Final Report

A Comprehensive Study on CMV Safety Using ITS in Work Zones on Freeways and Arterials

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Work zones pose significant safety challenges on highways, with Commercial Motor Vehicles (CMVs) being particularly susceptible to higher risk due to their larger size, slower acceleration/deceleration rates, and expanded blind spots. This study aimed to assess the impact of various work zone warning measures on the driving behavior of CMV operators. These measures encompassed static work zone signs, Intelligent Transportation Systems (ITS) warning devices, connected and autonomous vehicle (CAV) technologies, as well as autonomous vehicle (AV) technologies. Over 50 subjects participated in this research to drive a simulated network in a driving simulator environment featuring three distinct work zones. A total of 20 scenarios, incorporating different traffic patterns, lighting options, and weather conditions, were utilized to observe driver's behavior under various warning systems. Vehicles' speed, brake use, throttle, longitudinal jerk, and lateral movement were analyzed to evaluate driver's behavior. The findings of the study demonstrated that the presence of signs and warnings significantly enhanced driver behavior compared to scenarios with no signs or warnings. While static signs led to more reactive behavior, ITS and CAV technologies encouraged proactive responses among drivers. Furthermore, when AV technology was introduced in the simulated work zones, the CMVs experienced quicker return to normal driving conditions, as far as speed adjustment and lane changing. This research suggests that the integration of CAV and AV technologies in CMVs serves as a valuable tool for improving highway safety, particularly within work zone areas.</td></tr>
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ABSTRACT

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Vehicles' speed, brake use, throttle, longitudinal jerk, and lateral movement were analyzed to evaluate driver's behavior. The findings of the study demonstrated that the presence of signs and warnings significantly enhanced driver behavior compared to scenarios with no signs or warnings. While static signs led to more reactive behavior, ITS and CAV technologies encouraged proactive responses among drivers. Furthermore, when AV technology was introduced in the simulated work zones, the CMVs experienced quicker return to normal driving conditions, as far as speed adjustment and lane changing. This research suggests that the integration of CAV and AV technologies in CMVs serves as a valuable tool for improving highway safety, particularly within work zone areas.

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1. Introduction

The work zone is a part of the highway with construction work that affects traffic flow and road users' activity. A typical work zone area consists of advance warning signs, re-routing devices to manage traffic movement, the actual work area (called the activity area) and the termination zone where drivers return to their regular route (Yue et al., 2009). The need for roadway construction increases as vehicular demand grows in the road network, leading to more work zone safety concerns over time. Work zone crashes concern transportation engineers and policymakers, and several ongoing research projects are developing new ideas to reduce work zone crashes. Speeding is a major contributor to work zone crashes. When compounded with lane closures and narrow lanes, speeding creates a more dangerous situation for drivers. As more construction takes place at night to prevent congestion on roadways, low visibility and driver fatigue present additional hazards in work zones. Due to safety concerns, some highway agencies are reluctant to modify or change current practices without substantial proof that such changes will not create additional hazards for the motorists or the construction workers (McAvoy, 2007). According to the Federal Highway Administration (FHWA) a crash occurs in a work zone every 5.4 minutes (per 2015 data) (Khalil and Samir, 2018). In 2020, 857 fatal work zone crashes occurred, which was a 3% increase over the previous year. Travelers or riders are not the only victims of work zone crashes; highway workers also suffered from fatal crashes. In 2017, 132 workers were killed, and heavy vehicles were involved in 222 crashes. A better understanding of the causal factors related to work zone crashes is essential to designing effective countermeasures. (FHWA Work Zone Facts and Statistics, 2019).

1.1. Problem Statement

Work zones play a key role in maintaining and upgrading roadways. According to the FHWA, 20% of the national highway system is repaired during construction season, and almost 12 billion vehicle-miles travel through work zones annually. Unfortunately, work zones increase the probability of crashes, injuries and fatalities because they reduce roadway capacity, create irregular traffic flow, change lane configurations and narrow rights-of-way. However, work zones are necessary to maintain and rehabilitate our transportation infrastructure. As our transportation system ages, more maintenance and construction are needed, creating the need for more work zones. Commercial motor vehicles (CMVs) are more prone to work zone-related crashes than passenger vehicles because they are typically wider, heavier and have larger blind spots. They also have lower acceleration and deceleration rates and greater distance between the driver's eyes and the vehicle's headlights. In work zones, closed shoulders and tighter lanes make CMV's specific characteristics more dangerous than those of other vehicles. It is also more challenging for CMVs to change lanes in a work zone, especially when exiting or entering a ramp. CMV crashes are also more prone to creating chain incidents due to their size (FHWA, 2017). Total work zone fatal crashes increased from 688 in 2016 to 710 in 2017, with about 90% of which occurring on arterials and freeways. Speeding was a major factor (28%) in fatal work zone crashes. Fatal work zone crashes involving large trucks and buses increased from 189 in 2016 to 222 in 2017, comprising 32% of all fatal crashes (FHWA, 2018). Various studies on work zone safety have been performed, some of which focused on CMV safety issues. Li and Bai (2009) found that trucks were involved in 42.4% of fatalities and 15.5% of injuries in work zones. They also found that the fatality likelihood is tripled when heavy trucks were involved in severe crashes. UMass Safe (2012) found that CMV crashes in work zones happen at about twice the rate as those of other vehicles. Also, the probabilities of injuries and fatalities of CMV crashes are twice as high as regular vehicle crashes in work zones. Akepati and Dissanayake (2011) found that 10.3% of work zone crashes involved heavy-duty vehicles. Swanson (2012) stated that 24% of work zone crashes involved school buses, and that a higher percentage of CMV crashes occur in work zones with a standing vehicle in dark visual conditions (nighttime driving).

1.2. Study Objectives

Reviewing the literature in this field, it appears that a comprehensive study to evaluate various ITS (Intelligent Transportation Systems) safety countermeasures in work zones is lacking. Furthermore, no connected autonomous vehicle (CAV) or autonomous vehicle (AV) technology has been deployed or tested to reduce crashes in work zones, especially for CMVs. The proposed research will evaluate the effect of CAV technologies to reduce crashes in work zones. The main objective of this study is to test different work zone warning measures (static signs, use of ITS, CAV and AV technologies) to design effective countermeasures.

The study utilizes a driving simulator and an eye-tracking system to evaluate the effect of various ITS (including CAV and AV) safety countermeasures and find the most effective method or combinations of methods to improve safety in work zones. This will be performed by simulating various driving scenarios for CMV near work zones. The scenarios will consist of work zones on an arterial and a highway. The driving behavior of CMV participants when approaching and passing a work zone in the presence of different work zone warning types is tested in the simulator environment. Participants from different sociodemographic groups are recruited to drive a simulated CMV.

2. Literature Review

2.1. Work zone Components

Different handbooks are available online for work zone safety and temporary traffic control zones. All of the handbooks divided the entire work zone into four parts as a temporary traffic control zone as follows: 1. Advance warning area; 2. Transition area; 3. Activity area and 4. Termination area. **Figure 1** shows a graphical representation of these segments.

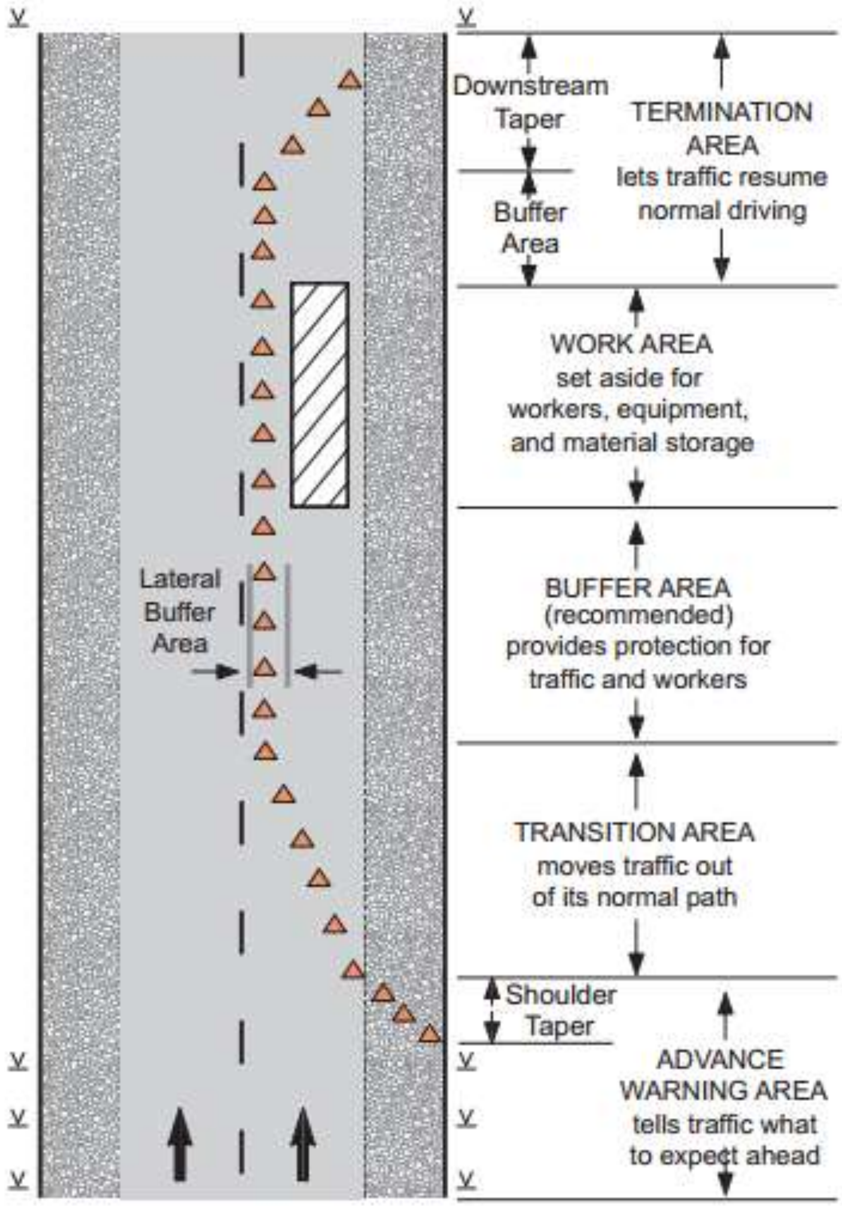


Figure 1: Component Part of Work-zone Area.

Source: Work-zone Safety: guidelines for construction, maintenance, and utility operation.

Advance warning area. This section starts before the work zone on any highway. In this section, users obtain information about the upcoming work zone through one or more signs.

Transition area. In transition areas road, users are typically redirected from their usual path on the highway. The transition area consists of a taper with channelizing devices to redirect vehicles. There are five types of tapers used in this area with different lengths for each type of taper. The length of the taper is measured based on the speed of traffic. The basic types of tapers with their respective lengths are presented in **Table 1**.

Table 1: Transition area type of taper and taper length.

Type of Taper	Taper Length
Merging Taper	L minimum
Shifting Taper	½ L minimum
Shoulder Taper	1/3 L minimum
Two-way traffic taper	100 feet (30m) maximum
Downstream taper	10 feet (30m) per lane minimum

For 40 MPH or less $L= W*S^2/2$ and 45 MPH and more $L= W*S$. Here, L= Taper length in feet; W= width of offset and S= Posted Speed.

Activity area. The activity area consists of three parts: a workspace, a buffer space and a traffic space.

Workspace. This is the portion of the highway where the actual work takes place. The workers, equipment, shadow vehicle and materials are situated in this area. The shadow vehicles are always placed in the workspace.

Buffer space. The buffer space is the lateral or longitudinal portion that separates the regular vehicle flow from the work area. The longitudinal buffer space prior to a work area in work zones provides a recovery space for an errant vehicle. No work activity takes place in the buffer area, and it is not recommended to place any equipment, material, or vehicles in this area. Buffer space length also depends on traffic speed. To measure how long the longitudinal buffer space should be, the posted speed, off-peak free flow 85^{th}-percentile speed, or the anticipated operating speed from the available data are used. **Table 2** represents the typical longitudinal buffer space lengths based on traffic speed.

Table 2: Buffer space length based on traffic speed.

Speed (mph)	Length (feet)	Speed (mph)	Length (feet)
20	115	45	360
25	155	50	425
30	200	55	495
35	250	60	570
40	305	65	645

Traffic space. The traffic space is the portion of the road in which road users are routed through the activity area.

Termination Area., The traffic returns to the typical path through the termination area. This part of the work zone area belongs from the downstream end to the "end road work" signs.

2.2. Contributing Factors to Work Zone Crashes

Existing highway facilities need regular upgrades and maintenance due to age and increasing traffic flow. Thus, work zones are permanent part of our roadway infrastructure, and the safety of these sections of the road remains a major concern. Work zones increase the number of crashes and make the roadway more dangerous for road users and workers. Past research has demonstrated this fact. Shi et al. (2008) showed that in Finland and Slovenia, road users are five times more vulnerable traveling through a work zone than a non-work zone area. The European Transport Safety Council reported in 2011 that almost one-quarter of highway road crashes in Germany occurred in work zones. One study about risks for work zone workers in the United Kingdom reported that 54% of workers saved themselves from moving vehicles by chance (UK Highways Agency, 2006). The United States also has a high work zone fatality and injury rate. Yingfeng & Yong (2009) showed that the majority of worker fatalities in work zones occurred when the victim was stuck by other vehicles or construction equipment.

Several factors contribute to work zone crashes. Shrock et al.'s study (2004) demonstrated that features of the work zone directly influenced 8% and indirectly influenced 39% of all work zone crashes. Roadway characteristics, road geometry, environmental conditions, secondary congestion, driver behavior and roadside hazards are some of the primary contributors behind work zone crashes (ETSC, 2006; Zhao et al, 2001, Chambless et al, 2002; Schrock et al, 2004; Arditi et al, 2007; Ullman et al, 2008; Dissanayake and Akepati, 2009; El-rayes et al, 2013). Other factors contributing to crashes in work zone areas include unprotected work areas, confusing signage, missing safety alarms for heavy machinery, road closures and missing buffers or tapers (Ibrahim umer, 2018). Bryden et al. (1998) found that work zone traffic control devices were involved in one-third of all work zone accidents, and that 37% of those crashes led to serious injury. Heavy vehicle involvement, collision type, light conditions and roadway classification were also significant variables in fatal work zone crashes (Daniel et al, 2000). Qi et al. (2005) found a correlation between weather conditions and rear-end crashes in work zones, whereas Schrock et al. (2004) identified weather and lighting conditions, alcohol and drug use as crucial factors behind fatal work zone crashes. Another study analyzed crash characteristics like the weather, vehicle conditions, alcohol involvement and injury severity and reported that most work zone crashes occur due to traffic control device deficiency and driver contribution (speeding, lack of yielding and inattentive driving) (Dissanayake and AKepati, 2009).

Other studies investigated the impact of work zones on crash rates and road safety. Several studies found that work zone crashes were more severe than non-work zone crashes. (Pigman and Agent, 1990; Garber and Zhao, 2002). Rouphail et al. (1998) examined the crash rate variation before and after a construction period. They found that the crash rate increased by 88% in the presence of the work zone during the construction period and decreased by 34% after the construction period ended. Another study by Hall and Lorenz (1989) also found that the crash rate increased by 26% during the construction period. Juergens (1962) discovered increases in the crash rate from 7% to 21% in 10 work zones. Short-term work zones likewise faced a constant accident rate of .80 crashes per mile per day. One study on multilane and two-lane highways in Virginia showed an average crash rate increase of 57% and 168%in the presence of work zones, respectively (Garber and Woo, 1990).

However, some studies showed that not all work zones experience an increased crash rate. Pigman and Agent (1990) showed that five out of the 19 work zones in their study did experience any crash rate increases, and other studies have even observed a lower crash rate during the construction period (Graham et al, 197; Jin et al, 2008).

2.3. Work Zone Crash Analysis by Area

Several studies investigated crash frequencies in different work zone sections (Nemeth and Migletz, 1978; Hargroves, 1981; Pigman and Agent, 1990; Schrock et al, 2009; Saleem and et al, 2006; Akepati, S.R., and S. Dissanayake, 2011; Garber and Zhao, 2002; Nemeth and Rathi, 1983; Khattak and Targa, 2004; Qin et al, 2007; Srinivasan et al, 2008). The activity area is identified as the most crash-prone location by most studies (Hargroves, 1981; Pigman and Agent, 1990; Schrock et al, 2009; Saleem and et al, 2006; Akepati, S.R. and S. Dissanayake, 2011; Garber and Zhao, 2002). Some studies found that 70% to 80% of work zone crashes occur in the activity areas (Garber and Zhao, 2002 and Pigman and Agent, 1990). Transition areas (Jin and Saito, 2009), buffer areas (Nemeth and Migletz, 1978) and advance warning areas (Nemeth and Migletz, 1978) were also identified as the most crash-prone areas in some studies. One literature review indicated that on average, about 55% of crashes occurred in buffer or activity areas (Yang and et al, 2014). Some studies described state highways and rural interstates as more crash-prone work zone locations (Pigman and Agent, 1990; Chambless et al, 2002). Garber and Zhao (2002) found that rural highways are less prone to work zone crashes than urban ones. They also stated that crashes decrease through activity and termination areas. (Garber and Zhao 2002). The ability of researchers to identify crash hot spots in work zones is limited, as the length of the work zone varies in different projects. Moreover, research studies mostly rely on crash reports and rarely obtain spatial data to analyze. Therefore, more comparisons among work zones at different facility types would be beneficial to identify work zone hot spots.

With respect to crash type, rear-end crashes were found to be the predominant work zone crash type (Rouphail et al, 1988; Hall and Lorenz, 1989; Pigman and Agent, 1990; Garber and Woo, 1990; Chambless and et al, 2002; Garber and Zhao, 2002; Wang and et al, 1996). One study found that during the construction period, rear-end crashes increased by 9% to 14% (Hall and Lorenz, 1989), while another study found a 50% increase of rear-end crashes during the construction period

(Rouphail et al, 1988). Daniel et al. (2000) found that head-on and single-vehicle crashes are leading cause of fatalities in work zone crashes. Heavy vehicle involvement also increased the likelihood of fatalities in crashes with multiple vehicles (Pigman and Agent, 1990; Schrock et al, 2004).

Other studies recognized time as an essential factor behind work zone crashes. Arditi et al. (2007) stated that nighttime construction is five-times more hazardous than daytime construction in terms of crash fatalities. However, different studies found that most work zone crashes occur in the daytime. Bai and Li (2007) found that 10 am to 4 pm (off-peak period) is when most crashes with injuries in the work zone occurred. One study found that most work zone crashes took place in broad daylight, while another study found no significant difference between daytime and nighttime on work zone crash risk (Ullman et al. 2008).

2.4. Simulator Studies Regarding Work Zones

It is nearly impossible to evaluate work zone safety measures and investigate driving behaviors on actual roadways. Driving simulators can safely and reliably evaluate safety measures and driver's behaviors through different experiments, however. Bella (2009) concluded that driving simulator studies provided enough visual information to allow participants to perceive speed and distance correctly. Other studies compared studies in simulated work zones with those of real-world work zones (Bella, 2004, 2006; Bham et al., 2014; McAvoy et al., 2007). Several studies also evaluated the behavior of drivers approaching and moving through work zones in a driving simulator (Allpress and Leland, 2010; Bella, 2009b; Gustafsson et al., 2014; McAvoy et al., 2011; Nelson et al., 2011; Sommers and McAvoy, 2013; Ullman et al., 2005, 2007). Domenichini et al. (2017) performed a driving simulator study with 42 participants to understand drivers' attitudes in response to nine different configurations of a highway crossover work zone. They collected speed and deceleration data, and the analysis demonstrated that drivers' speeds were always higher than the posted speed in work zones. The speeds decreased when participants drove within bypasses. Long et al. (2016) performed simulator-based research with 75 participants to evaluate drivers' responses to work zone sign configurations. This study compared the Conventional Lane Merge (CLM) configurations with the Missouri Department of Transportation (MoDOT) alternative configurations. The results were also compared with MoDOT's previous study. No differences were found in travel time or speed between the different scenarios. Aghazadeh et al. (2013) performed a similar simulation study to evaluate drivers' behaviors in work zone conditions. They used three different scenarios to compare the Conventional Lane Merge (CLM) and Joint Lane Merge (JLM) configurations. The results showed that driving time in the JLM configuration was 18.8% longer than that of the CLM. However, no significant difference in speed was found between two configurations. The overall analysis suggested that JLM configuration encourages drivers to remain in the closed lane longer.

McAvoy et al. (2011) performed a simulator study to determine the primary factors in work zone crashes. They had 45 participants drive through 24 different work zone configurations. The study found that the most hazardous work zone configurations were divided roadways with a lane closure in low-density traffic conditions and stopped vehicles. In an earlier study, McAvoy et al. (2007) assessed the ability of a driving simulator to evaluate the effectiveness of temporary traffic control devices in a work zone during nighttime hours. The research was performed in two phases through field study and simulator study. The simulator study had 127 human subjects drive through work zone scenarios. They used statistical analysis to determine the difference in participant's performance in the simulator and field. Their study found significant speed differences in comparison to field and simulated study.

Reyes et al. (2010) evaluated the effect of various work zone interventions on driver performance in a driving simulator. They had 25 participants drive in simulated work zones with concrete barriers. The results showed that drums and channelizers affected driving performance differently depending on the work zone conditions. The 4-ft lateral buffer helped to reduced speed variability, and areas of high work zone activity produced a slower average speed and increased speed variability. Bella (2009) conducted a study in a driving simulator to understand driver behavior close to crossover work zones. In this study, four work zone scenarios were used, and the mean speeds and deceleration rate data were collected in response to different types of signaling and work zone geometry. The results found that drivers drive at higher speeds than the posted limit, and that the mean speeds are lower only in the crossover area.

