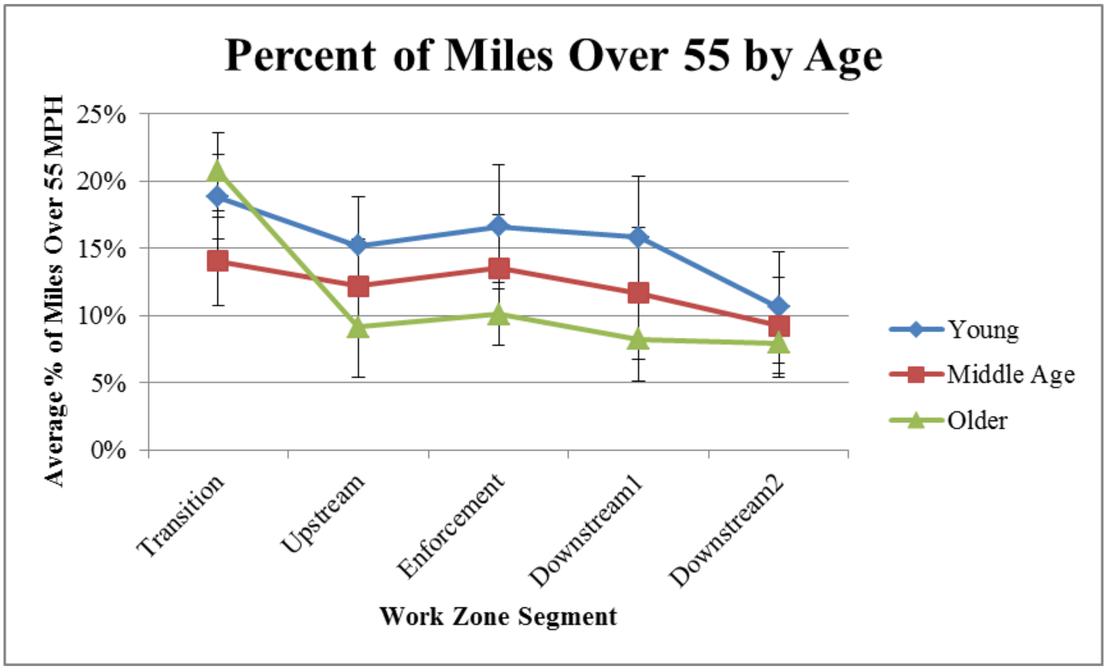


Figure E. 4. Percent of miles participants drove over 55 mph by age group and simulation segment (without introductory and conclusion segments).

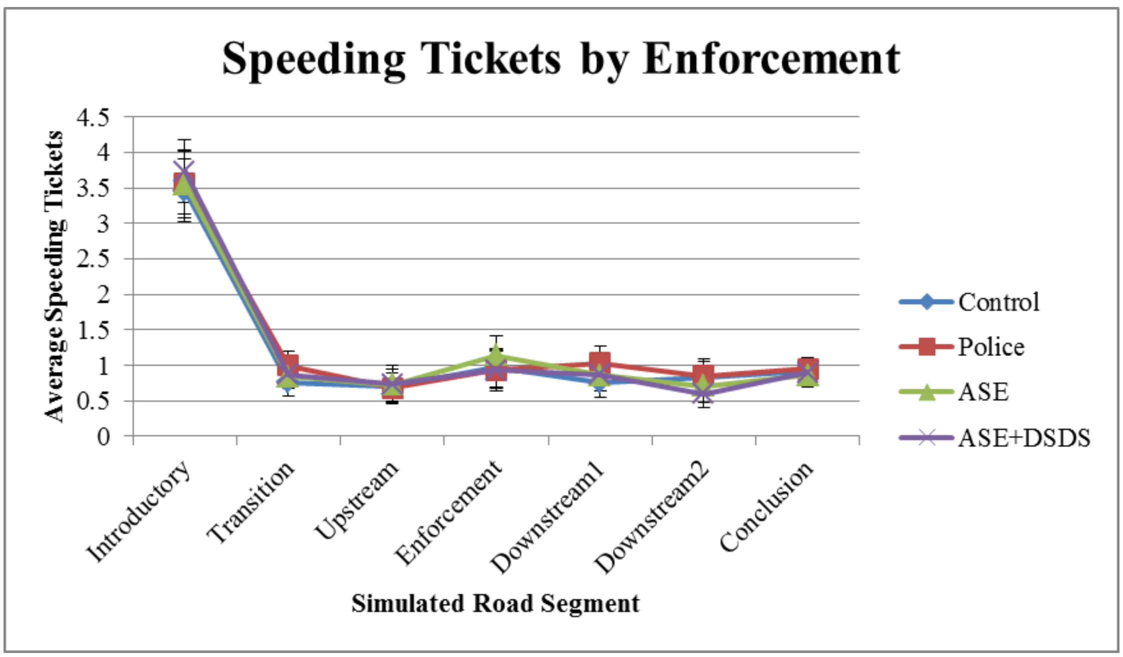


Figure E. 5. Frequency of "speeding tickets" in which participants crossed over the 55 mph threshold by enforcement condition and simulation segment (including introductory and conclusion segments).