2.5. Heavy Vehicle Involvement in the Work Zone Studies

Commercial motor vehicles (CMVs) are more prone to crashes while traveling through work zones due to their limited maneuverability and large blind spots. Different studies have indicated that heavy truck-related crashes increase the probability of multiple vehicle involvement and fatalities in work zone crashes. Swansen (2012) performed a study on the relationship between work zone-related crashes and work zone design. The analysis determined that from 2008 to 2009, work zone-related crashes increased from 1000 to 2000, respectively. Another interesting finding was that 24% of work zone crashes involved school buses, and a higher percentage of CMV crashes occurred in work zones with standing vehicles in dark visual conditions. As in the work zones, the lanes are narrow which made it harder for CMV drivers to navigate around a parked vehicle. Another study performed by Schrock et al. (2004) found that 29% of fatal crashes involved large trucks. Their study also revealed that in such cases, large trucks would often hit up to three or more vehicles, particularly when driving in work zone areas. Hill et al. (2003) at Texas Tech University analyzed fatal work zone crashes in the State of Texas. They analyzed different parameters including the involvement of heavy commercial trucks. Their evaluation indicated that commercial truck-related crashes in work zones involved multiple vehicles.

Daniel et al. (2000) evaluated all fatal work zone crashes in Georgia from 1995 to 1997 using the state's crash report database. The data evaluation shows that in Georgia, 20% of fatal crashes involved trucks in work zones compared with only 13% of non-work zone fatal crashes. Ha and Nemeth (1995) conducted a study of effective work zone traffic control strategies. In the first stage of the study, they performed a literature review stating that the involvement of trucks in crashes at work zone crossovers was significant. Benekohal et al. (1995) conducted a survey with semi-trailer drivers in Illinois to study truck drivers' concerns about traffic control in work zones. The survey results indicate that 90% of truck drivers felt that driving through a work zone is hazardous. Half of the drivers requested more warning signs 3 to 5 miles ahead of work zones.

2.6. Using Safety Measures in the Work Zone

Different strategies are taken by government agencies to reduce work zone crashes and improve safety. Walter and Broughton (2011) performed a study on the effect of speed indicator devices (SIDs) on reducing speed. For the study, SIDs were installed in 10 different places in south London for one- to three-week periods. They found that the mean speed reduces by 1.4 mph and the number of the vehicles exceeding the speed limit fell after the devices were installed. However, once the SID was removed, the mean vehicle speed returns to its level prior to installation. Franz and Chang (2011) performed a pilot study for the Maryland State Highway Administration to evaluate the effectiveness of an automated speed enforcement system in work zones. They compared two data sets before and during the analysis periods. At the time of the automated speed enforcement period, motorists drove less aggressively, and researchers observed a more stable speeding distribution in the work zone. Another comparison from two of the three data sets showed that motorists adjust their speed near speed enforcement areas. In a study in Illinois, Benekohal et al. (2010) found that speed photo radar enforcement (SPE) results in a reduction of mean speed. For a regular car, the mean speed was reduced by 6.3-7.9 mph in the median lane and 4.1-7.7 mph in the shoulder lane. For CMV, the reduction was 3.4-6.9 mph in the median lane and 4.0-6.1 mph in the shoulder lane. The speeding behavior of both cars and trucks reduced after the enforcement zone. Benekohal et al. (2009) performed a similar study which found that in one work zone, the average speed of trucks was reduced by 1.8-2.7 mph. The percent of speeding cars and trucks in both lanes was also reduced. A study by Medina et al. (2009) also showed a minor mean speed reduction pattern after an SPE installation. The cars showed a speed reduction of 2 to 2.9 mph, and trucks reduced their speed by up to 7.5 mph. Their study finds that both cars and trucks have a speed reduction of 1.5 miles downstream from the SPE location.

The Washington DOT had an automated enforcement pilot project from 2008 to 2009 in two highway work zones. They compared the data from before, during, and after the enforcement period. The comparison found that the enforcement program reduced speeding behavior and the average speed of motorists overall. Instances of drivers moving at more than 70 mph declined from 18% before ASE deployment to 8-13% during the enforcement period. The Oregon DOT performed a similar study for six months from March to September of 2009 and found a 27% reduction in speeding during the enforcement period. In both cases, the travelers returned to their previous speeding behavior when the enforcement vehicle was removed. Sommers and McAvoy (2013) conducted a driving simulator experiment, and their post hoc tests indicated that the presence of construction workers, construction vehicles, law enforcement, speed photo enforcement and shifting lanes reduced speeds in work zones most effectively. The least-effective speed reduction measures were strips, concrete barriers, other channelizing devices and changeable message signs, which reduce speeds by only 10 mph. Sun et al. (2011) used Sequential Flashing

Lights (SFL) set at 60 flashes per minute. These SFLs were deployed near the right lane on a two-lane interstate highway with a 60-mph speed limit. The result showed a mean speed decrease of 1 to 2.21 mph.

Transportation agencies are using Intelligent Transportation Systems (ITS) to improve work zone safety (Ullman et al. 2014) by identifying traffic conditions before and within work zones and displaying real-time messages with traffic conditions (slow traffic, travel times, delays). Providing automated, real-time information helps improve driver behavior and reduce distraction. The Michigan Department of Transportation (MDOT) and Wayne State University transportation group jointly developed an ITS function called advanced dynamic early lane merge traffic control system (DELMTCS) for two- to three-lane transition work zones. DELMTCS encouraged motorists to merge early through an enforceable no passing zone. DELMTCS was installed on the I-94 freeway in Michigan, and the implementation study reveals that the system encouraged smoother traffic with a decrease in average delay time and aggressive driving patterns. The Minnesota DOT (2008) also developed an ITS toolbox that included information related to travel time, speed, stopped traffic advisories, traffic responsive temporary signals, temporary ramp metering and dynamic merging. This toolbox can detect an approaching car's speed and uses VMS to display speed information and warning messages. The messages can be selected and used according to the type and location of construction sections.

The Texas Transportation Institute performed a simulation study using portable changeable message signs (PCMS). The PCMSs conveyed messages regarding upcoming traffic conditions in four- and five-unit messages. The study found that the four-unit message sign is easier for drivers to understand than those with five or more units of information (Ullman and et al, 2007). Firman et al. (2008) performed a study in Kansas to evaluate the effectiveness of PCMS. Their study found that the active PCMS reduces the speed of motorists. Another study used a combination of speed photo enforced signs, dynamic speed display signs and reduced speed limit signs to investigate drivers' speeding behavior in work zones. The study used a driving simulator, and the results indicated the speed photo enforced sign was the most effective of the three signs (Banerjee et al. 2019). Another important ITS technology is the end-of-queue (EOQ) warning system. The EOQ warning system consists of a highly portable work zone transportation system with radar speed sensors, which can link with a PCMS. The study shows that the EOQ system positively influences work zone safety and reduces crashes by almost 44%. This technology also reduces crash severity and nighttime crash costs by $1.36 million nationally (Ullman and et al, 2016). One study observed connected vehicles (CVs) in and around a work zone using a microscopic traffic simulator to examine the impact of CVs on mobility. The study used two scenarios; one had a lane closure with ordinary traffic management, and the other was the same scenario with a different penetration rate of CVs. The results showed that CVs can use the re-route system and contribute to congestion mitigation and mobility improvement around the work zone (Olia et al., 2012). Nauto, an artificial intelligence technology company, conducted a study mainly focused on commercial fleet safety by using the in-cab alert system. The results showed that in-cab alert activation reduced drivers' distraction by 40%, duration of distraction by 43% and distracted distance traveled by 47%.

3. Methodology

This chapter describes the tools and research methods used to develop the study network and analyze driving behavior. The research goal is to evaluate work zone safety for Commercial Motor Vehicle (CMV) drivers while using different ITS, CAV, and AV technologies. This research developed each CAV application in a driving simulator environment and used an eye-tracking device to monitor participants' behavior.

3.1. Participants and Study Design

This study recruited fifty-one participants from Morgan State University and the Baltimore metro area. The participants were recruited by distributing flyers manually, online and on social media. The advertisement described a summary of the study's requirements, information regarding COVID-19 restrictions and an explanation of the monetary compensation for participating in the driving simulator study. All the participants were required to have a valid U.S. driver's license and were compensated at $15/ hour (for regular drivers) and $20/hour (for CMV drivers) for their study participation. The study primarily targeted CMV drivers to participate. The research team contacted private and public suppliers of drivers with commercial driving licenses (CDL). The research group also distributed the flyers to bus drivers at local bus stops.

The entire driving experiment lasted 2.5 to 3 hours, and each participant completed twenty scenarios. One principal investigator and a team of graduate and undergraduate students observed and carried out the investigation. In addition, the participants filled up a pre- simulation and a post-simulation survey that was IRB approved. The pre-survey questionnaire collected data on participants' sociodemographic status.

All the simulated scenarios were played on three 40-inch LCD screens and showed the roadway objects from a CMV perspective. The simulator's driver compartment provided a view of the roadway and dashboard instruments, including a speedometer (**Figure 2**). The simulated vehicle also consisted of engine sounds, road noise and sounds of passing traffic to depict the naturalistic aspects of the real world. In addition, the vehicle's kinematics and dynamics specifications, such as brake and throttle measurements, were adjusted to replicate a CMV. Simulated vehicle types (cars, trucks, and buses) with varying speeds and volumes were also randomly generated in the network to interact with the participant's CMV in the road.

Figure 2: The Driving Simulator

The data on the participant's performance were collected through the driving simulator. The data included the vehicle's instant speed, throttle, brake, lateral movement, offset from the road center and lateral movement. All these attributes were logged at second-by-second intervals. A Tobii Pro head-mounted mobile eye-tracking system [34] was also used in this study to collect the participant's gaze frequency and duration. The participant shown in the right image of **Figure 2** wore this eye-tracking system.

Pre-Simulation Questionnaire: The research team developed a pre-simulation questionnaire to understand participants' sociodemographic characteristics, their knowledge about the connected automated vehicle functions, their understanding of different safety applications and their driving strategy near the work zone. Some questions regarding the driver's expectations about future safety applications are also asked. The participants filled this questionnaire before starting the driving sessions. The questionnaire is added in Appendix A.

Post-Simulation Questionnaire: A post-simulation survey was developed to analyze participants' experiences after the driving sessions ended. The questions investigated the effect of different ITS, CAV and AV functions on the driver's behavior, as well as any aspects of the simulator study that may have created a negative impact on the participant's driving behavior. The questionnaire is added in Appendix B.

3.2. Study Network

The VR-Design studio software developed by FORUM8 was used to create a real transportation network northwest of Baltimore consisting of a section of White Marsh Boulevard running towards Southbound I-95. The network started from the intersection of White Marsh Boulevard and Honeygo Boulevard and continued through MD-43 to enter I-95 southbound. The participants were expected to continue driving through I-95 for more than 3 miles and take exit 64 towards Towson. The study network is shown in **Figure 3** with a background map. **Figure 4** also depicts driver's view of the network.

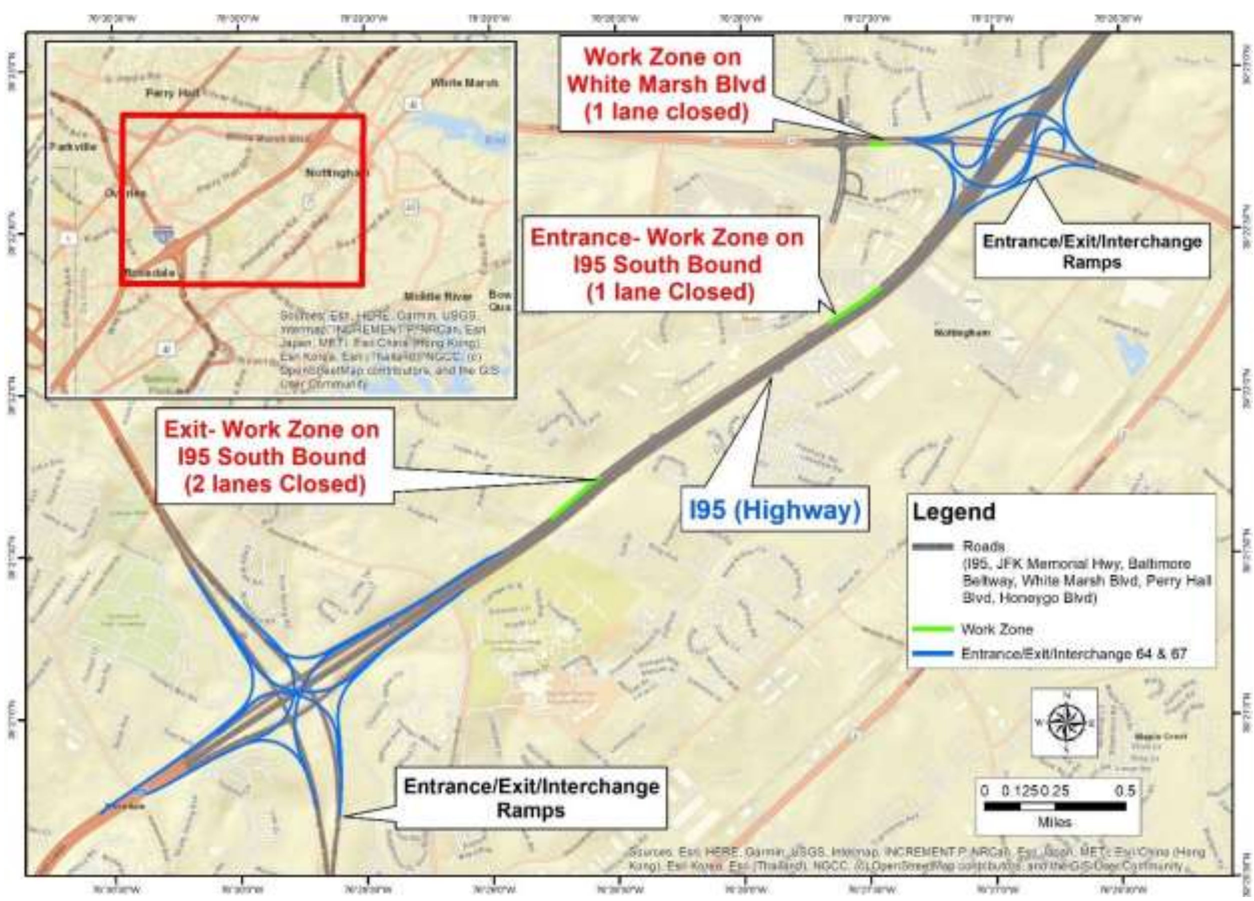


Figure 3: Study Area & Road Network

Figure 4: The starting of the Scenario before Honeygo Boulevard in White Marsh.

3.3. Scenario Design

The research scenarios designed in this study fall under three main categories: base scenario, ITS function and CAV function. Each category has eight potential individual scenarios depending on weather, traffic and vision conditions, shown in **Table 3**. As shown in **Figure 3**, there are three different work zones in each scenario with different work zone characteristics:

- White Marsh Blvd. work zone: one arterial lane closed
- First I-95 work zone: one highway lane closure, right after the in-ramp
- Second I-95 work zone: two-lane closures due to work zones, right before exit 64.

Table 3: Eight sets of weather, traffic, and vision conditions.

Weather Condition	Traffic Condition	Vision Condition
Dry	Mild	Day
Dry	Mild	Night
Dry	Heavy	Day
Dry	Heavy	Night
Foggy	Mild	Day
Foggy	Heavy	Day
Rain	Mild	Night
Rain	Heavy	Night

3.3.1. Base Scenario:

The base scenario consisted of two groups:

- Base scenarios without work zone: In this scenario, participants drove the entire network without any disruptions from work zones.
- Base scenario with work zone, but no warning: In this Scenario, participants were faced with three work zones without a prior warning.

3.3.2. Intelligent Transportation System (ITS):

In this category, participants received a prior warning from different ITS functions such as a Portable Changeable Message Sign (PCMS), Variable Speed Limits (VSL), automated enforcement, Queue Warning System (QWS), and Dynamic Lane Merge System (DLMS). There were five scenarios with a combination of different ITS functions, weather, traffic, and visibility (later in **Table 4**). These scenarios were designed under three weather conditions, two traffic and two visibility conditions. **Figure 5** presents a portable changeable message sign (PCMS) in the driving simulator environment. This ITS function alerted drivers almost 1 mile before the work zone starts (the message changed by scenario).

Figure 5: Use of Portable Changeable Message Sign.

Figure 6 shows a Dynamic Lane Merge sign informing drivers about the next work zone and where they need to merge. In addition, some messages inform the drivers just before the lane merge area with an arrow sign. **Figure 7** represents the weather conditions and time of day in the scenarios, such as rain at nighttime.

Figure 6: Dynamic Lane Merge System (DLMS)

Figure 7: Rain in Nighttime.

3.3.3. Connected Automated Vehicle functions:

The simulator vehicle was coded with some connected automated vehicle functions in these scenarios. Near the work zones, the vehicle sent warnings to the participants through visual messages and voice commands. For example, the CAV exit/entrance warning alerted participants one mile before the next exit or entrance. Other automated vehicle functions included in the study were automated driving voluntarily and automated driving involuntarily. Automated driving voluntarily is an autonomous level 3 capability in which the vehicle warns the driver when approaching a work zone and asks the driver to give control to the automated car. If the driver accepts, the vehicle will automatically pass through the work zone without the driver's interaction. Under the automated driving involuntarily scenario, the vehicle automatically takes control without asking the driver's permission, although it informs the driver ahead of time.

Figure 8 displays the CAV function informing the driver before and after any work zone. In another scenario, the CAV function asked the drivers if they wanted the vehicle to drive itself near work zone #2 (activation of the AV mode). In work zone #1 and work zone #3, the vehicle involuntarily drives itself. The information appeared as a visual message and via a voice command.

Figure 8: Connected & Automated Vehicle function showing work zone entrance warning.

3.3.4. Scenario List

The research started pilot data collection with 50 scenarios under various weather, traffic and visibility conditions. However, due to the long driving sessions (each scenario took between 6 to 11 minutes to complete depending on traffic conditions and participant's speed), the total experiment took more than 6 hours without a break. This was impossible to execute, even by taking breaks as needed. Bringing back the same participants to continue and complete the remaining scenarios had been a major challenge from past research performed in this lab. Therefore, it was decided to merge some scenarios and reduce the number of driving tests. First, we merged all ITS scenarios to cover all the ITS functions (DLMS, PCMS, QWS, VMS) and all variables. Similarly, we combined all the connected autonomous vehicle scenarios into four sets and all the automated driving scenarios into three sets. There were twenty scenarios in all, as shown in **Table 4**.

Table 4: List of Scenarios.

No	Scenario ID	Description of Scenarios	Weather Condition	Traffic	Visibility
1	S0	No work zone	Dry	Mild	Day
2	S1_1	Work zone, No Sign/warning	Dry	Mild	Day
3	S1_2	Work zone, No Sign/warning	Dry	Heavy	Day
4	S2_1	Work zone Static Warning	Dry	Mild	Night
5	S2_2	Work zone Static Warning	Dry	Heavy	Day
6	S2_3	Work zone Static Warning	Rain	Heavy	Day
7	S2_4	Work zone Static Warning	Rain	Mild	Night
8	S2_5	Work zone Static Warning	Rain	Heavy	Night
9	S3_1	ITS (DLMS/VSL/QWS/PCMS)	Dry	Mild	Night
10	S3_2	ITS	Dry	Heavy	Day
11	S3_3	ITS	Foggy	Heavy	Day
12	S3_4	ITS	Rain	Mild	Night
13	S3_5	ITS	Rain	Heavy	Night
14	S4_1	Automated	Dry	Heavy	Day
15	S4_2	Automated	Foggy	Mild	Day
16	S4_3	Automated	Rain	Mild	Night
17	S5_1	All CAV	Dry	Mild	Night
18	S5_2	All CAV	Dry	Heavy	Day
19	S5_3	All CAV	Foggy	Heavy	Day
20	S5_4	All CAV	Rain	Mild	Night

4. Analysis and Discussion

4.1. Data Cleaning & Preparation

Fifty-five subjects initially participated in driving the 20 scenarios, however, after reviewing and cleaning driving logs, only fifty-one participants' datasets were found to be complete and clean of errors for further analysis. The preliminary screening step assessed the raw data from all subjects through all 20 scenarios in all three work zones. Each participant's data then was broken into three Excel spreadsheets for ease of analysis by work zone: work zones #1, #2 and #3. Each work zone consisted of twenty scenarios. The data was then divided into five categories based on different attributes for extraction and analysis to better analyze driving behavior. These attributes were speed, brake, jerk, throttle, and lateral movement. Individual spreadsheets were made for each attribute with 20 worksheets representing the 20 study scenarios. The focus was on the values of these attributes at critical points along the road, such as where the signs were located, the start and end points of work zone, the transition and buffer areas, etc. to identify the effect of various work zone

4.2. Descriptive Analysis

The pre-simulation and post-simulation questionnaire data were used for descriptive analysis. Participants' socio-demographic information is presented in **Table 5**. Gender, age, ethnicity, education level, household size, employment, income level and car ownership were among the information obtained. The participants were also asked additional questions to determine their knowledge about CAVs. The response showed that only 31.6% of participants had good prior knowledge about CAVs, while 26.3% had never heard about it. **Figure 9** illustrates the survey results about participants' CAV background knowledge.

When asked about their driving strategy near work zones, one-third of the participants stated they would re-route to avoid the work zone, whereas 54% stated they would drive the same route, but would take more caution (**Figure 10**).

Table 5: Participants Socio-Demographic Distribution.