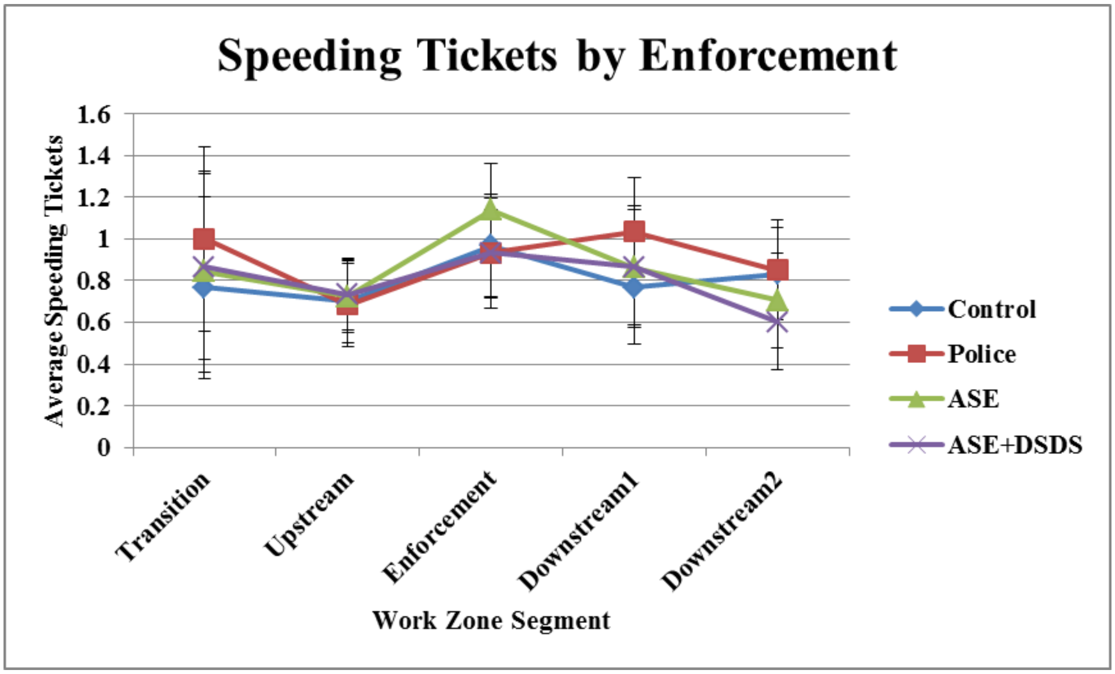


Figure E. 6. ***Frequency of "speeding tickets" in which participants crossed over the 55 mph threshold by enforcement condition and work zone segment (without introductory and conclusion segments).***

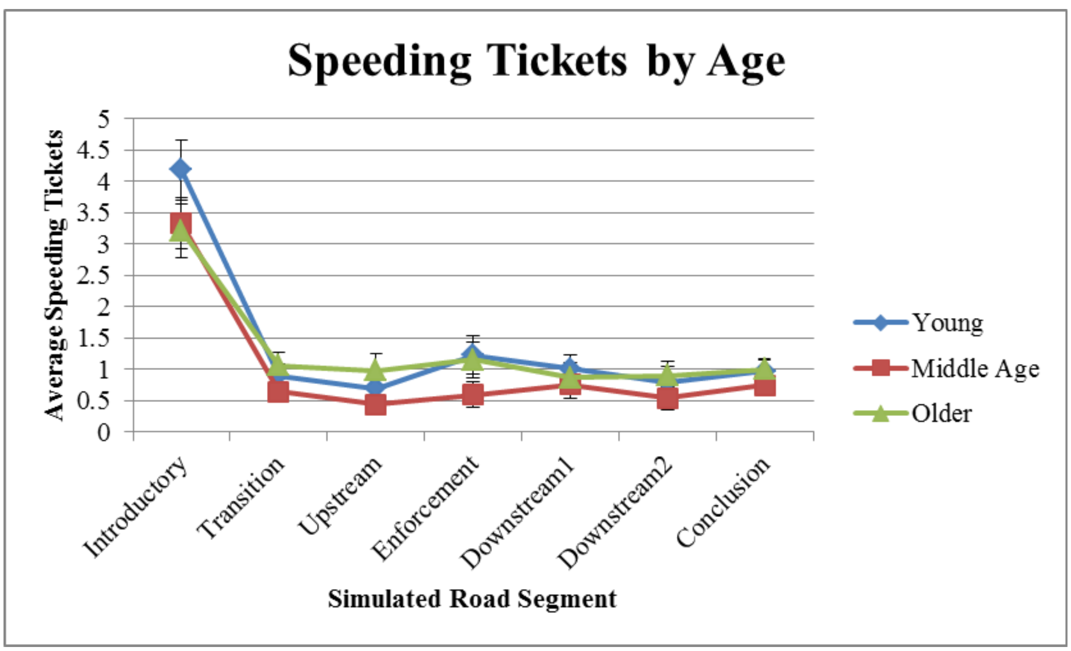


Figure E. 7. ***Frequency of "speeding tickets" in which participants crossed over the 55 mph threshold by age group and simulated road segment (including introductory and conclusion segments).***

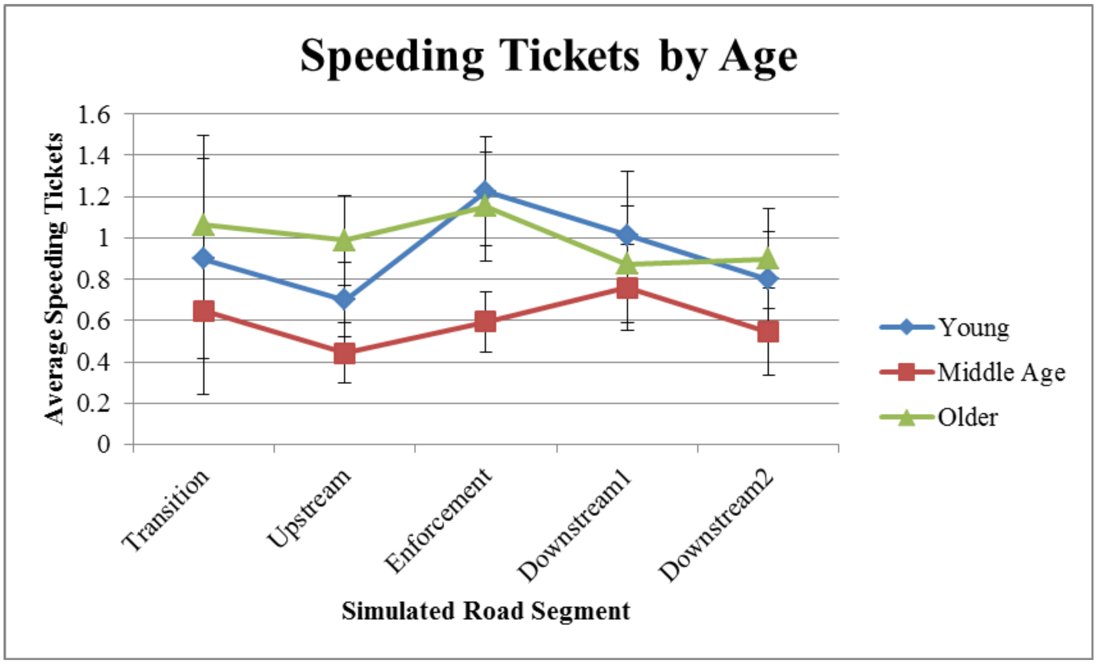


Figure E. 8. Frequency of "speeding tickets" in which participants crossed over the 55 mph threshold by age group and work zone segment (without introductory and conclusion segments).

E.2. Car-Following Performance Data

Car following did not begin until the lead vehicle entered the transition zone. The lead vehicle traveled at a constant speed in the introductory and conclusion segments of the simulated roadway. Hence, the two segments are not included in Coherence or Modulus data visualizations. It is of interested to examine how closely participants drove to the lead vehicle inside and outside the work zones, so the extraneous road segments are included in the Median Time Headway and 85th Percentile Time Headway visualizations.

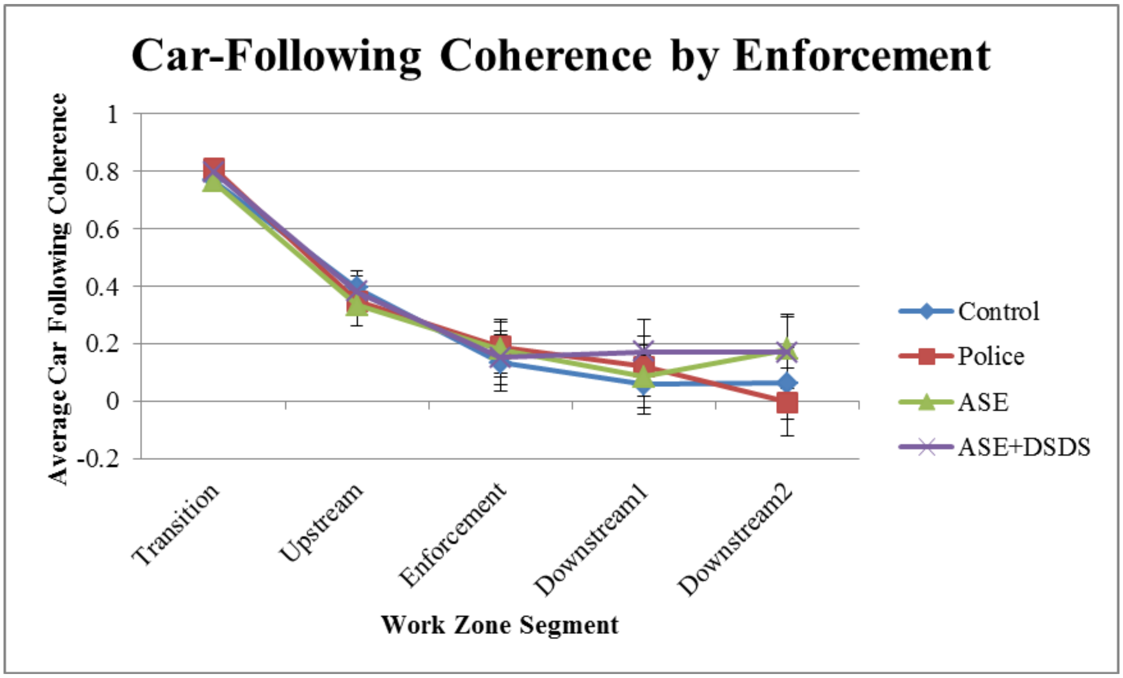


Figure E. 9. Average coherence to speed changes by lead vehicle by enforcement condition and work zone segment (without introductory and conclusion segments).