Variable	Groups	Percent (%)
Gender	Male	61.4
	Female	31.6
Age	18-25	28.1
	26-35	33.3
	36-45	21.1
	46-55	7
	56-65	3.5
	65+	7
Ethnicity	White	22.8
	Black/African American	59.6
	Asian	10.5
	Other	7
Education	High School or less	5.3
	Associate	1.8
	Undergraduate	26.3
	Graduate	42.1
	Postgraduate	24.6
Household Size	Only me	35.1
	2 persons	21.1
	3 persons	15.8
	4 or more	28.1
Employment Status	Full time	42.2
	Part-time	28.1
	Unemployed	29.8
Income (Annual)	< $20,000	18.5
	$20,000-$29,000	16.7
	$30,000-$49,999	22.2
	$50,000-$74,999	22.2
	$75,000-$99,999	5.6
	More than $100,000	14.8
Vehicle Ownership	Car owner	92.9
	No Car	7.1
	None	6.3

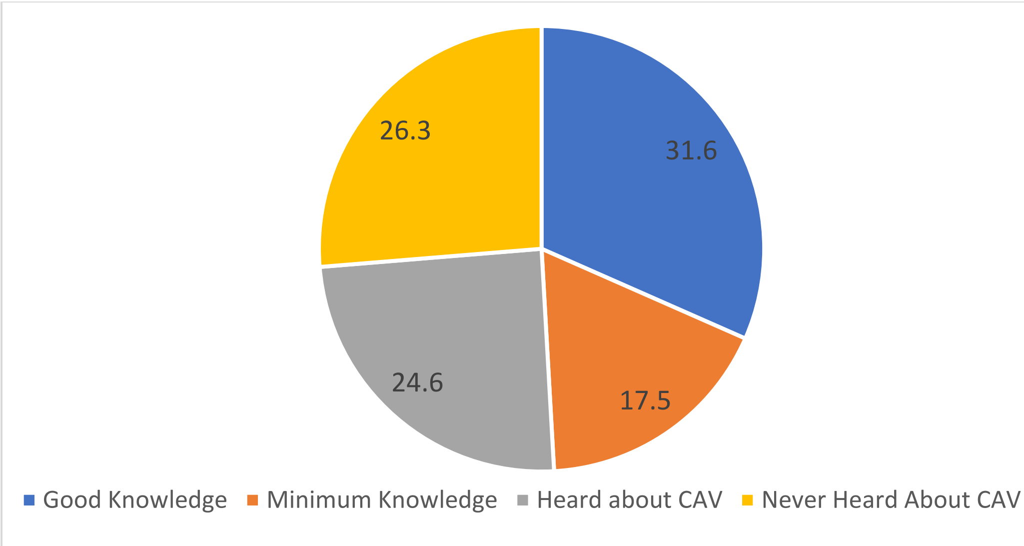


Figure 9: Participants Knowledge about Connected and Autonomous Vehicle (CAV)

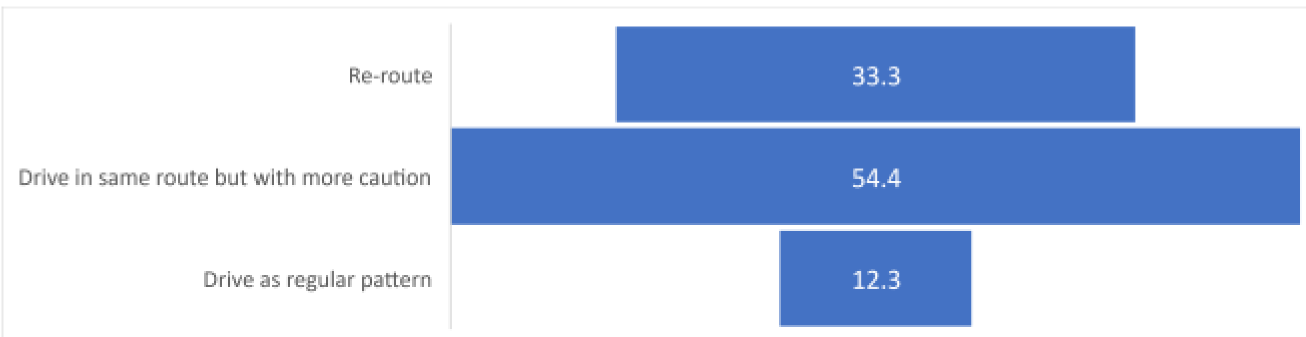


Figure 10: Participants Route Strategy Near Work Zone

Upon completion of the driving sessions, participants were asked about their experience with the CAV and AV functions of the car while driving. The survey results showed that 56% of participants found these features helpful for a safe driving experience. Similarly, 67% stated that the CAV function would be a useful tool for safe driving (**Figure 11**).

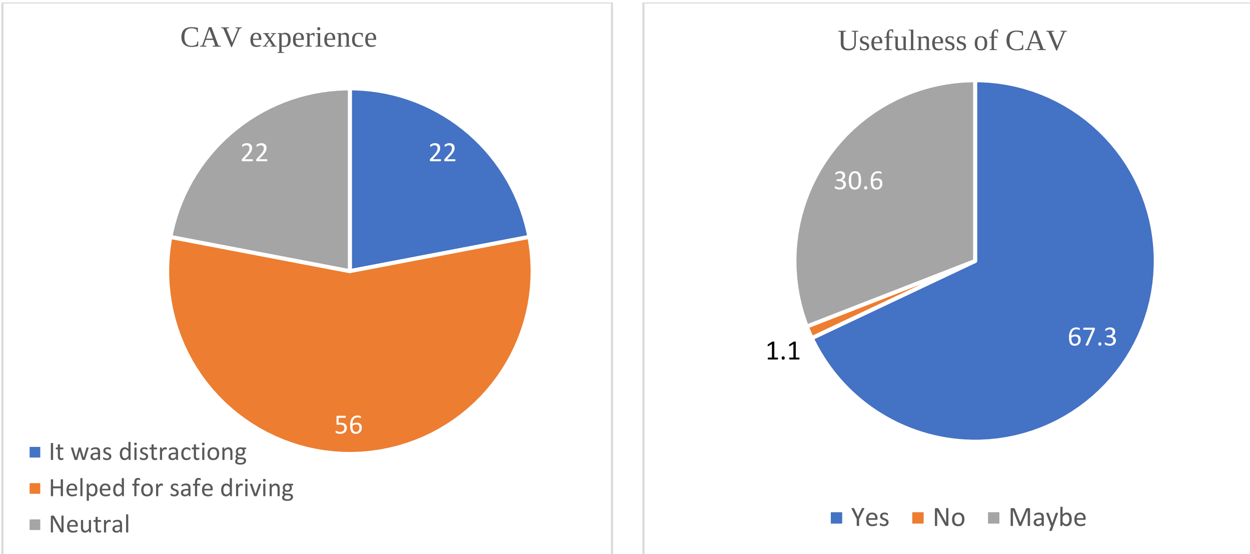


Figure 11: Participants Perception about helpfulness and usefulness of CAV feature (percent)

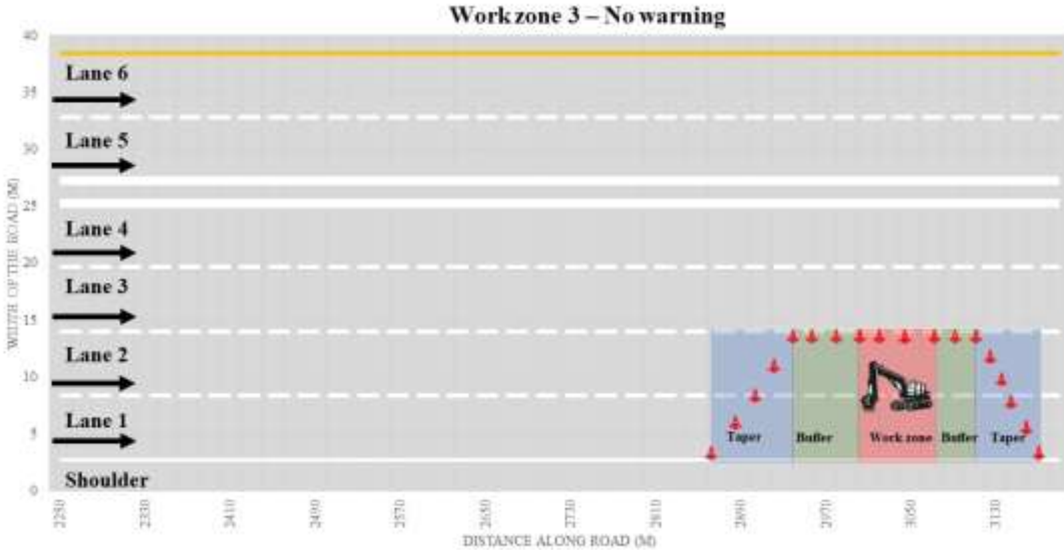
4.3. Statistical Data Analysis

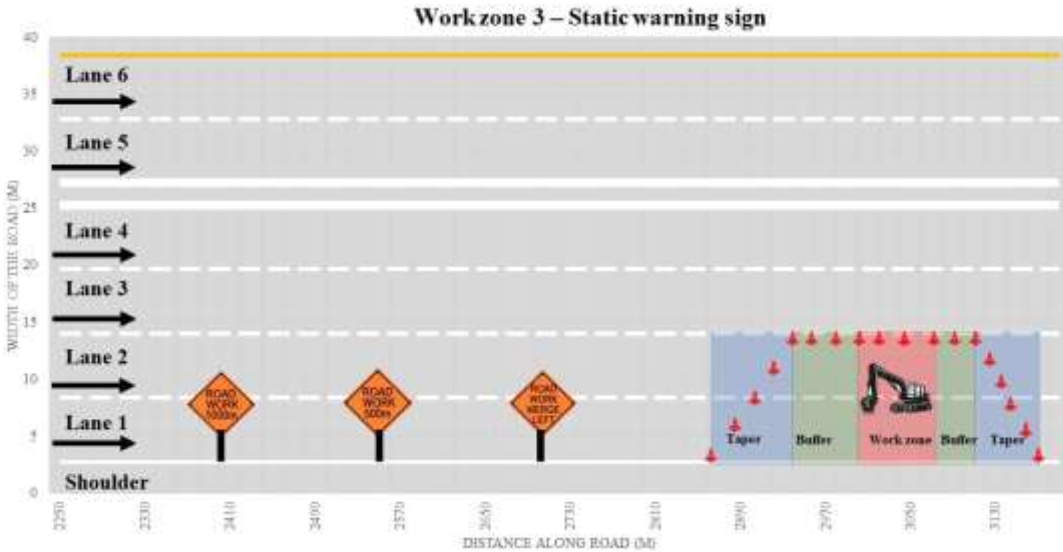
Each participant drove 20 scenarios through a network with 3 different work zones. Other than the base scenario (S0), the remaining scenarios simulated five various warning methods: work zone with no sign/warning, with static warning, with ITS warning, with Automated drive mode, and with All CAV mode. Moreover, these five categories have some sub-categories with different traffic conditions (mild or heavy), weather conditions (dry, rainy, or foggy), and visibility (day or night) to evaluate the combined effect of multiple factors on driving behavior around the work zones under different warning types. To study the drivers' behavior, five major variables were analyzed in this research: speed, brake, throttle, jerk, and distance to right/left border. Each variable was investigated in the 3 different work zones.

4.3.1. Work Zone #3 (Highway with 2 lanes closed)

4.3.1.1. Aggregate Analysis

Figure 12 shows major points (signs, cones, start and end points, etc.) under different scenarios along the road where participants encountered the work zone with 2 lanes closed in the highway. **Table 6** presents and compares the mean and variances (in parenthesis) of all participants' speeds in each scenario for these 9 critical points along the road. **Table 7** compares the mean and variances (in parenthesis) of all participants' lateral distance (distance to the right border of the roadway) in each scenario for these 9 critical points along the road. A description of the study scenarios was presented earlier in **Table 4**.





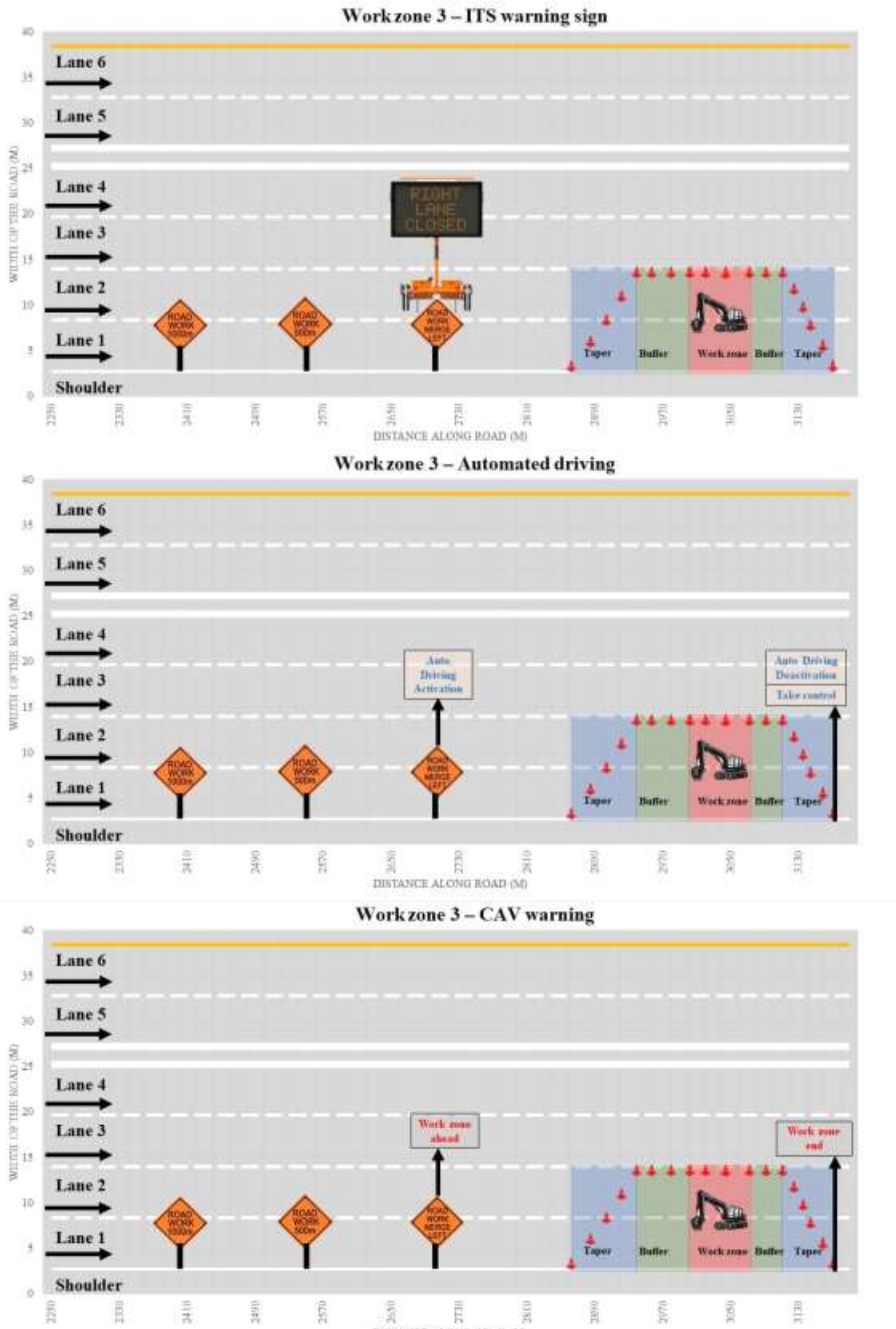


Figure 12: Work zone #3 illustration and critical points under various scenarios

Table 6: Mean (variance) speed in each scenario at 9 critical locations in work zone #3

Scenario \ Point	Sign 1	Sign 2	Sign 3	cone 1	cone 2	cone 3	cone 4	cone 5	cone 6
S0	71.6	71.7	71.5	70.8	70.8	71.1	71.3	71.3	71.3
	(52.8)	(53.5)	(49.1)	(49.8)	(49.8)	(41.9)	(41.0)	(40.6)	(40.5)
S1_1	70.8	70.7	67.0	57.0	57.6	59.9	60.8	61.7	63.4
	(61.5)	(60.5)	(117.1)	(274.8)	(218.9)	(135.9)	(98.9)	(82.9)	(68.8)
S1_2	65.3	58.5	28.4	32.8	39.9	47.2	52.2	54.6	57.0
	(48.4)	(254.6)	(613.4)	(367.0)	(246.7)	(121.2)	(74.9)	(56.4)	(43.0)
S2_1	72.3	72.0	68.5	60.9	60.7	60.1	60.8	61.5	63.0
	(55.0)	(51.6)	(99.2)	(185.90)	(137.2)	(100.7)	(79.6)	(64.6)	(47.6)
S2_2	63.6	56.5	29.1	27.5	36.8	46.4	52.6	55.4	58.1
	(31.4)	(192.9)	(494.1)	(244.4)	(154.7)	(76.3)	(51.9)	(42.8)	(33.9)
S2_3	63.5	59.5	27.6	32.0	39.9	47.9	52.8	55.3	57.8
	(84.3)	(221.6)	(593.3)	(310.7)	(219.1)	(109.0)	(68.5)	(51.3)	(38.6)
S2_4	68.8	67.8	65.5	55.1	55.9	57.9	59.2	60.2	61.4
	(75.5)	(65.8)	(136.4)	(300.2)	(220.1)	(154.9)	(123.7)	(98.8)	(75.3)
S2_5	63.2	57.9	32.2	33.1	41.7	49.9	54.9	57.3	60.2
	(70.1)	(166.1)	(547.5)	(330.4)	(210.9)	(108.2)	(66.3)	(53.3)	(35.9)
S3_1	71.2	70.2	67.6	58.3	58.8	59.3	61.1	62.3	64.0
	(48.8)	(53.9)	(67.2)	(229.1)	(174.5)	(143.7)	(100.5)	(81.7)	(67.2)
S3_2	61.3	54.1	25.6	29.2	38.2	46.2	51.3	53.8	56.5
	(113.7)	(284.6)	(488.8)	(277.4)	(192.0)	(123.6)	(88.5)	(75.4)	(57.1)
S3_3	63.2	56.4	25.4	29.6	38.7	46.4	51.4	54.0	56.9
	(74.5)	(277.6)	(518.9)	(330.5)	(186.3)	(116.6)	(89.9)	(70.3)	(49.8)
S3_4	69.2	68.1	64.8	52.5	53.0	55.2	57.4	59.0	61.5
	(97.8)	(85.0)	(191.1)	(232.8)	(198.7)	(125.7)	(84.1)	(70.3)	(58.2)
S3_5	66.5	61.5	36.4	37.2	43.6	50.6	54.9	56.7	58.7
	(45.8)	(129.8)	(569.4)	(346.3)	(232.5)	(121.5)	(83.8)	(67.5)	(47.5)
S4_1	62.9	56.7	27.1	37.7	44.3	37.7	44.3	51.6	54.5
	(73.4)	(189.5)	(526.7)	(223.9)	(142.4)	(223.9)	(142.4)	(16.9)	(4.3)
S4_2	71.8	71.0	68.8	52.0	52.5	52.0	52.5	53.6	54.7
	(77.6)	(87.7)	(105.3)	(43.7)	(38.4)	(43.7)	(38.4)	(9.6)	(0.0)
S4_3	74.1	73.9	70.0	52.3	52.9	52.3	52.9	53.3	54.7
	(67.7)	(65.9)	(166.0)	(33.0)	(26.0)	(33.0	(26.0)	(15.4)	(0.0)
S5_1	73.0	71.4	67.5	59.0	60.1	61.3	62.6	63.7	65.2
	(61.3)	(77.0)	(127.5)	(215.3)	(165.5)	(123.6)	(97.8)	(87.6)	(72.1)
S5_2	63.4	57.1	27.0	28.6	38.4	46.9	52.5	55.0	57.3
	(70.3)	(150.1)	(483.6)	(280.9)	(167.3)	89.5146	(60.3)	(45.5)	(34.8)
S5_3	61.8	54.5	27.1	32.2	40.6	48.2	53.1	55.2	57.5
	(137.2)	(185.7)	(474.9)	(280.6)	(188.3)	(105.3)	(72.6)	(61.5)	(52.5)
S5_4	70.9	68.1	63.6	58.5	58.8	58.6	60.0	61.3	63.3
	(61.5)	(82.2)	(262.5)	(259.5)	(112.0)	(102.3)	(78.7)	(66.1)	(53.6)

Table 7: Average (variance) lateral distance of vehicle in each scenario at 9 critical locations in work zone #3

Point / Scenario	Sign 1	Sign 2	Sign 3	cone 1	cone 2	cone 3	cone 4	cone 5	cone 6
S0	8.13	7.98	7.78	7.51	7.54	7.61	7.42	7.45	7.42
	(8.64)	(10.62)	(10.55)	(11.71)	(13.15)	(12.44)	(12.01)	(11.38)	(11.98)
S1_1	10.99	11.31	13.17	16.79	17.73	18.17	18.21	17.92	15.31
	(29.11)	(33.66)	(26.3)	(6.68)	(5.21)	(5.44)	(6.13)	(6.96)	(14.56)
S1_2	11.73	11.83	14.06	17.02	18.48	18.99	18.82	18.43	16.15
	(40.13)	(46.6)	(34.83)	(20.91)	(8.96)	(7.03)	(6.99)	(7.97)	(18.42)
S2_1	12.29	12.41	13.53	16.71	17.58	17.92	17.95	17.85	15.84
	(33.37)	(34)	(28.15)	(7.23)	(4.83)	(4.99)	(5.11)	(5.3)	(10.88)
S2_2	9.96	10.38	12.32	15.66	17.72	18.42	18.33	18.11	16.07
	(33.89)	(34.97)	(35.44)	(19.78)	(7.6)	(5.93)	(6.05)	(6.68)	(14.21)
S2_3	11.77	12.16	13.55	16.76	18.36	18.68	18.31	17.98	15.66
	(31.97)	(29.41)	(31.87)	(18.54)	(8.75)	(7.85)	(7.44)	(7.66)	(16.84)
S2_4	12.03	12.38	13.25	16.85	17.97	18.29	17.96	17.72	15.8
	(39.43)	(37.14)	(36.3)	(13.09)	(9.18)	(9.66)	(10.01)	(10.35)	(16.99)
S2_5	11.63	12.58	14.95	18.07	19.05	19.59	19.34	19.05	16.92
	(36.63)	(35.06)	(35.36)	(23.77)	(14.97)	(12.45)	(12.2)	(12.79)	(24.52)
S3_1	12.57	12.83	14.94	17.5	18.26	18.63	18.36	18	15.66
	(36.62)	(31.52)	(23.03)	(11.04)	(6.48)	(5.87)	(5.98)	(7.08)	(17.56)
S3_2	12.16	12.66	14.31	16.85	18.29	18.51	18.44	18.2	16.07
	(34.03)	(33.2)	(30.23)	(16.11)	(7.36)	(7.02)	(7.22)	(7.65)	(15.6)
S3_3	10.91	11.5	13.3	16.82	17.94	18.25	18.31	18.03	15.79
	(27.55)	(25.89)	(32.46)	(14.39)	(7.18)	(6.95)	(6.41)	(6.95)	(13.76)
S3_4	10.73	11.41	13.21	16.72	17.59	18.07	17.94	17.71	15.55
	(26.39)	(25.63)	(21.26)	(11.81)	(10.08)	(9.88)	(10.21)	(11.42)	(19.95)
S3_5	14.42	15.07	16.05	18.48	19.36	19.53	19.11	18.83	16.83
	(44.14)	(37.17)	(30.64)	(18.34)	(11.43)	(10.49)	(10.08)	(11.44)	(21.51)
S4_1	12.02	12.57	13.99	20.57	20.54	20.6	20.6	20.56	20.55
	(30.14)	(28.04)	(29.99)	(27.04)	(26.73)	(26.85)	(26.95)	(26.9)	(26.86)
S4_2	10.49	12.8	14.04	20.68	20.69	20.73	20.7	20.68	20.67
	(0)	(25.85)	(22.67)	(24.15)	(24.26)	(24.14)	(24.14)	(24.15)	(24.17)
S4_3	12.95	13.27	14.46	20.35	20.36	20.38	20.36	20.34	20.33
	(26.53)	(29.2)	(24.72)	(25.66)	(26.14)	(26.05)	(26)	(26)	(25.95)
S5_1	13.96	14.42	16.28	17.5	18.6	18.95	18.86	18.57	16.33
	(32.06)	(28.49)	(17.99)	(11.04)	(7.18)	(6.89)	(7.18)	(7.63)	(15.17)
S5_2	11.25	11.99	13.97	17.34	18.29	18.59	18.48	18.23	16.16
	(38.37)	(34.03)	(33.98)	(13.42)	(6.82)	(6.77)	(7.15)	(8.7)	(17.49)
S5_3	12.14	12.66	14.54	17.56	18.68	19.04	18.81	18.58	16.74
	(34.45)	(29.05)	(28.21)	(15.28)	(8.29)	(8.45)	(7.71)	(7.96)	(16.58)
S5_4	11.4	11.69	13.52	16.95	17.51	17.75	17.56	17.31	15.44
	(31.06)	(31.81)	(23.91)	(5.47)	(3.96)	(4.02)	(4.47)	(5.02)	(9.78)

4.3.1.2. Work Zone Effect under No Sign/Warning

In this section of the report, the effect of work zone on driving behavior was evaluated by comparing the base scenario (S0) where there was no work zone with scenario S1_1 where there was work zone activity without any advanced warnings or signage. The participants drove both scenarios in that daytime under dry weather and mild traffic conditions. **Figures 13** to **17** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these two scenarios when approaching and passing work zone #3.