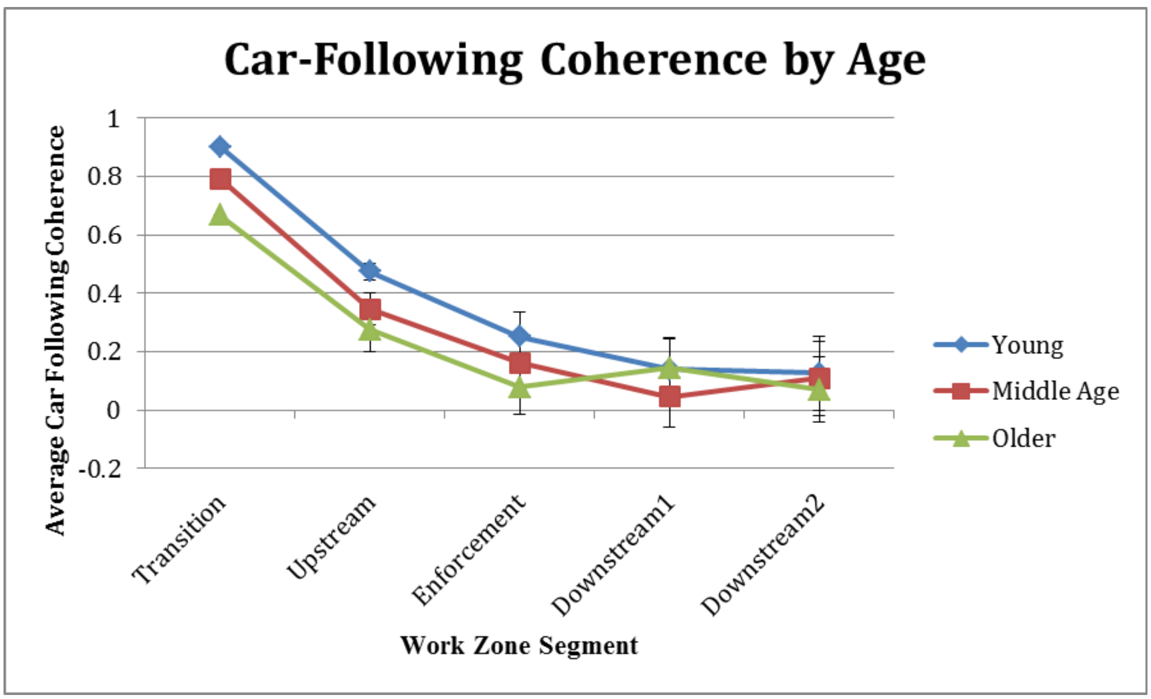


Figure E. 10. Average coherence to speed changes by lead vehicle by age group and work zone segment (without introductory and conclusion segments).

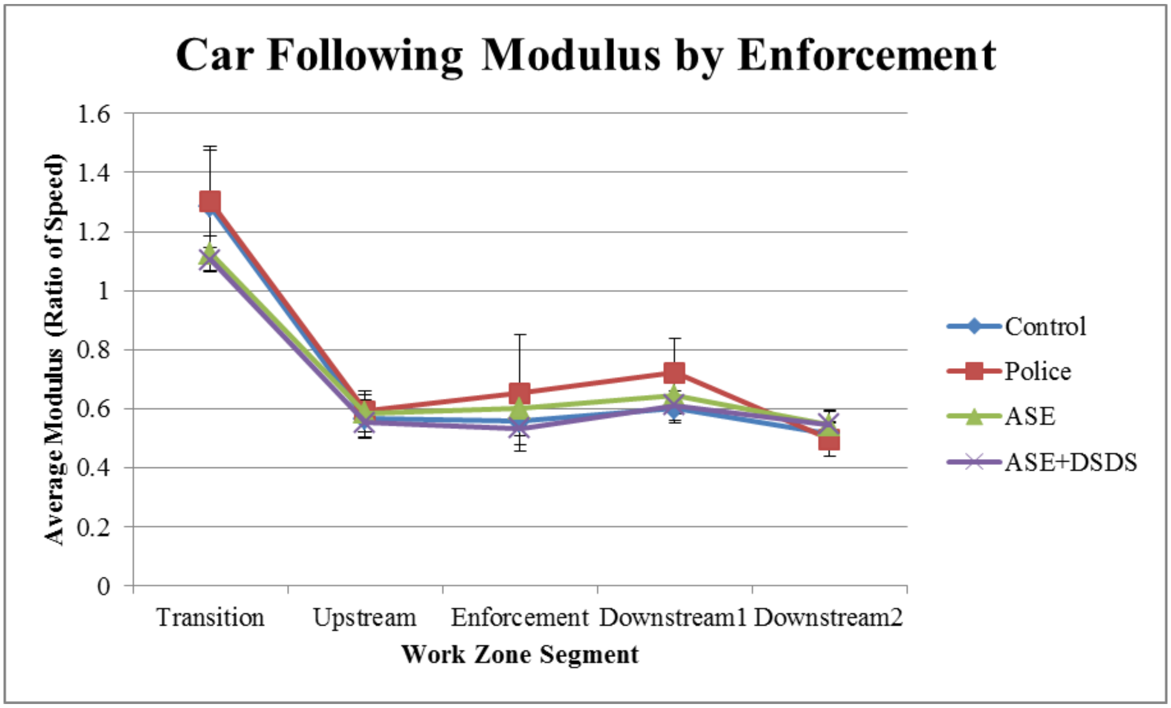


Figure E. 11. Average modulus, or ratio, of participant matching minimum speeds of lead vehicle by enforcement condition and work zone segment (without introductory and conclusion segments).