These following charts clearly demonstrate the changes in driving behavior, where drivers slowed their speed as soon as the first cones were visible (~ 700 ft or 215 m upstream). Statistical analysis showed significant drops in the drivers' average speed. The brake pedal was being pushed more forcefully, and drivers shifted to lane 3 as soon as possible after recognizing that lanes one and two were blocked. However, increased brake use and declines in speed occurred earlier than the lane change, indicating the need to provide advanced warning to drivers about the lane blockage ahead so the drivers could safely position themselves without having to suddenly change their speed.

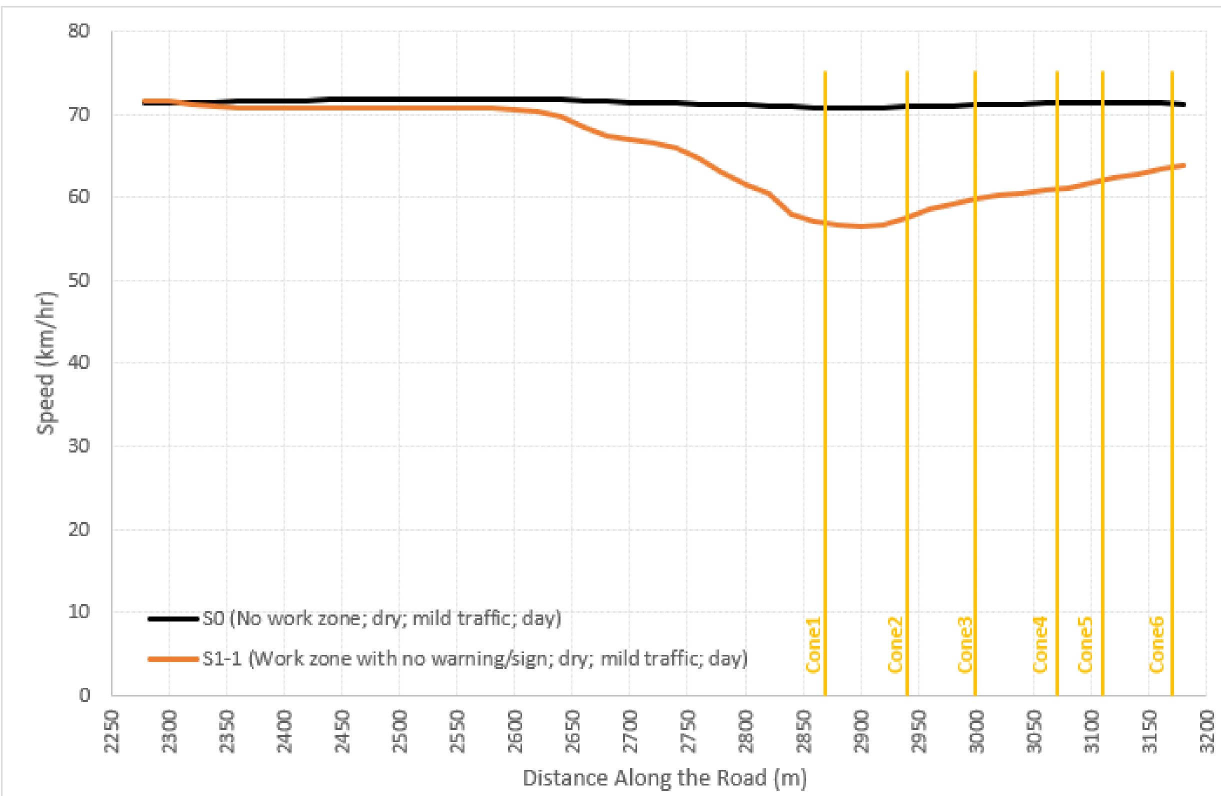


Figure 13: Mean speed comparison between no-work-zone and work zone scenarios in work zone #3

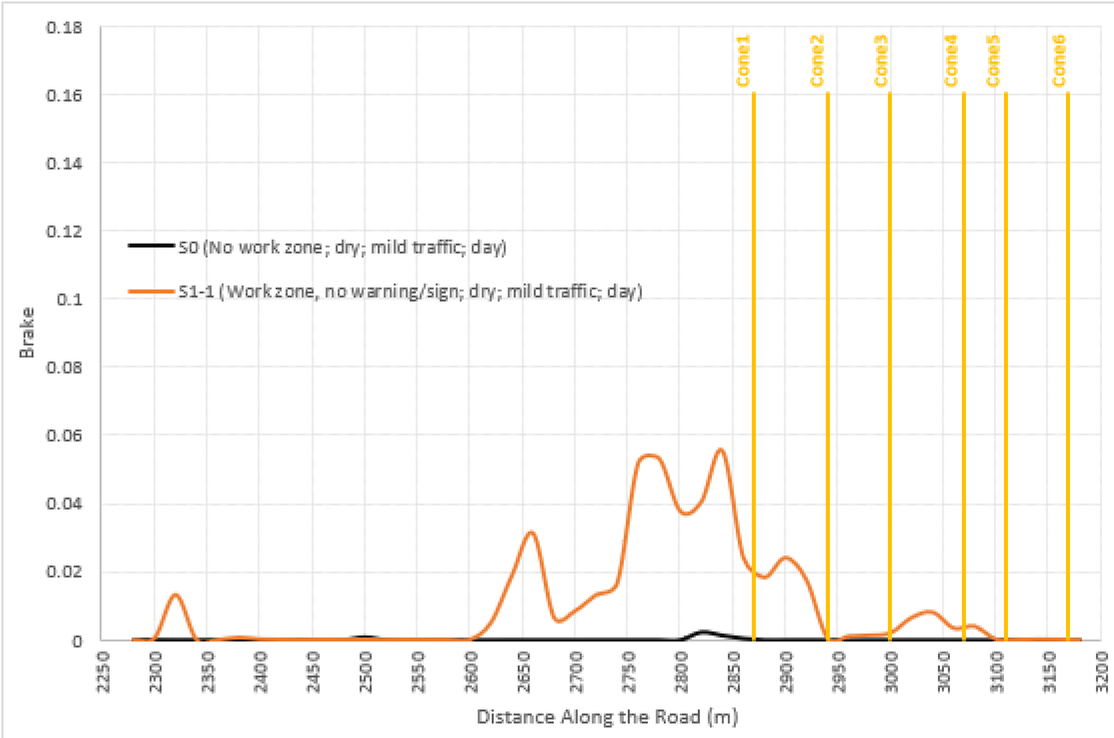


Figure 14: Brake use comparison between no-work-zone and work zone scenarios in work zone #3

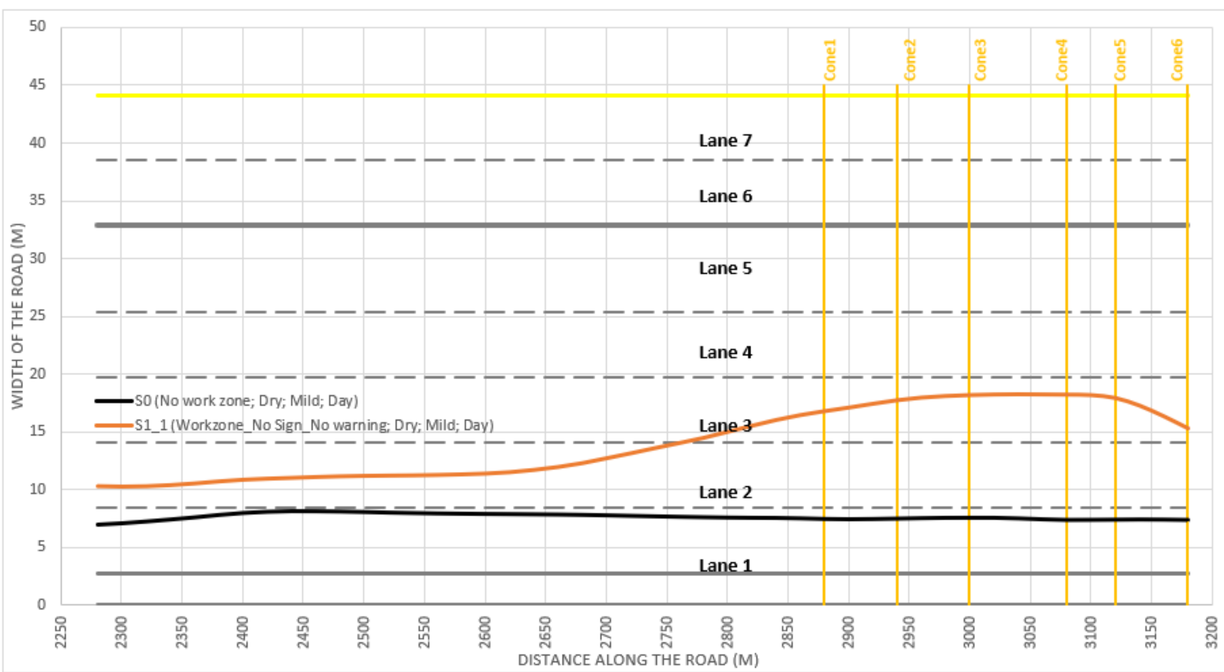


Figure 15: Lateral distance movement comparison between no-work-zone and work zone scenarios in work zone #3

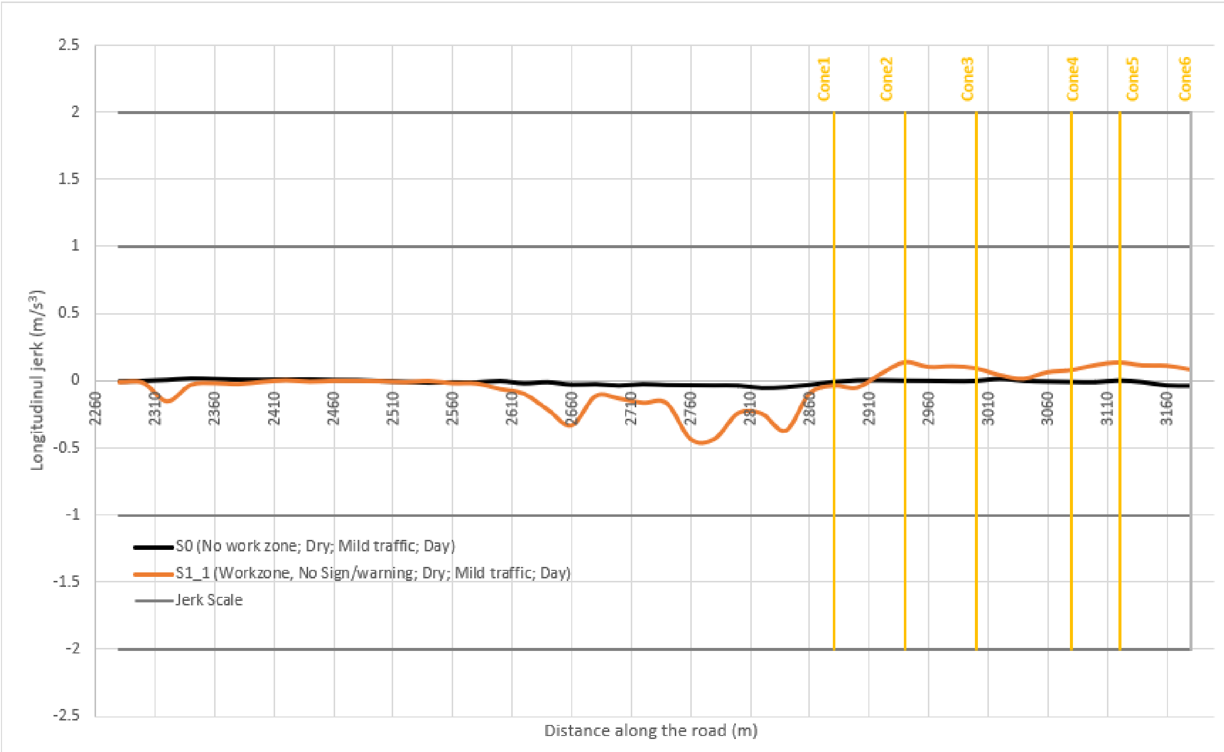


Figure 16: Vehicle jerk comparison between no-work-zone and work zone scenarios in work zone #3

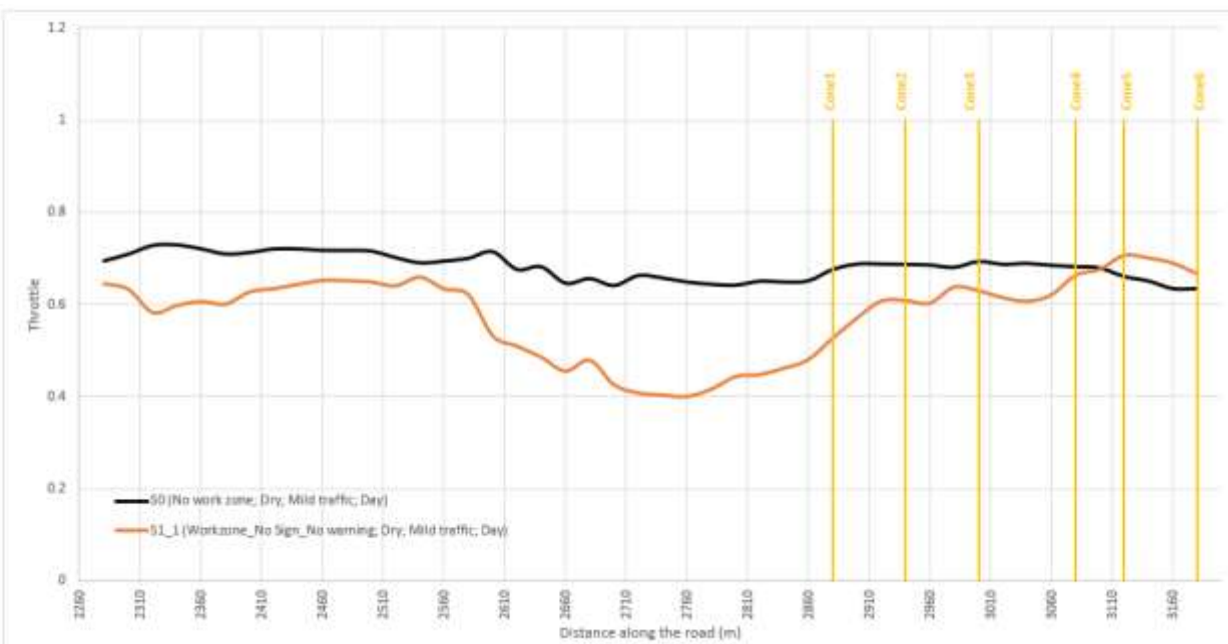


Figure 17: Vehicle throttle comparison between no-work-zone and work zone scenarios in work zone #3

4.3.1.3. Work Zone Warning Effect (No Sign vs. Static Sign vs. ITS Sign vs. Automated vs. CAV) under Heavy Traffic

In this section, the effect of various work zone warning types on driving behavior was evaluated by comparing five different scenarios: S1-2, S2-2, S3-2, S4-1, and S5-2. The participants drove all these scenarios in daytime in dry weather with heavy traffic conditions. **Figures 18** to **22** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. These charts reveal that under heavy traffic conditions, where it's hard for drivers to find a gap and change lane, driving behavior is consistent across different work zone warning methods. Statistical analysis showed that changes in drivers' average speed was not significant between scenarios in any of the analysis points along the road except for the "automated" scenario at the first 3 cone locations, where the driver had no control over the speed of the car, when it was activated after the last work zone sign.

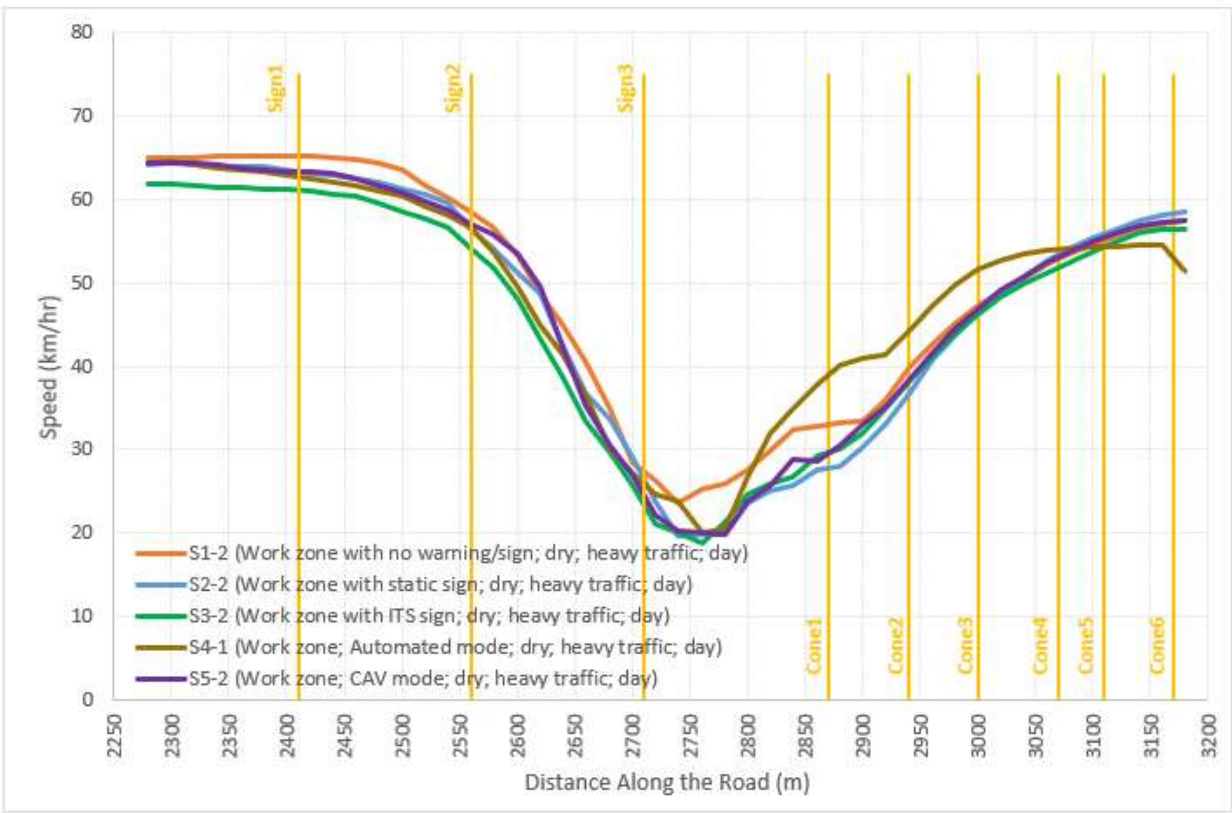


Figure 18: Mean speed comparison among various types of warning scenarios in work zone #3 (heavy traffic)