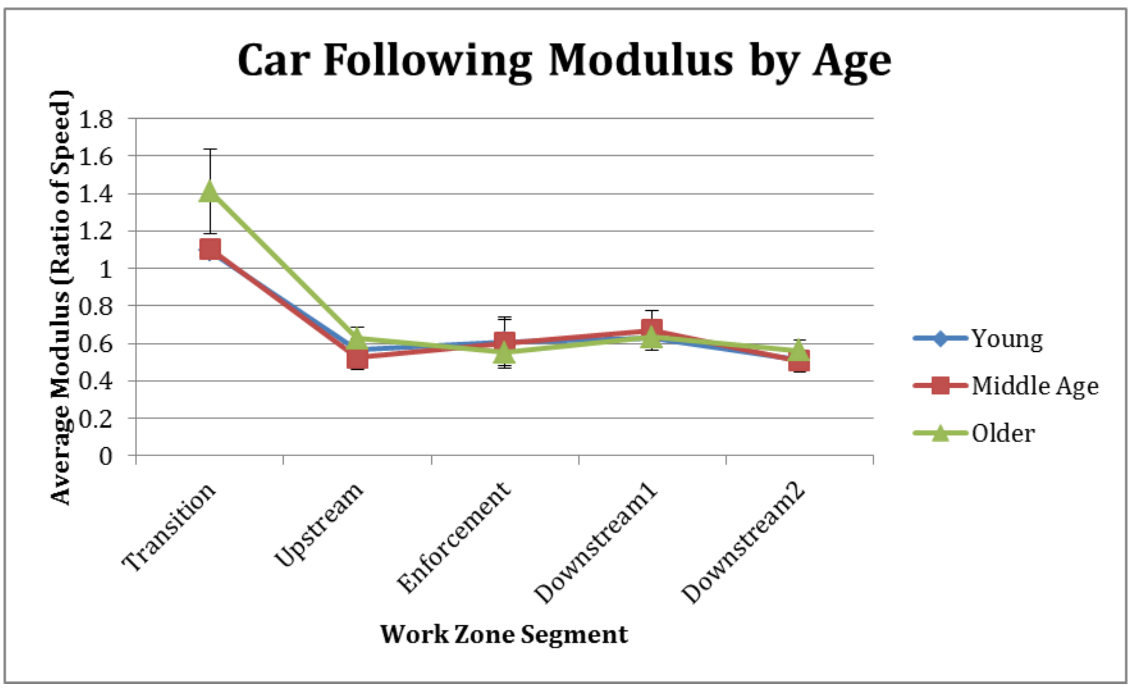


Figure E. 12. Average modulus, or ratio, of participant matching minimum speeds of lead vehicle by age group and work zone segment (without introductory and conclusion segments).

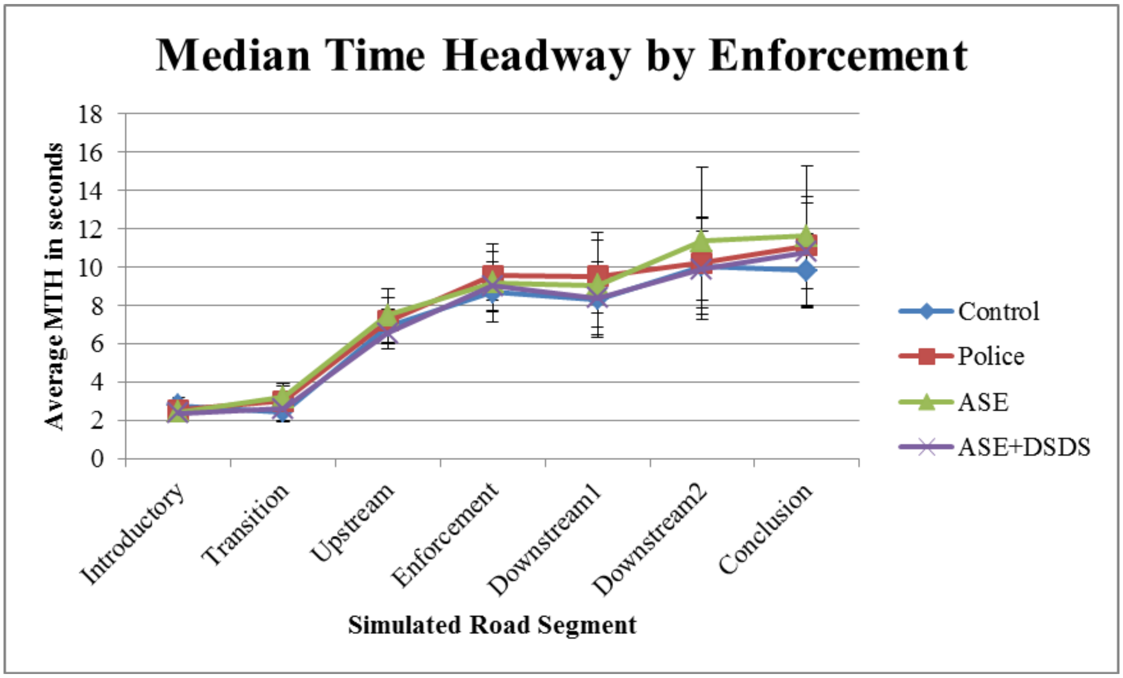


Figure E. 13. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in by enforcement condition and simulated road segment (including introductory and conclusion segments).