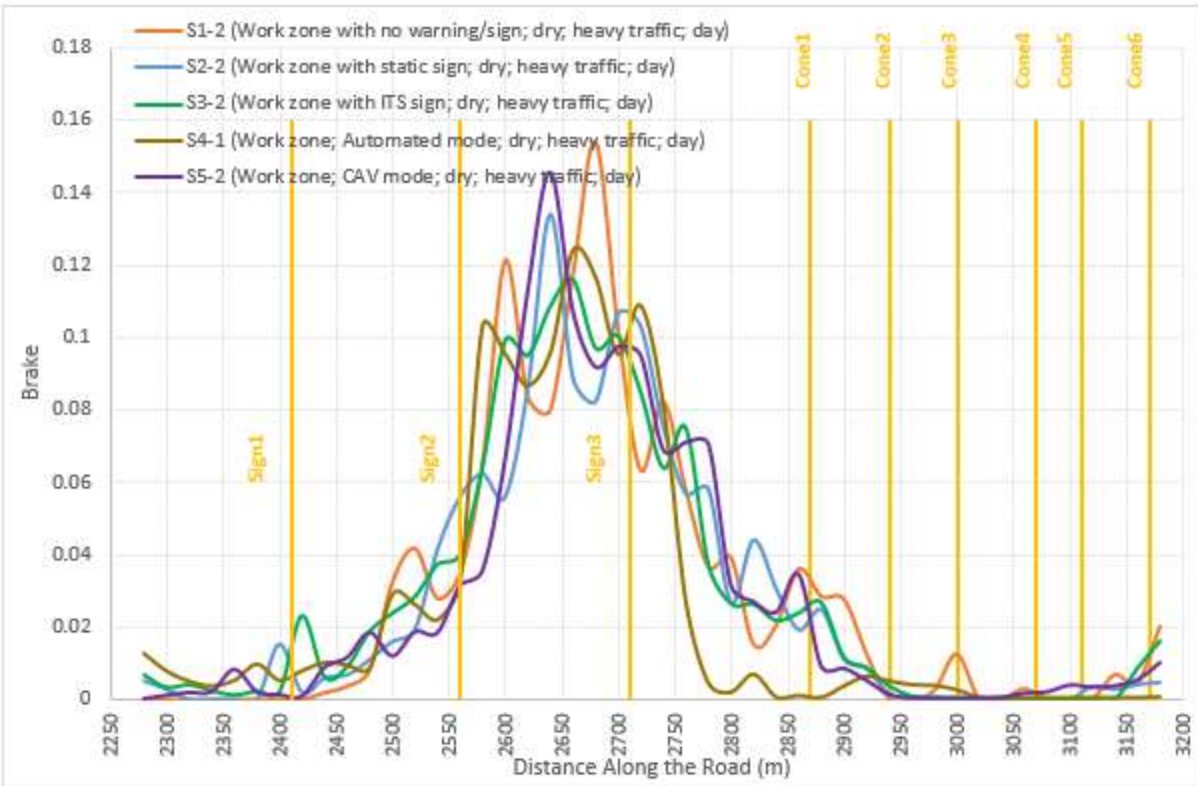


Figure 19: Brake use comparison among various types of warning scenarios in work zone #3 (heavy traffic)

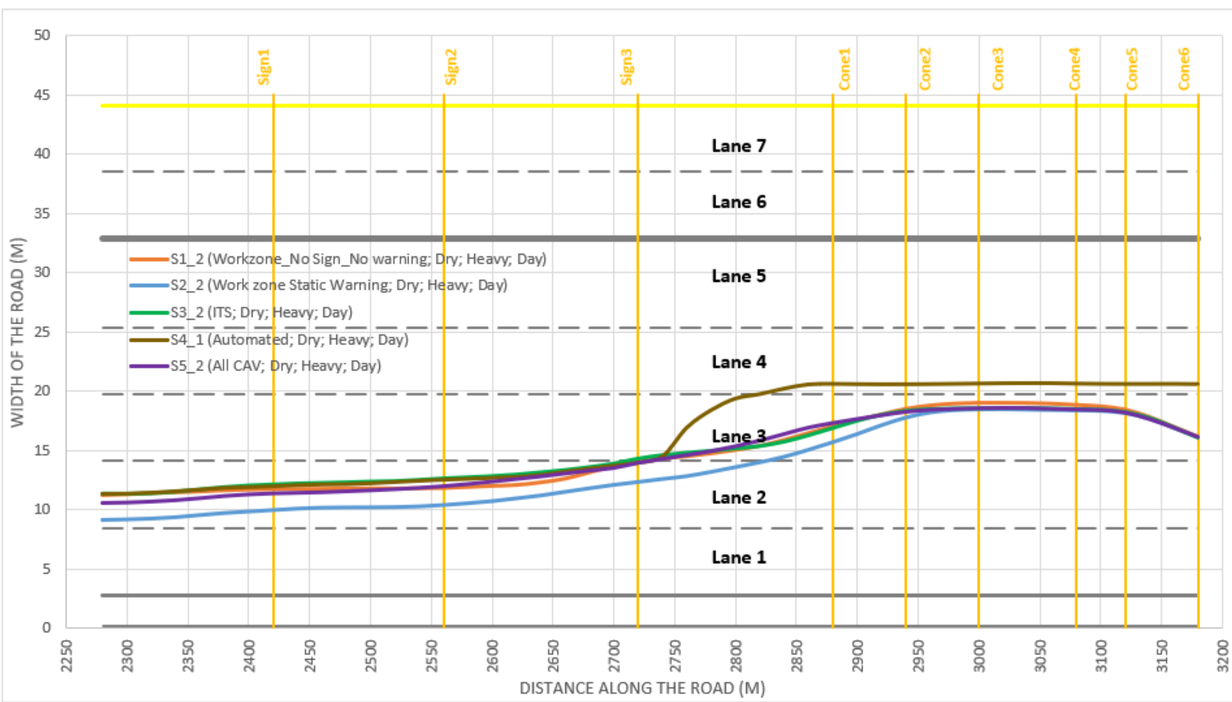


Figure 20: Lateral distance movement comparison among various types of warning scenarios in work zone #3 (heavy traffic)

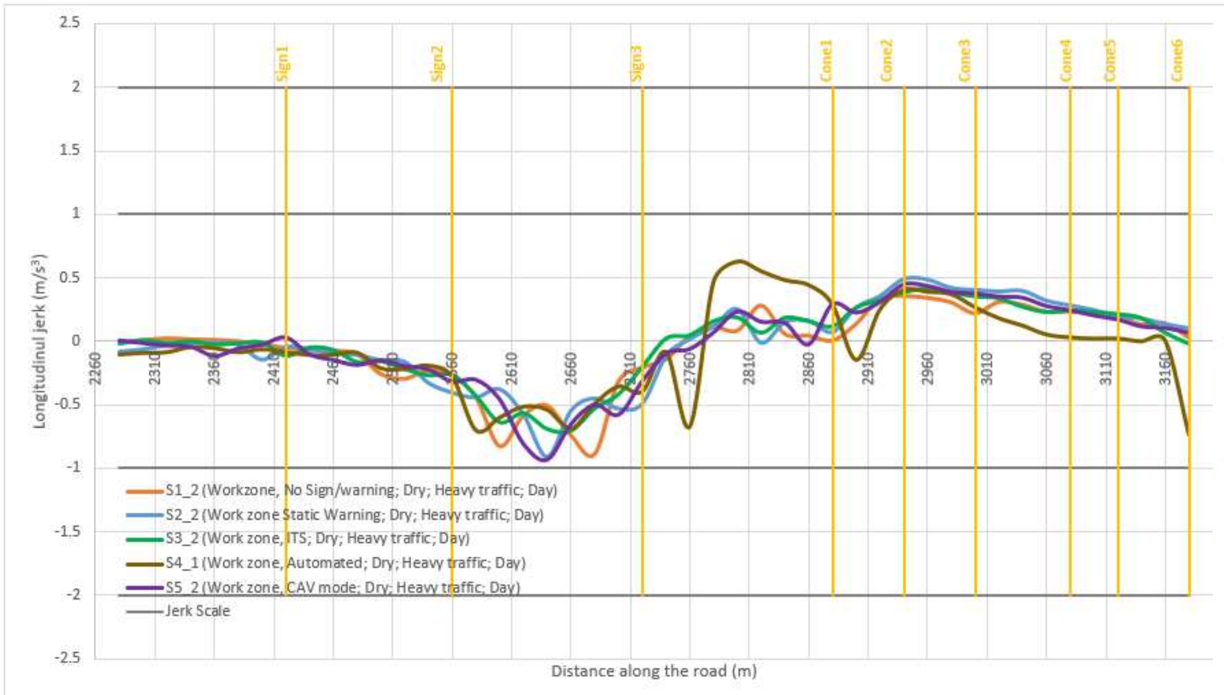


Figure 21: Vehicle jerk comparison among various types of warning scenarios in work zone #3 (heavy traffic)

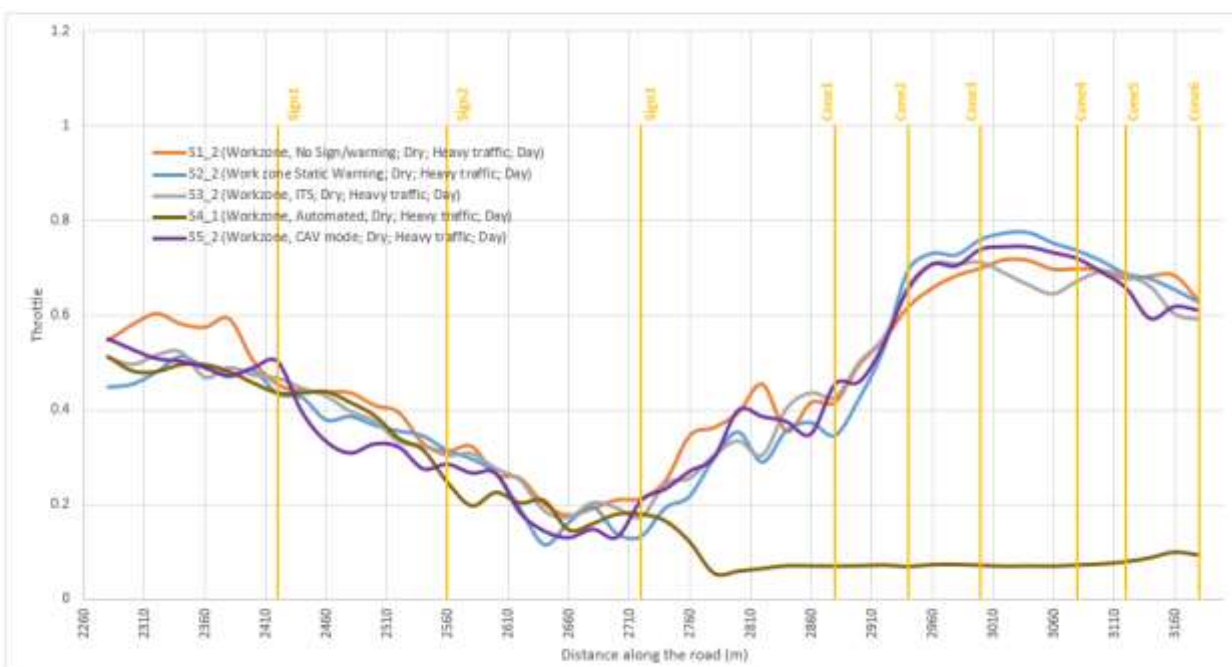


Figure 22: Vehicle throttle comparison among various types of warning scenarios in work zone #3 (heavy traffic)

4.3.1.4. Work Zone Warning Effect (Static Sign vs. ITS Sign vs. CAV) in Nighttime

The effect of various work zone warning types on driving behavior was evaluated by comparing three different scenarios: S2-1, S3-1, and S5-1. The participants drove all these scenarios at *nighttime* in dry weather and mild traffic conditions. **Figures 23** to **27** show and compare graphs of the average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. The results reveal that at night, when traffic volume is moderate, driving behavior is consistent across different methods of work zone warning. Statistical analysis showed that changes in drivers' average speed was not significant between scenarios in any of the analysis points along the road.

Figure 23: Mean speed comparison among various types of warning scenarios in work zone #3 (nighttime)

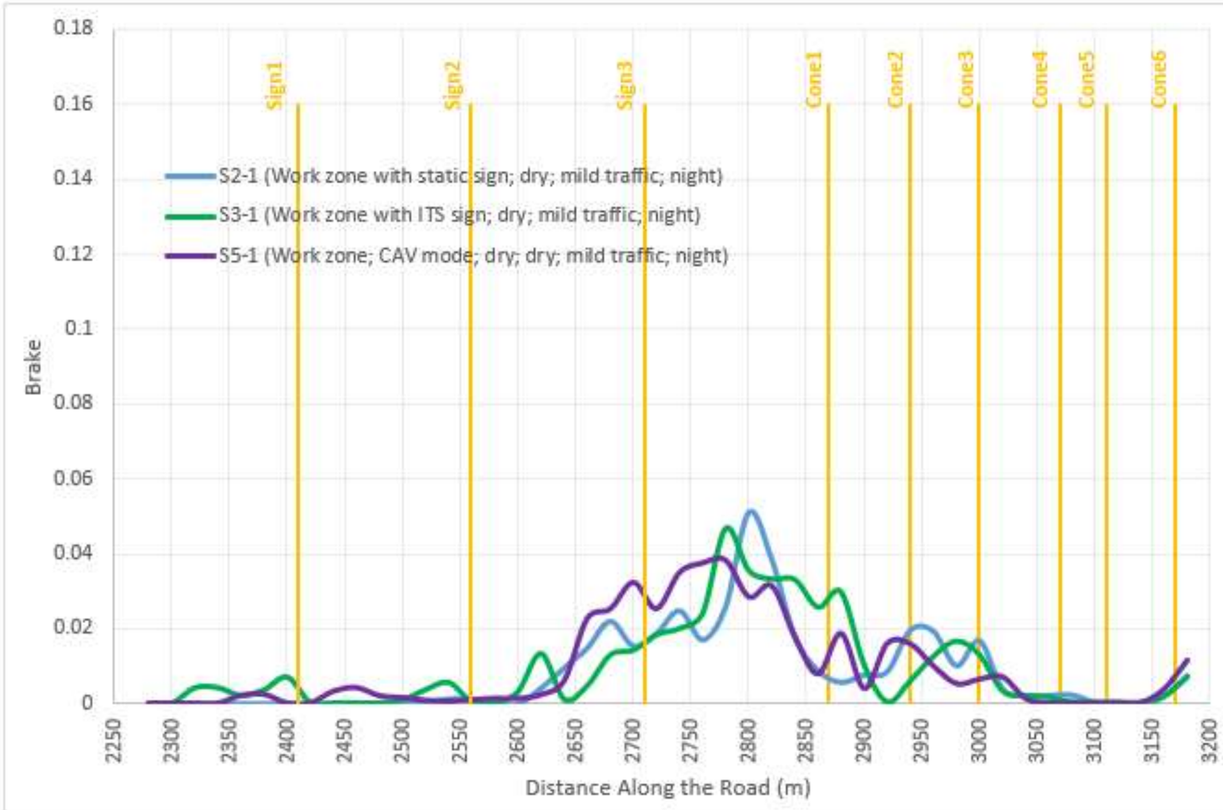


Figure 24: Brake use comparison among various types of warning scenarios in work zone #3 (nighttime)

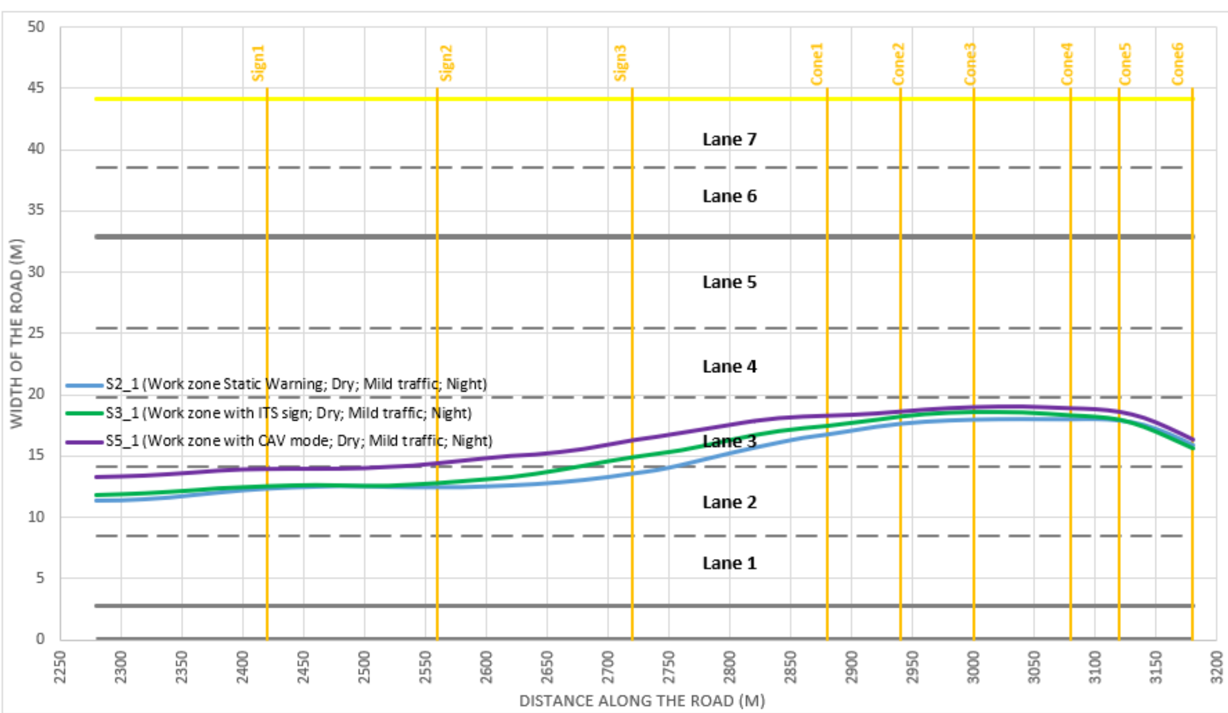


Figure 25: Lateral distance movement comparison among various types of warning scenarios in work zone #3 (nighttime)

Figure 19: Lateral distance movement comparison among various types of warning scenarios in work zone #3 (nighttime)

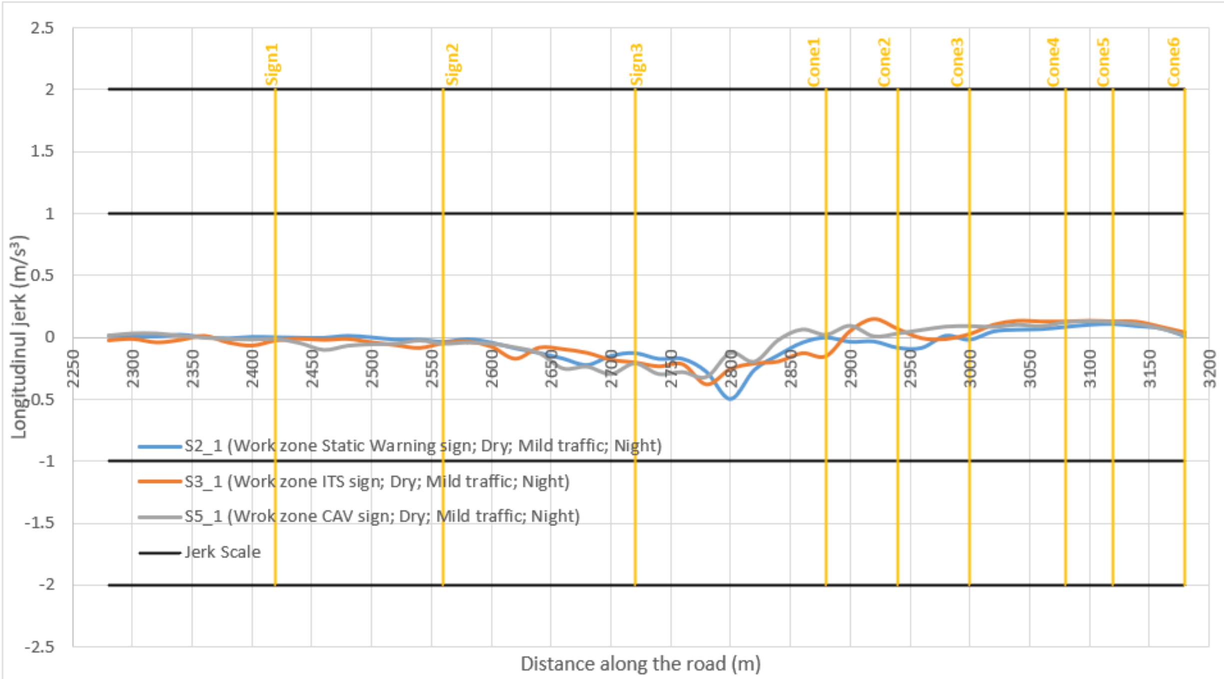


Figure 26: Vehicle jerk comparison among various types of warning scenarios in work zone #3 (nighttime)

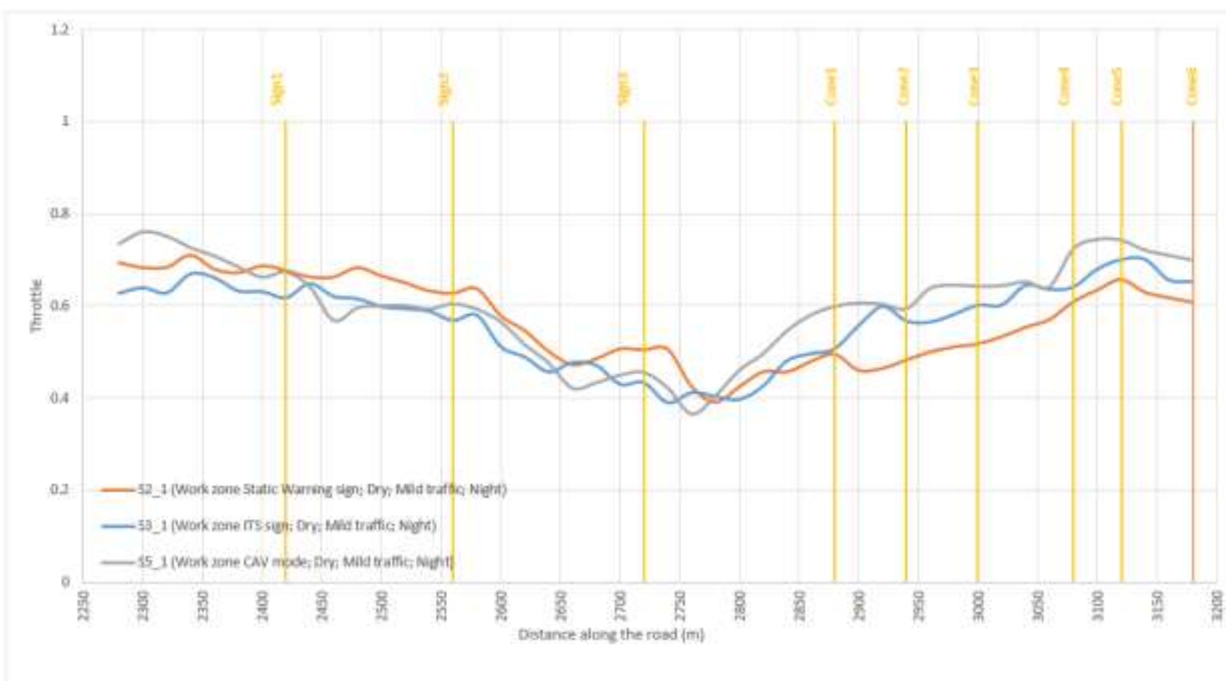


Figure 27: Vehicle throttle comparison among various types of warning scenarios in work zone #3 (nighttime)

4.3.1.5. Work Zone Warning Effect (Static Sign vs. ITS Sign vs. Automated vs. CAV) under Rainy Night

The effect of various work zone warning types on driving behavior was evaluated by comparing four different scenarios: S2-4, S3-4, S4-3, and S5-4. The participants drove all these scenarios at *nighttime* in *rainy* weather and mild traffic conditions. **Figures 28** to **32** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. These charts reveal that at nighttime in rainy weather conditions, driving behavior is generally consistent across different methods of work zone warning when traffic volume is moderate. Statistical analysis showed that changes in drivers' average speed was not significant between scenarios in any of the analysis points along the road except for in the "automated" scenario, where the driver had no control over the speed of the car once it was activated after the last work zone sign. However, ITS warning caused the biggest speed drop and highest use of the brake among all scenarios.