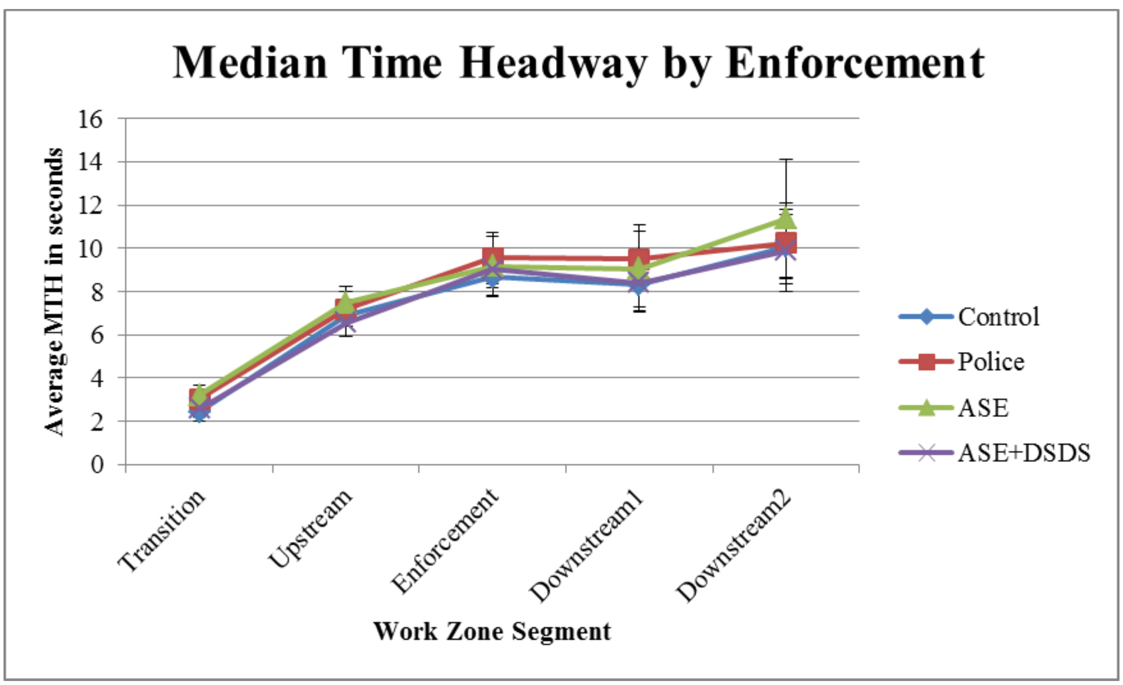


Figure E. 14. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in by enforcement condition and work zone segment (excluding introductory and conclusion segments).

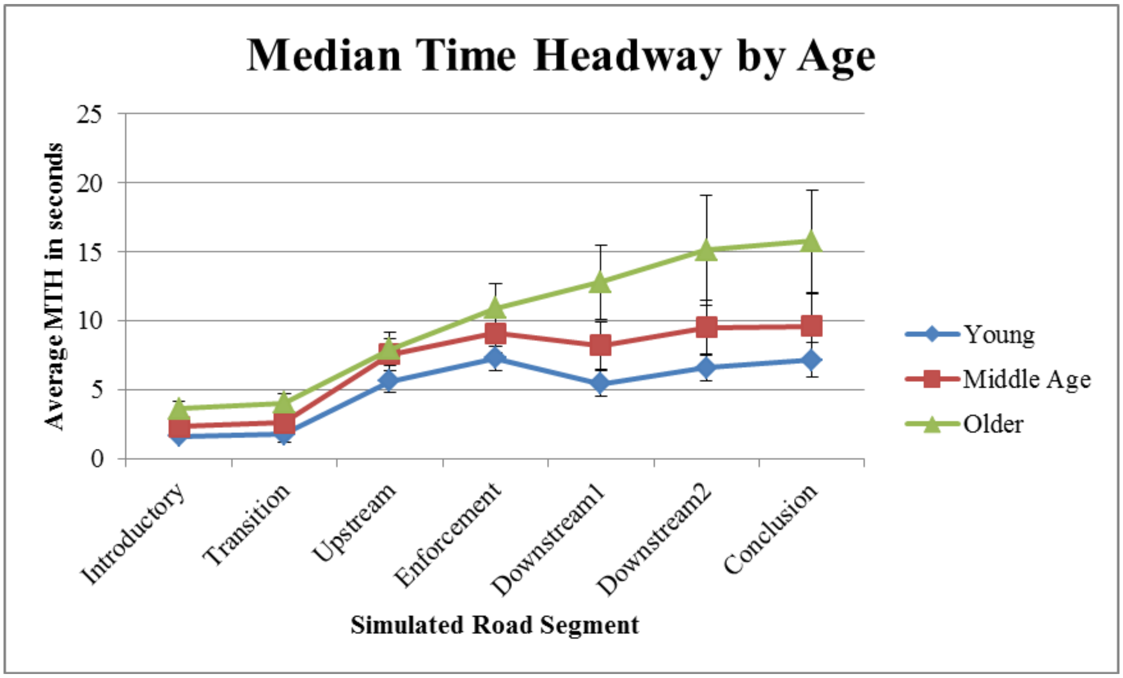


Figure E. 15. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in by age group and simulated road segment (including introductory and conclusion segments).

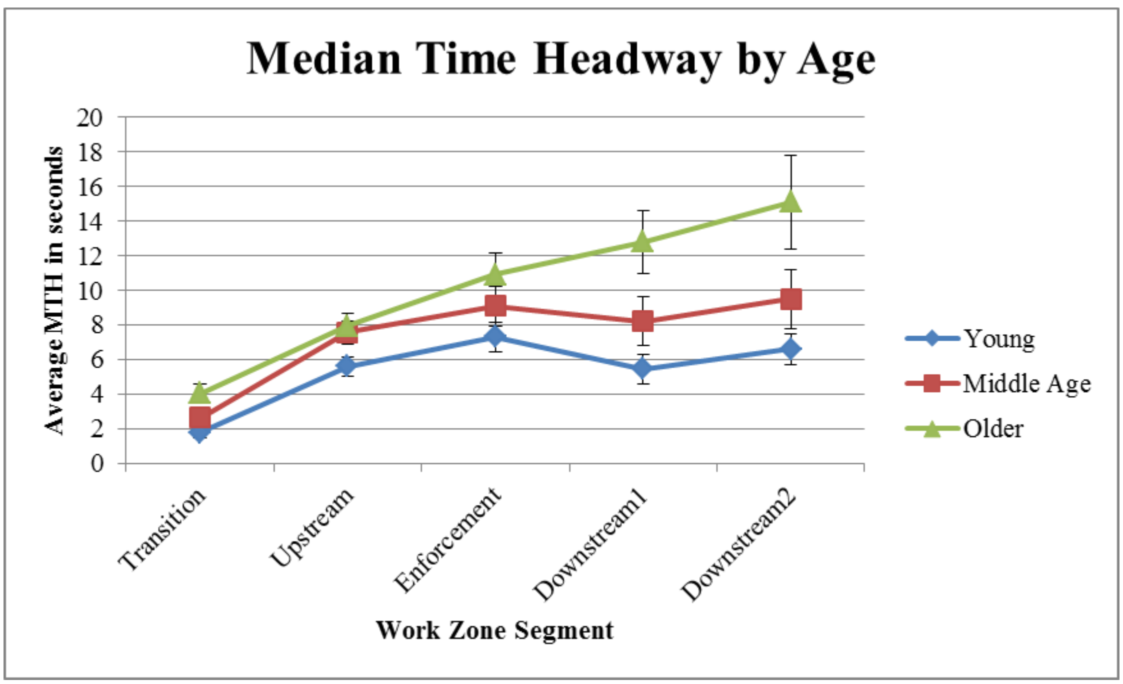


Figure E. 16. Average following distance, measured as Median Time Headway (MTH), to lead vehicle in by age group and work zone segment (excluding introductory and conclusion segments).