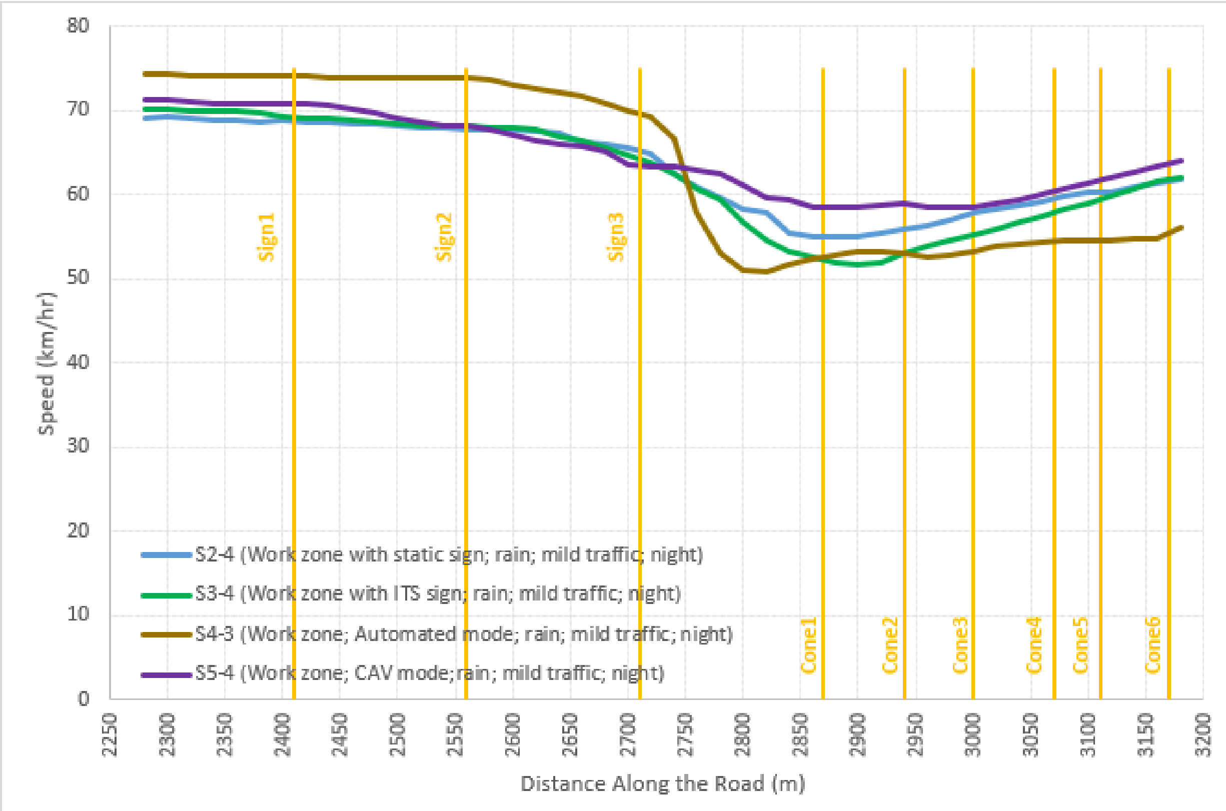


Figure 28: Mean speed comparison among various types of warning scenarios in work zone #3 (rainy night)

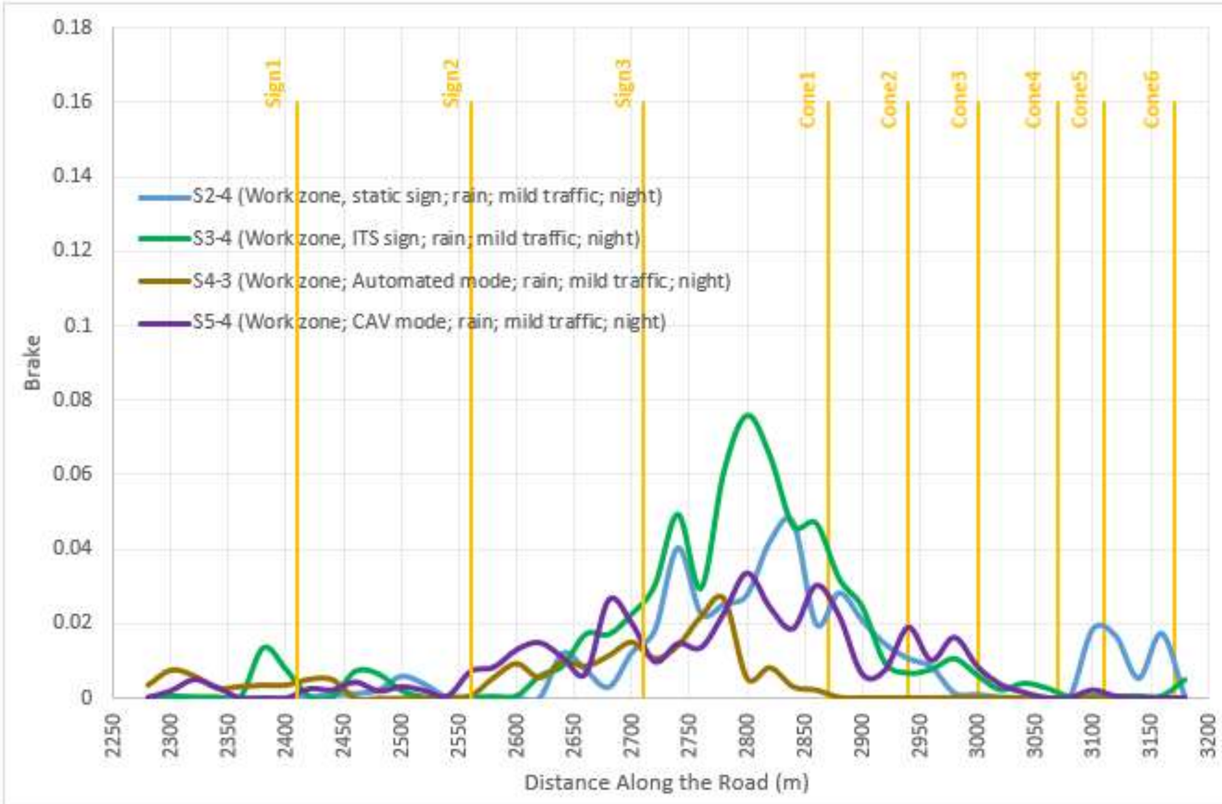


Figure 29: Brake use comparison among various types of warning scenarios in work zone #3 (rainy night)

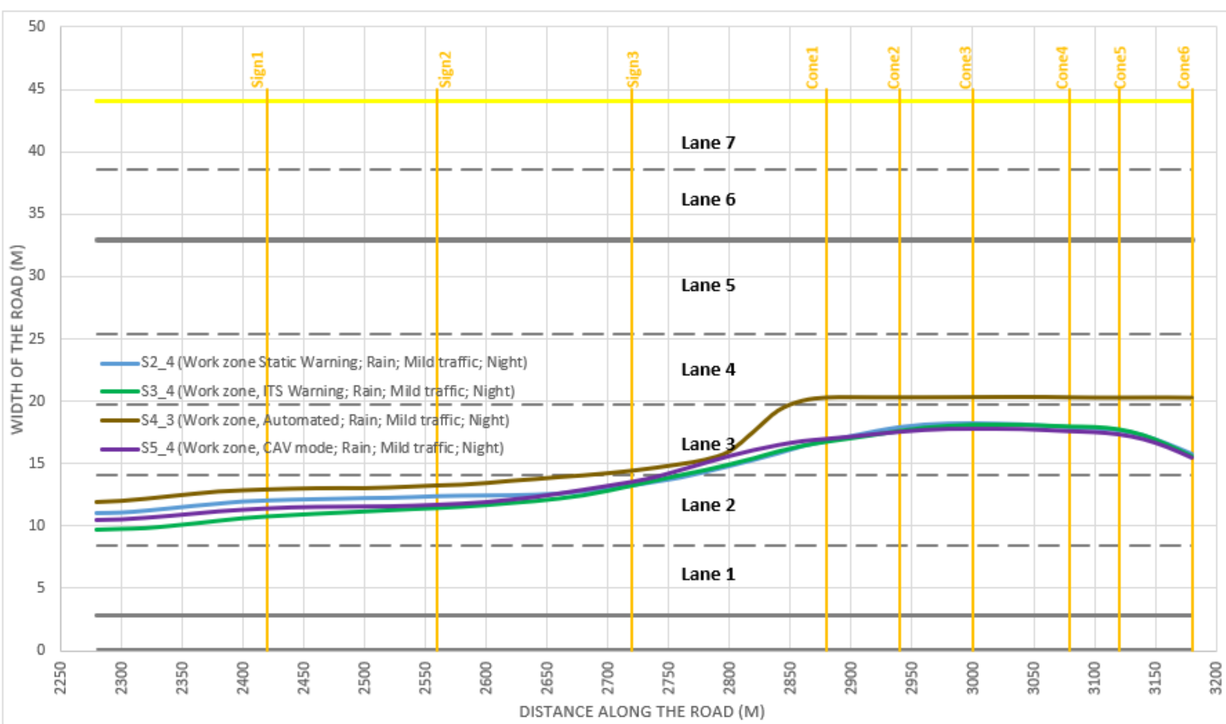


Figure 30: Lateral distance movement comparison among various types of warning scenarios in work zone #3 (rainy night)

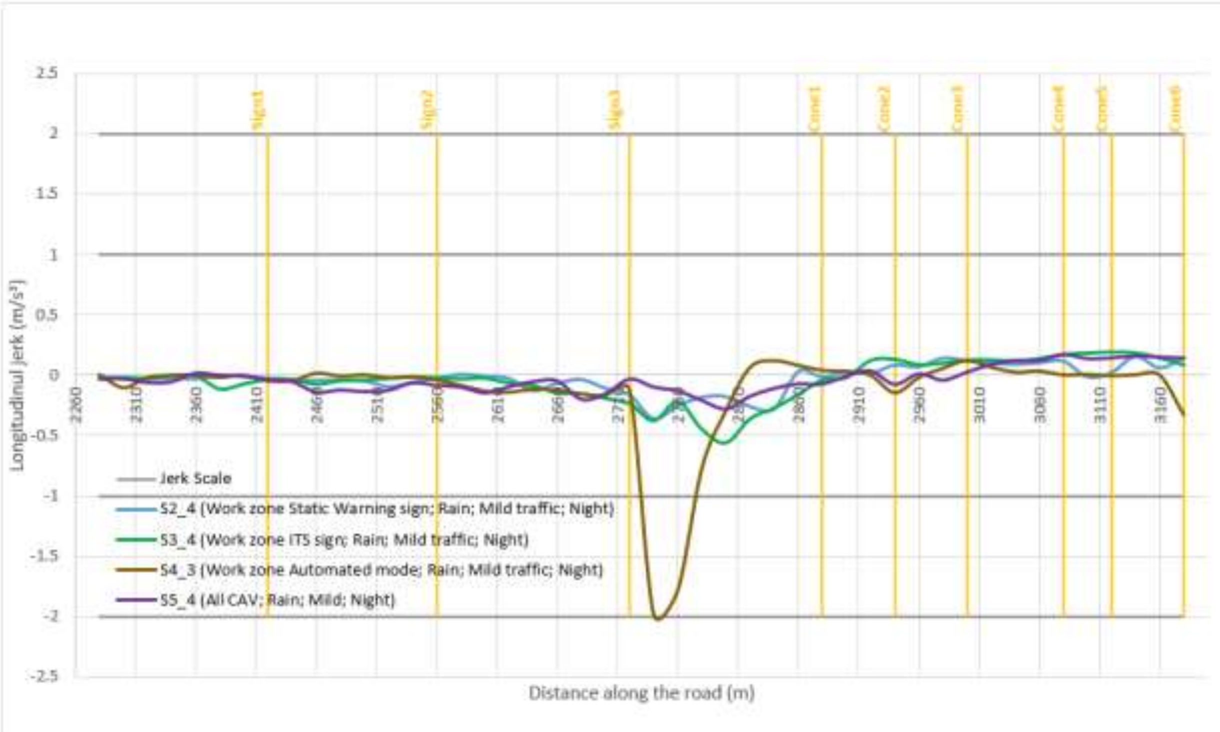


Figure 31: Vehicle jerk comparison among various types of warning scenarios in work zone #3 (rainy night)

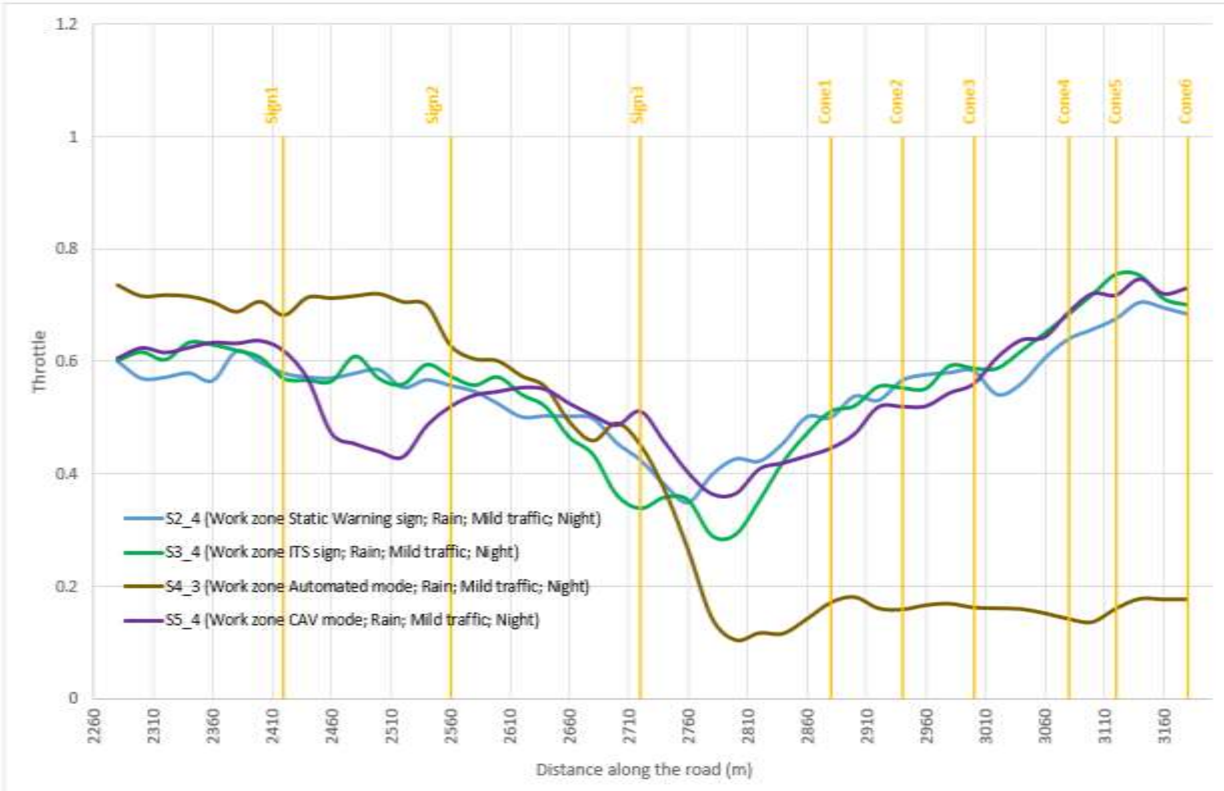


Figure 32: Vehicle throttle comparison among various types of warning scenarios in work zone #3 (rainy night)

4.3.1.6. Work Zone Warning Effect (Static Sign vs. ITS Sign) under Rainy Night and Heavy Traffic

The effect of ITS vs. static work zone warning types on driving behavior, as evaluated by comparing two different scenarios of S2-5 and S3-5. The participants drove these scenarios at *nighttime* in *rainy* weather and *heavy* traffic conditions. **Figures 33** to **37** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. The results reveal that at nighttime in rainy weather conditions, the ITS is a better strategy than the static signage to warn drivers of an advance work zone when traffic volume is heavy. Drivers' speeds were generally higher in the ITS scenario than the static signage before reaching the work zone, where the speed change at the first sign location was statically significant. Drivers made the lane change earlier in the ITS scenario that the static one which indicated the effectiveness of the ITS scenario.

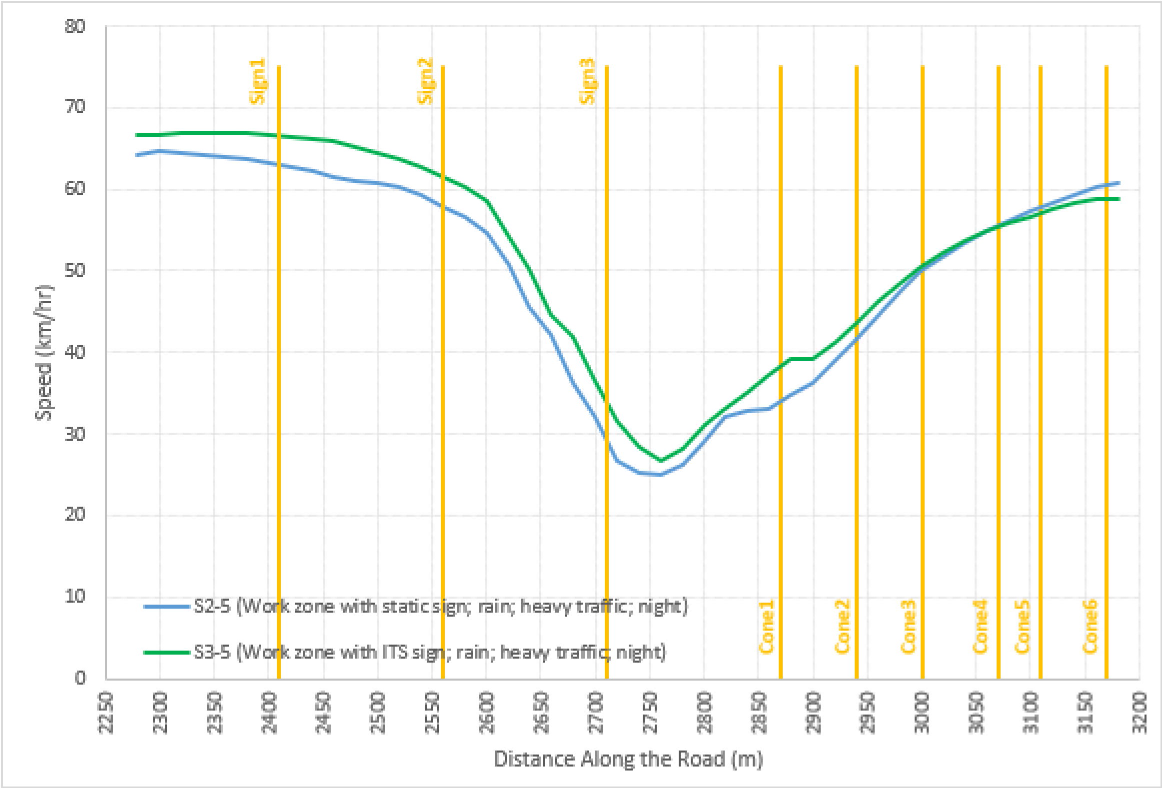


Figure 33: Mean speed comparison between static & ITS warning scenarios in work zone #3 (rainy night & heavy traffic)

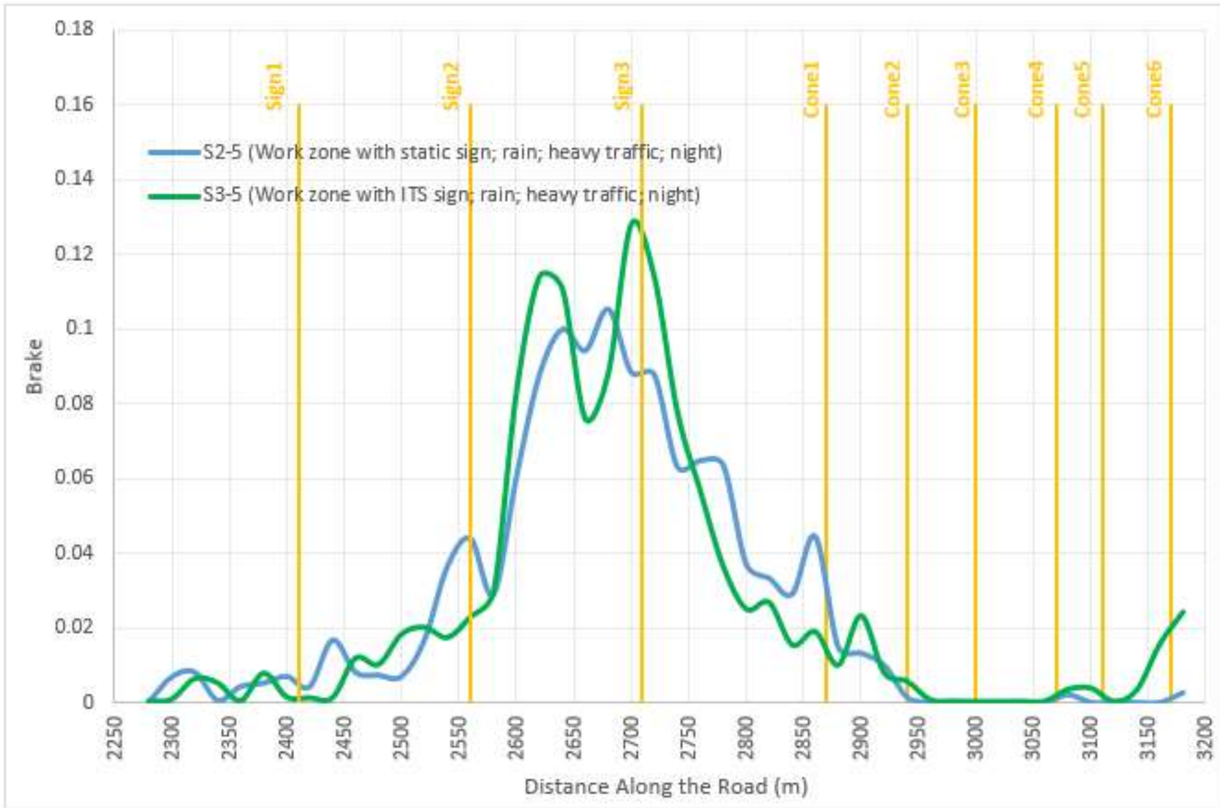


Figure 34: Brake use comparison between static & ITS warning scenarios in work zone #3 (rainy night & heavy traffic)

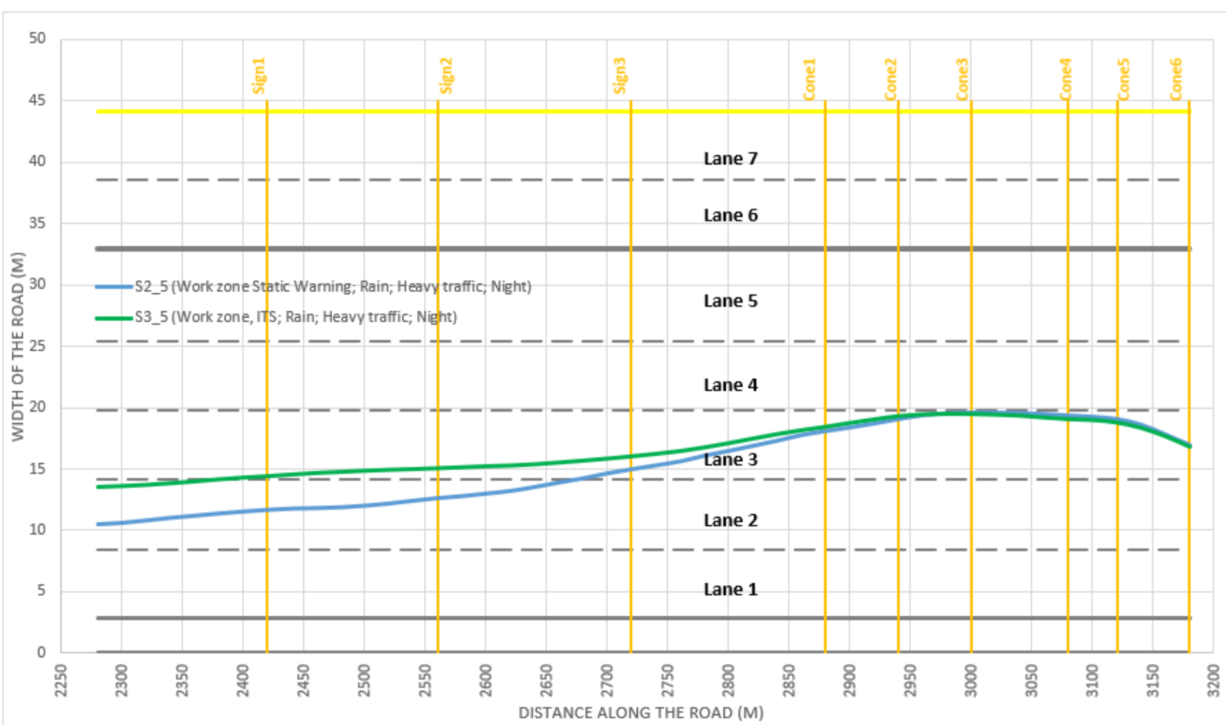


Figure 35: Lateral distance movement comparison between static & ITS scenarios in work zone #3 (rainy night & heavy traffic)

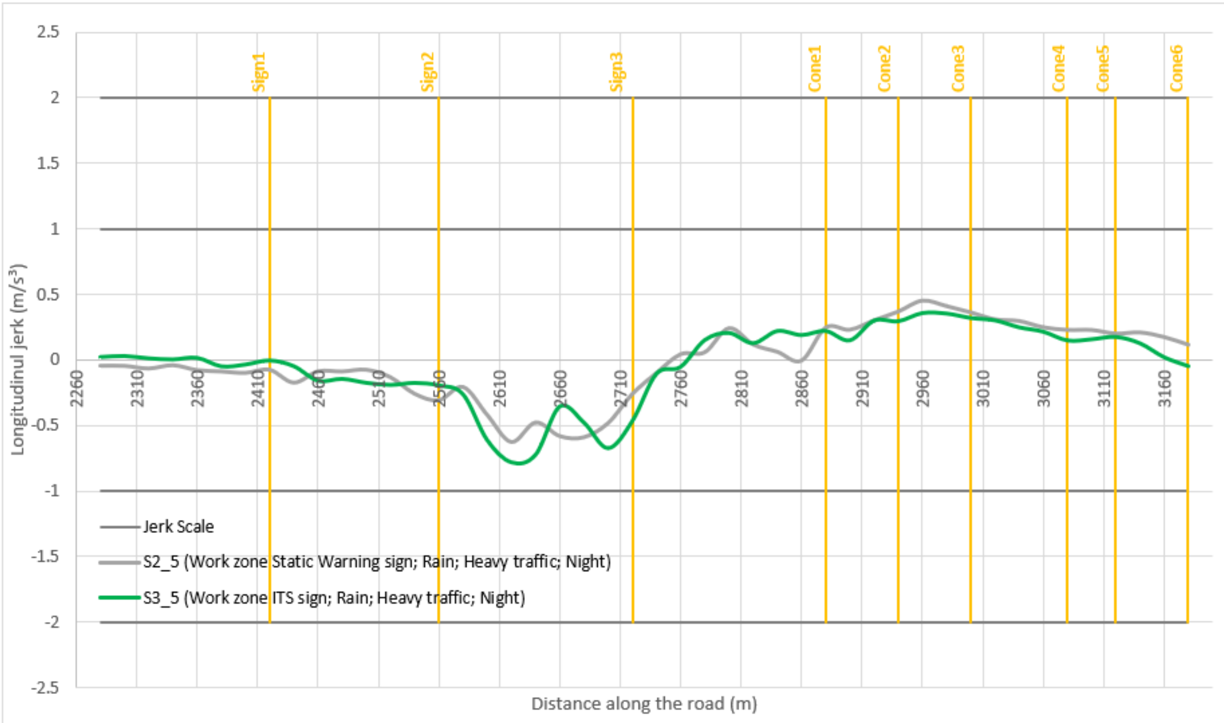


Figure 36: Vehicle jerk comparison between static & ITS warning scenarios in work zone #3 (rainy night & heavy traffic)

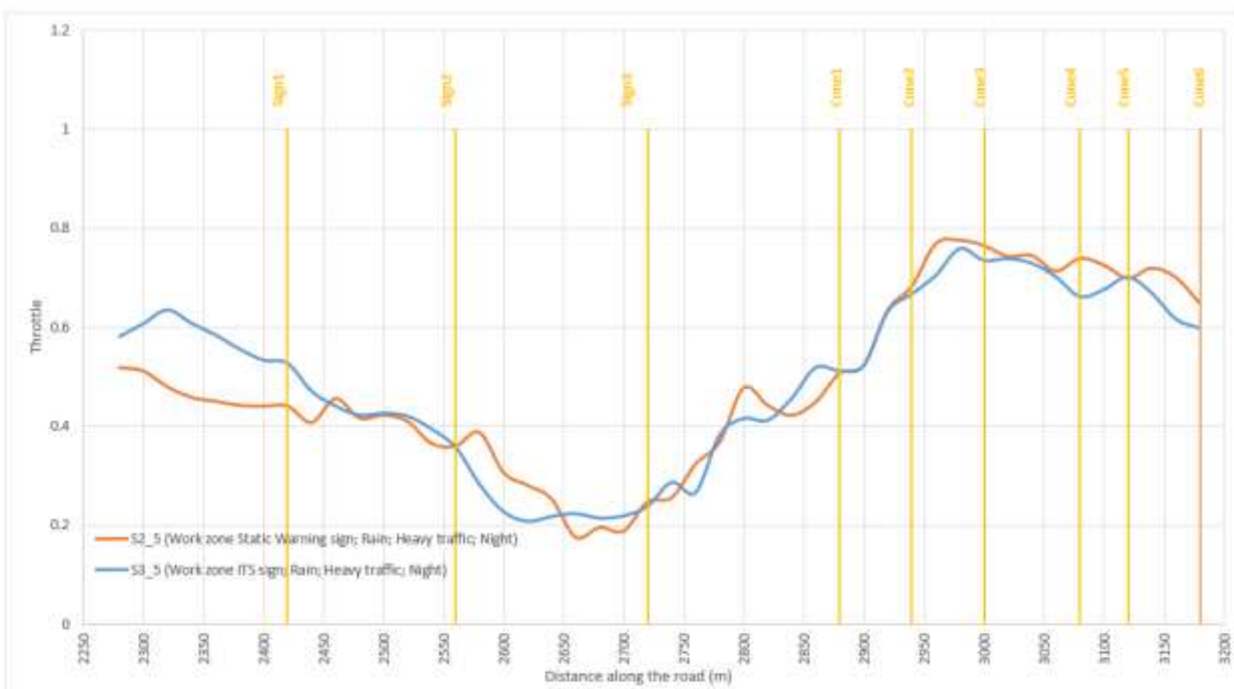


Figure 37: Vehicle throttle comparison between static & ITS warning scenarios in work zone #3 (rainy night & heavy traffic)

4.3.1.7. Work Zone Warning Effect (CAV vs. ITS Warning) under Foggy Weather and Heavy Traffic

The effect of ITS vs. CAV work zone warning types on driving behavior was evaluated by comparing scenarios S3-3 and S5-3, where the participants drove the scenarios in daytime in *foggy* weather and *heavy* traffic conditions. **Figures 38** to **42** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. The results reveal that in foggy weather and heavy traffic conditions, there was no significant differences between the ITS and CAV strategies to warn drivers of an advance work zone. Drivers' performance was generally the same in these 2 scenarios. However, drivers generally maintained a longer lateral distance to the work area in the CAV scenario that the ITS one.

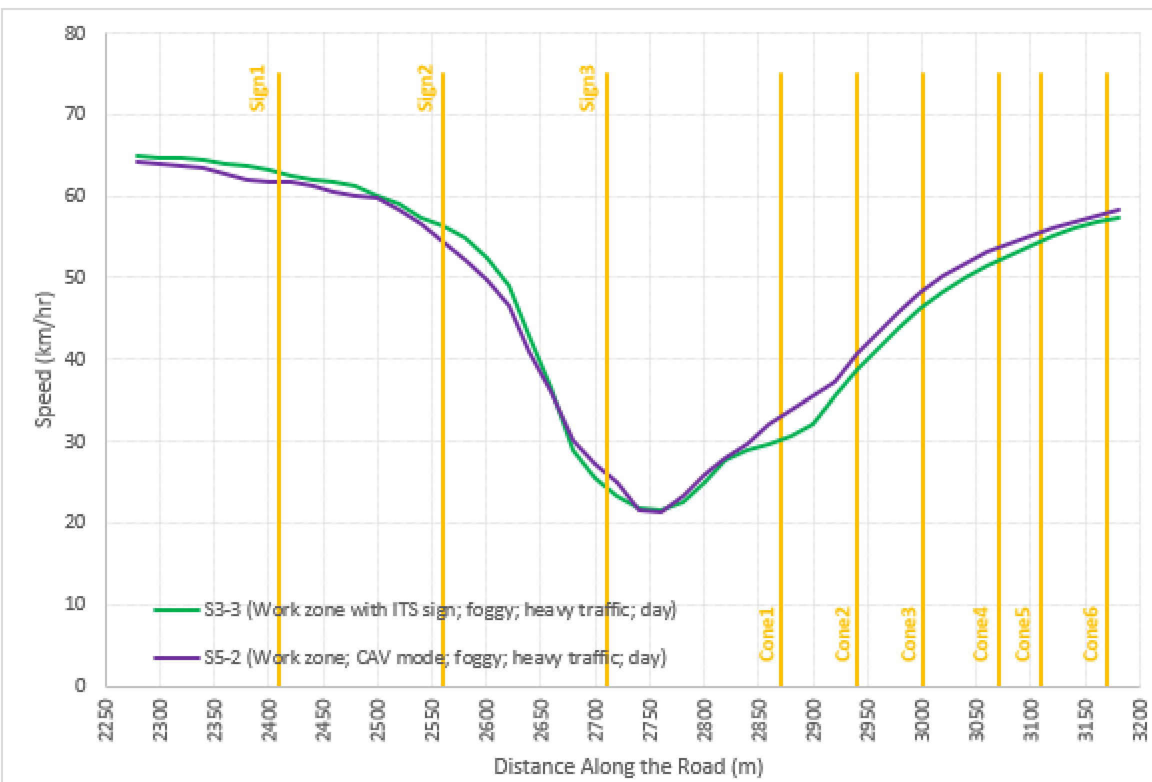


Figure 38: Mean speed comparison between CAV & ITS warning scenarios in work zone #3 (foggy & heavy traffic)

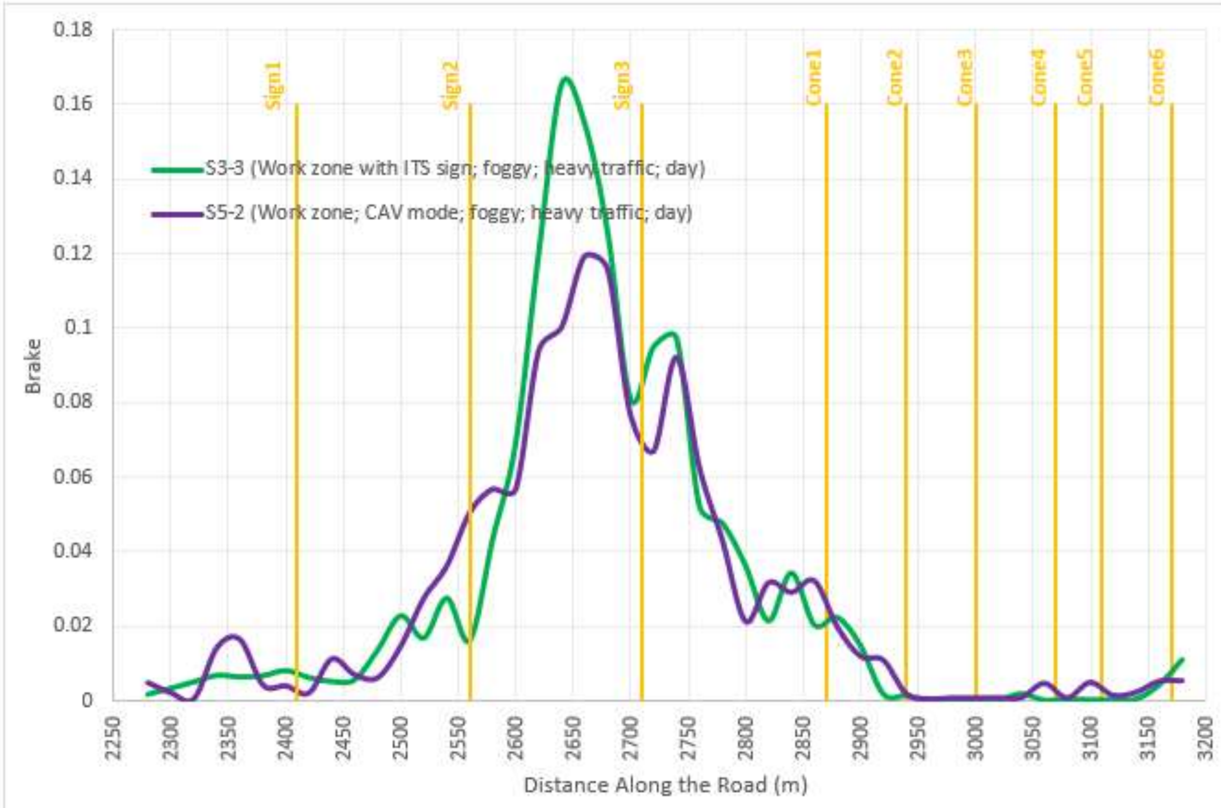


Figure 39: Brake use comparison between CAV & ITS warning scenarios in work zone #3 (foggy & heavy traffic)

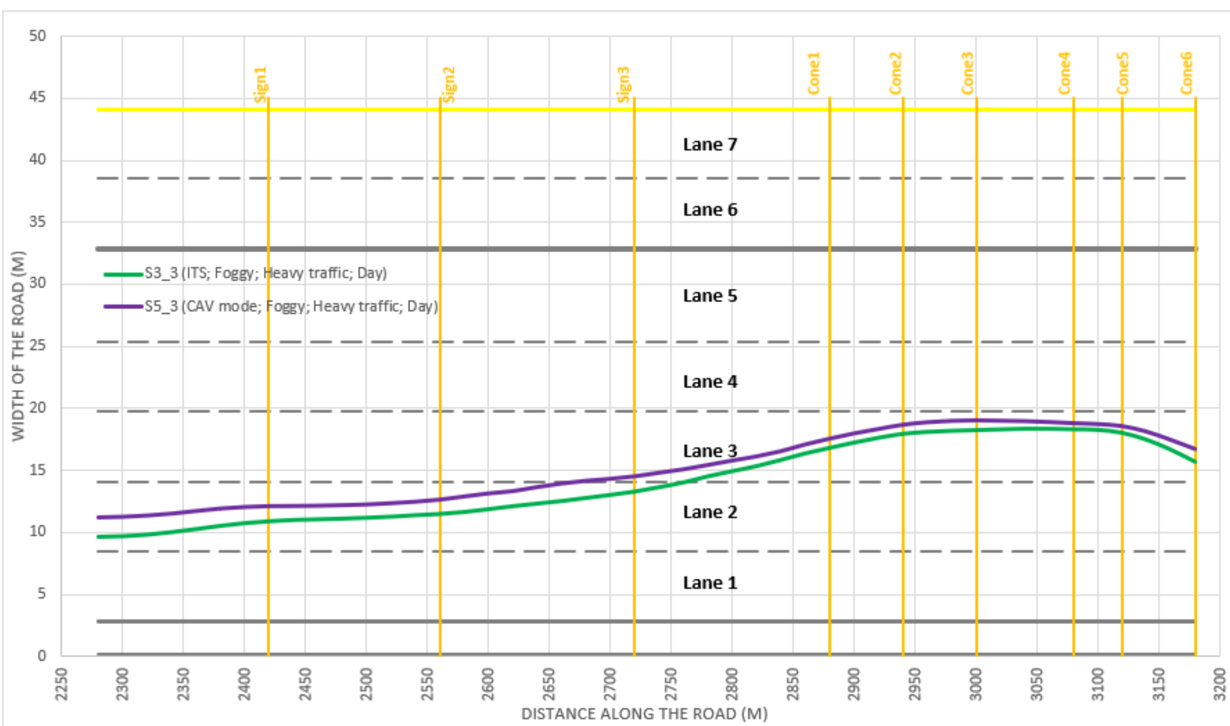


Figure 40: Lateral distance movement comparison between CAV & ITS scenarios in work zone #3 (foggy & heavy traffic)

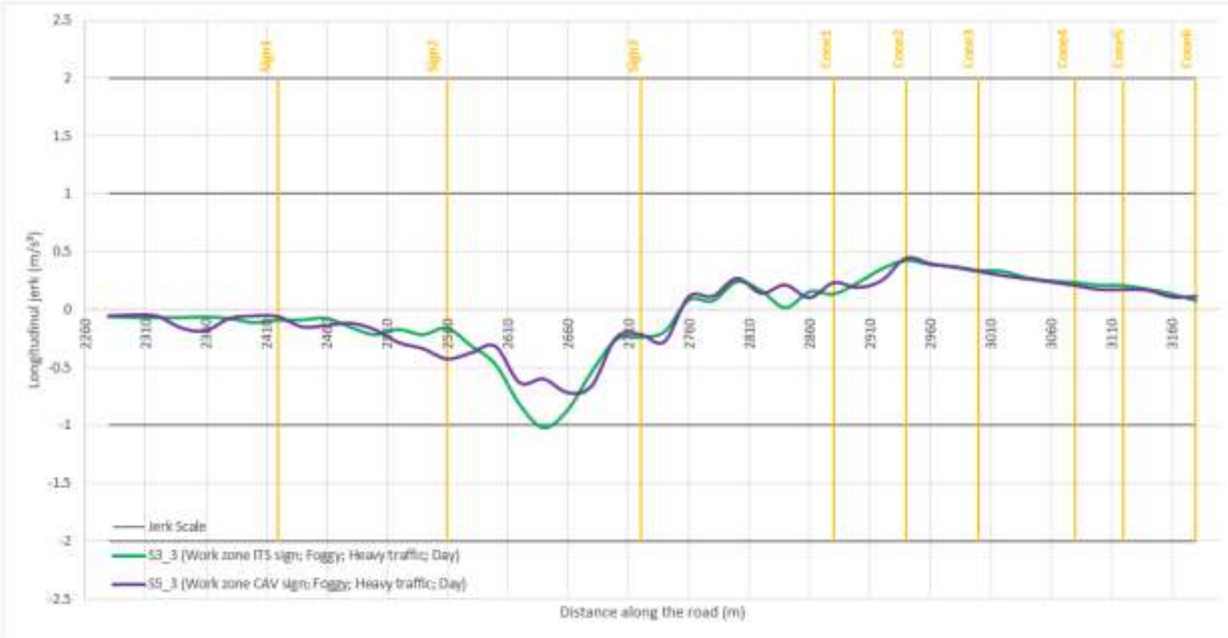


Figure 41: Vehicle jerk comparison between CAV & ITS scenarios in work zone #3 (foggy & heavy traffic)