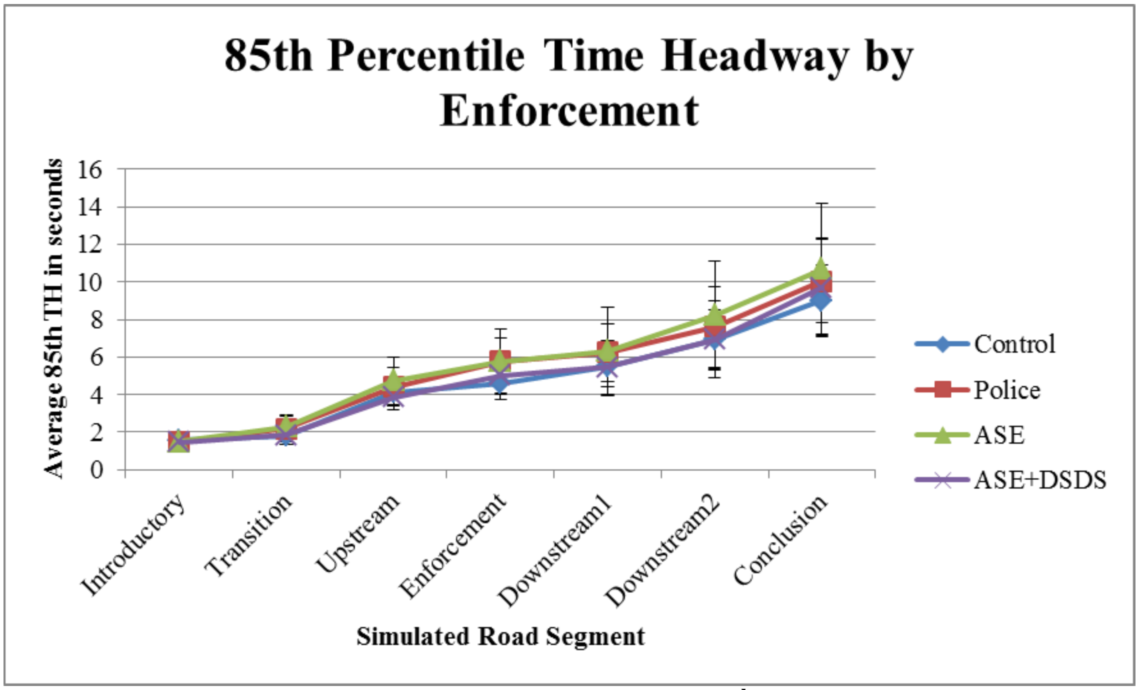


Figure E. 17. Average following distance, measured as 85th Percentile Time Headway (85th TH), to lead vehicle in by enforcement condition and simulated road segment (including introductory and conclusion segments).

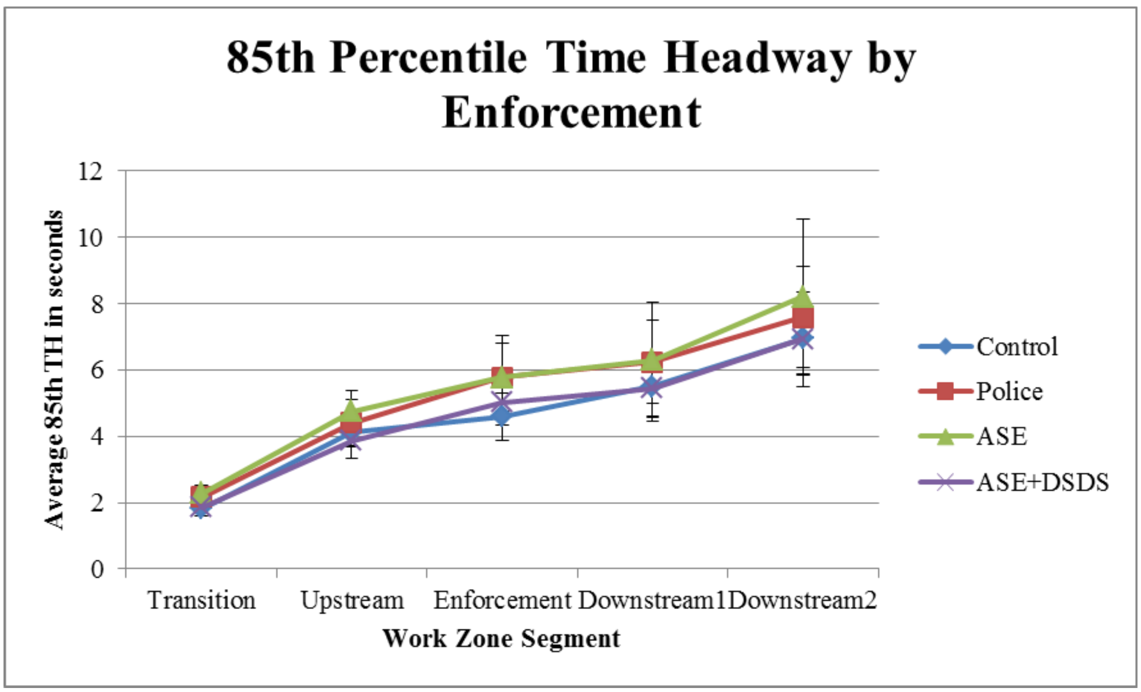


Figure E. 18. Average following distance, measured as 85th Percentile Time Headway (85th TH), to lead vehicle in by enforcement condition and work zone segment (excluding introductory and conclusion segments).

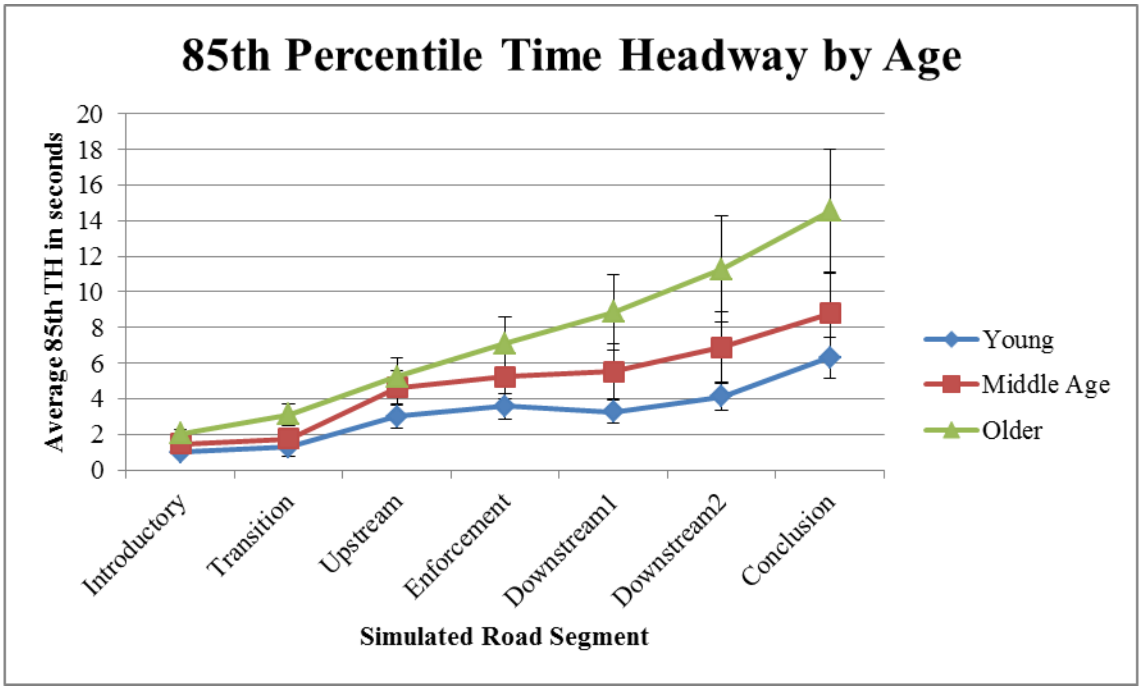


Figure E. 19. Average following distance, measured as 85th Percentile Time Headway (85th TH), to lead vehicle in by age group and simulated road segment (including introductory and conclusion segments).

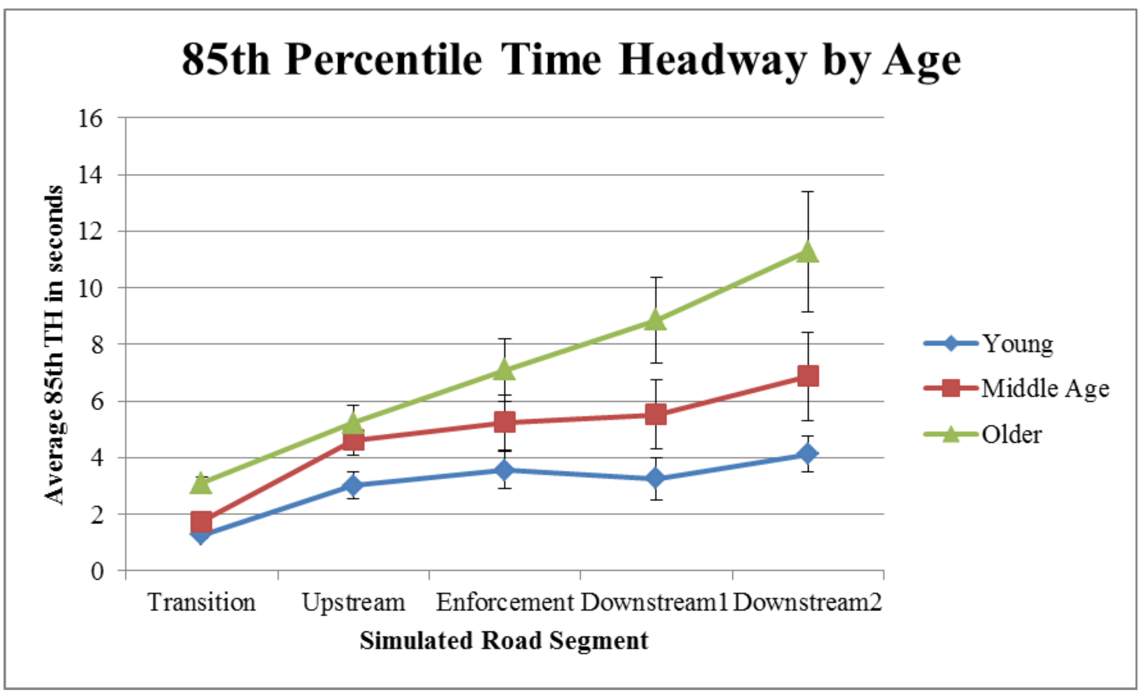


Figure E. 20. Average following distance, measured as 85th Percentile Time Headway (85th TH), to lead vehicle in by enforcement condition and work zone segment (excluding introductory and conclusion segments).