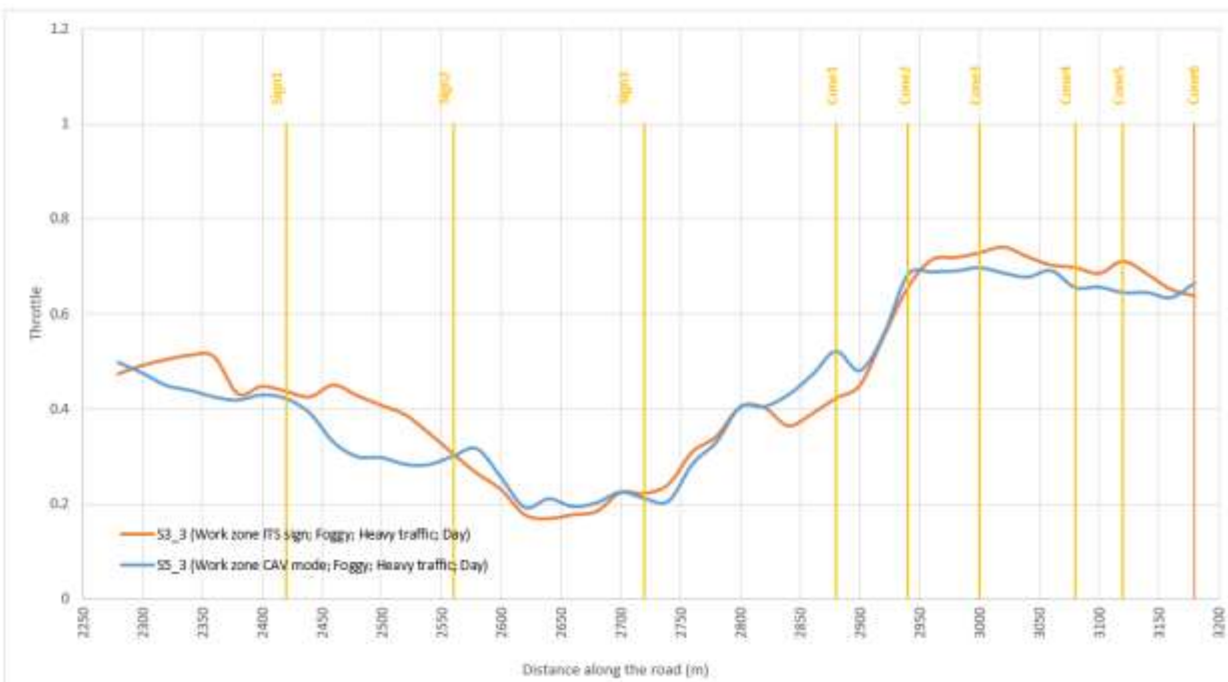


Figure 42: Vehicle throttle comparison between CAV & ITS scenarios in work zone #3 (foggy & heavy traffic)

4.3.1.8. Traffic Condition Impact on Driving Behavior in Work Zone with No Warning/Signage

The effect of traffic level (mild vs. heavy) on driving behavior was evaluated by comparing two different scenarios, S1-1 and S1-2, in a work zone with no warning/signage. The participants drove the scenarios during the daytime in dry weather conditions. **Figures 43** to **47** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. These graphs indicated the significant effect of traffic volume on driver's longitudinal behavior (speed and brake), while there was no significant impact on lateral movement behavior (lane changing). There was likely no difference in lateral movement between these 2 scenarios due to the lack of advance warning.

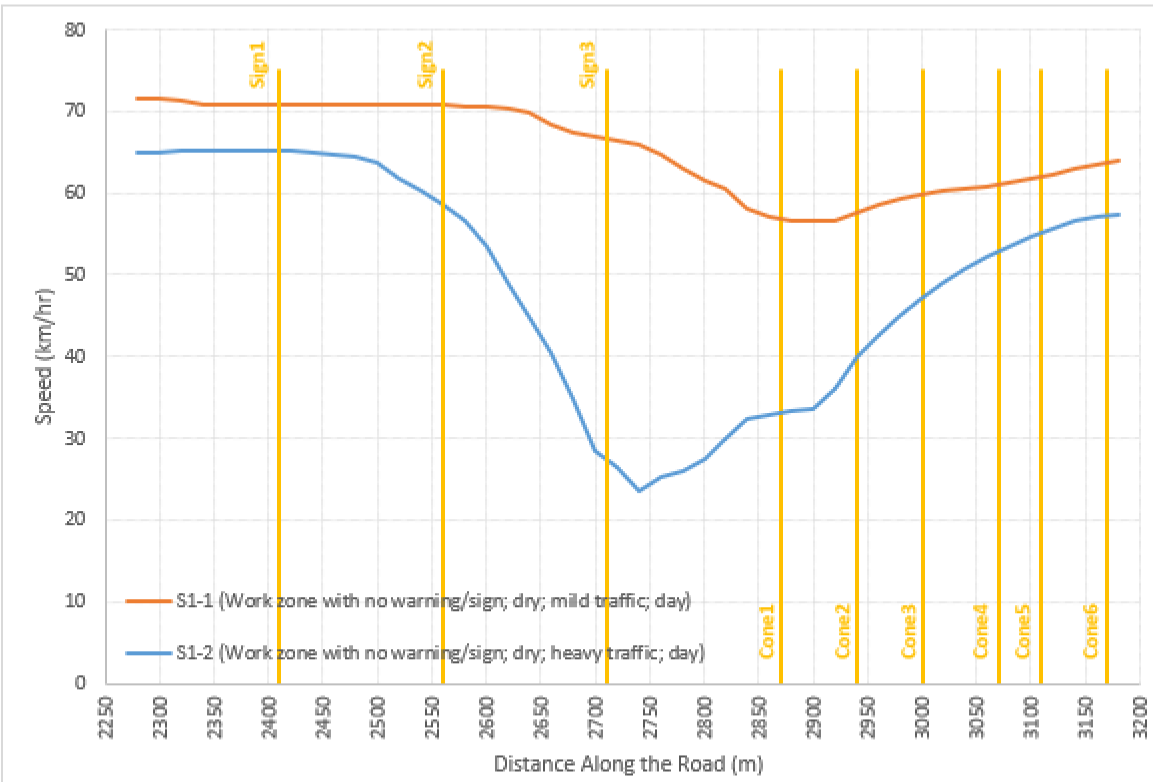


Figure 43: Mean speed comparison between mild & heavy traffic condition in work zone #3 with no warning/signage

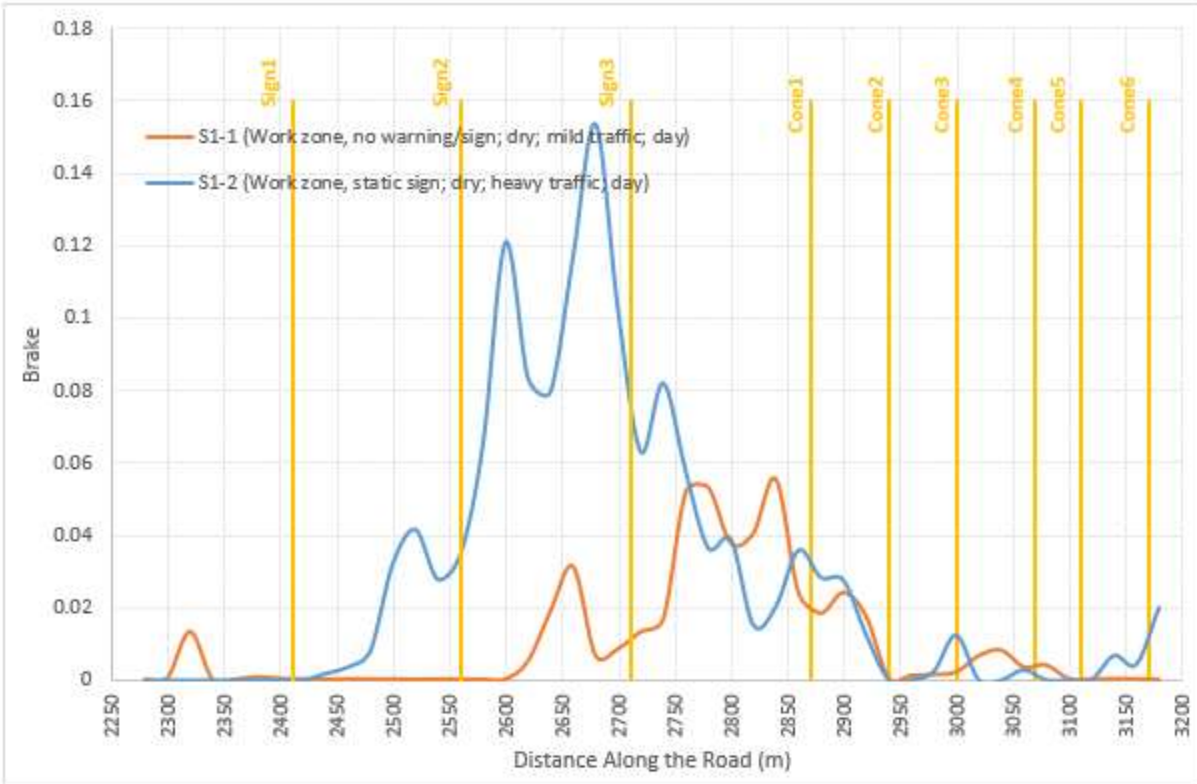


Figure 44: Brake use comparison between mild & heavy traffic condition in work zone #3 with no warning/signage

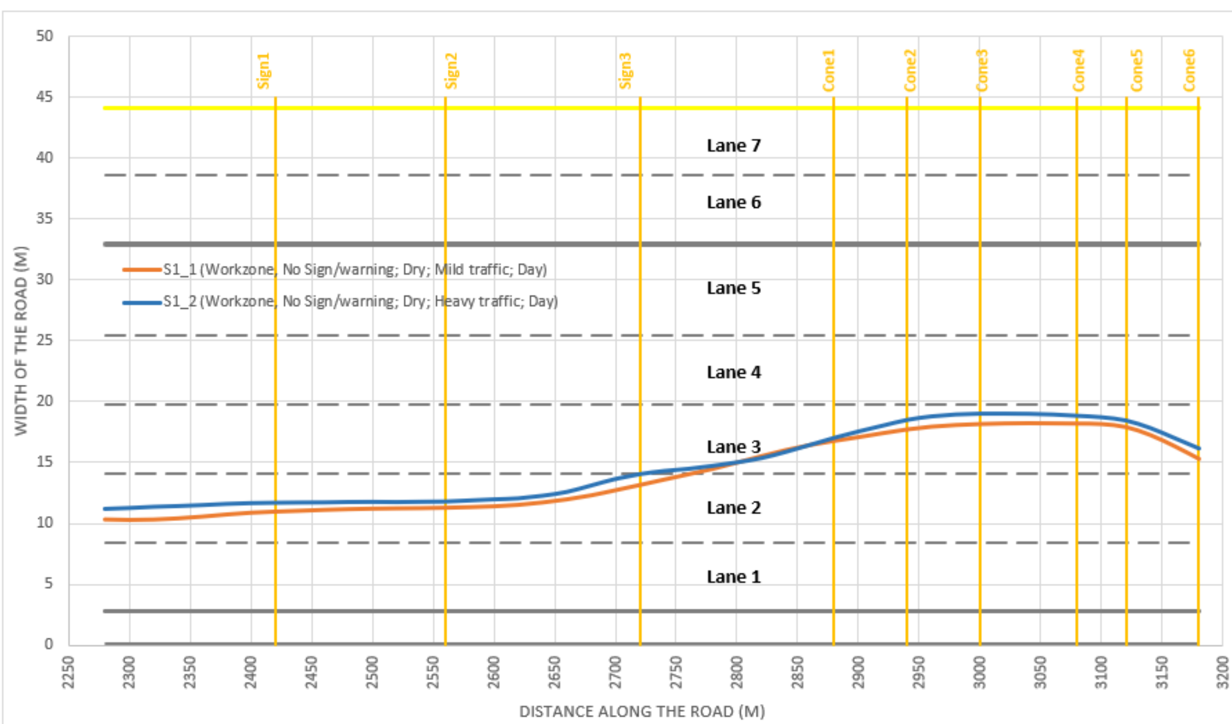


Figure 45: Lateral distance movement comparison between mild & heavy traffic in work zone #3 with no warning/signage

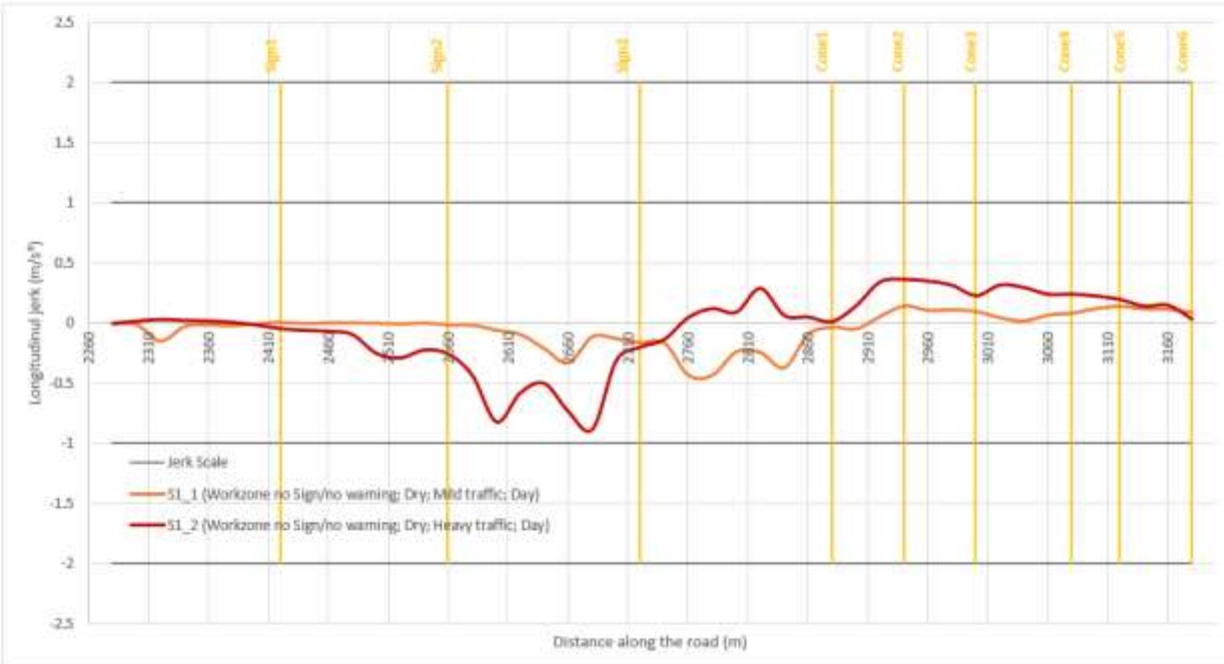


Figure 46: Vehicle jerk comparison between mild & heavy traffic in work zone #3 with no warning/signage

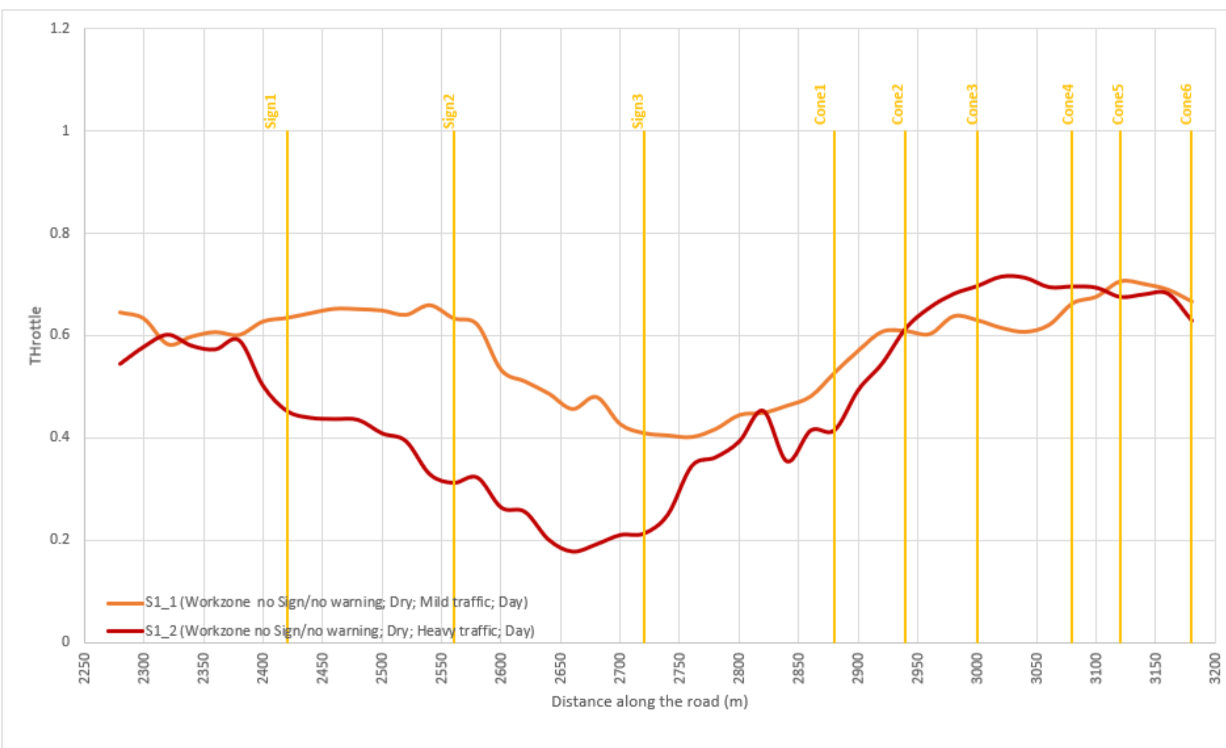


Figure 47: Vehicle throttle comparison between mild & heavy traffic in work zone #3 with no warning/signage

4.3.1.9. Weather Condition Impact on Driving Behavior in Work Zone with Static Warning

The effect of weather conditions (dry vs. rainy) on driving behavior was evaluated by comparing two different scenarios, S2-2 and S2-3, in a work zone with a static warning. The participants drove the scenarios during the daytime in *heavy* traffic conditions. **Figures 48** to **52** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarioswhen approaching and passing work zone #3. No significant change in driving behavioral parameters were observed between the dry and rainy weather conditions when the traffic volume was heavy.

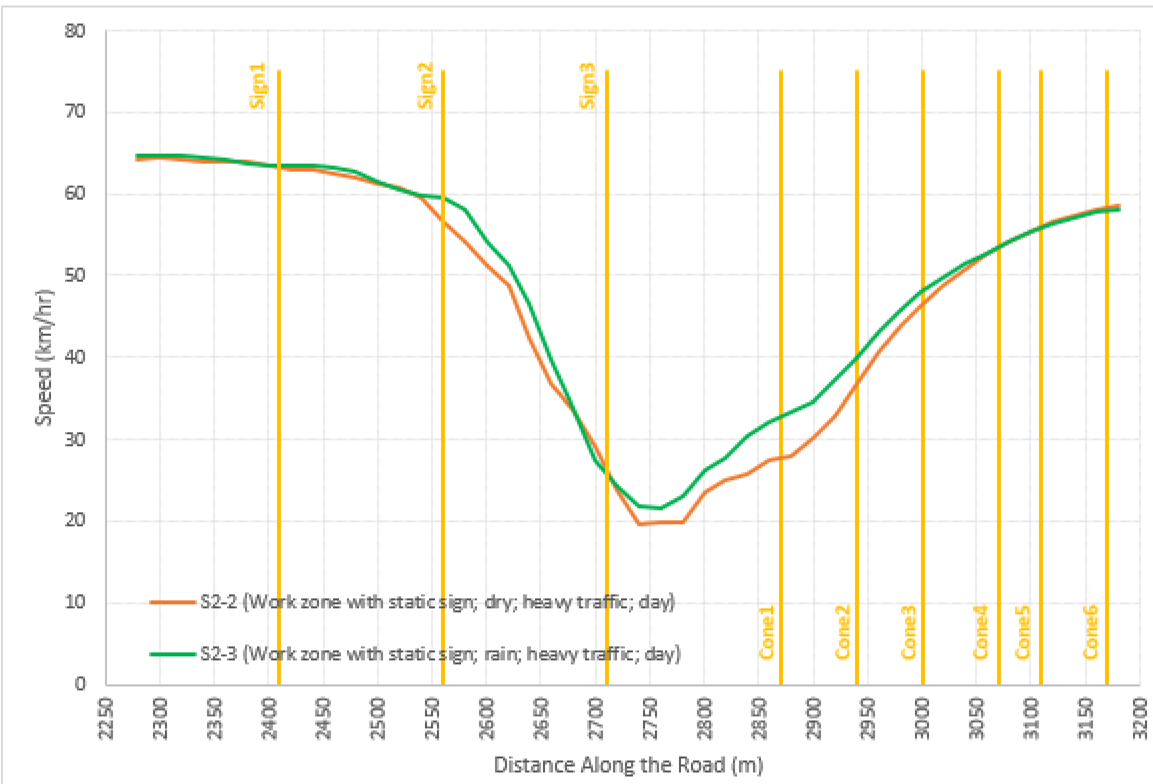


Figure 48: Mean speed comparison between dry and rainy weather condition in work zone #3 with static warning

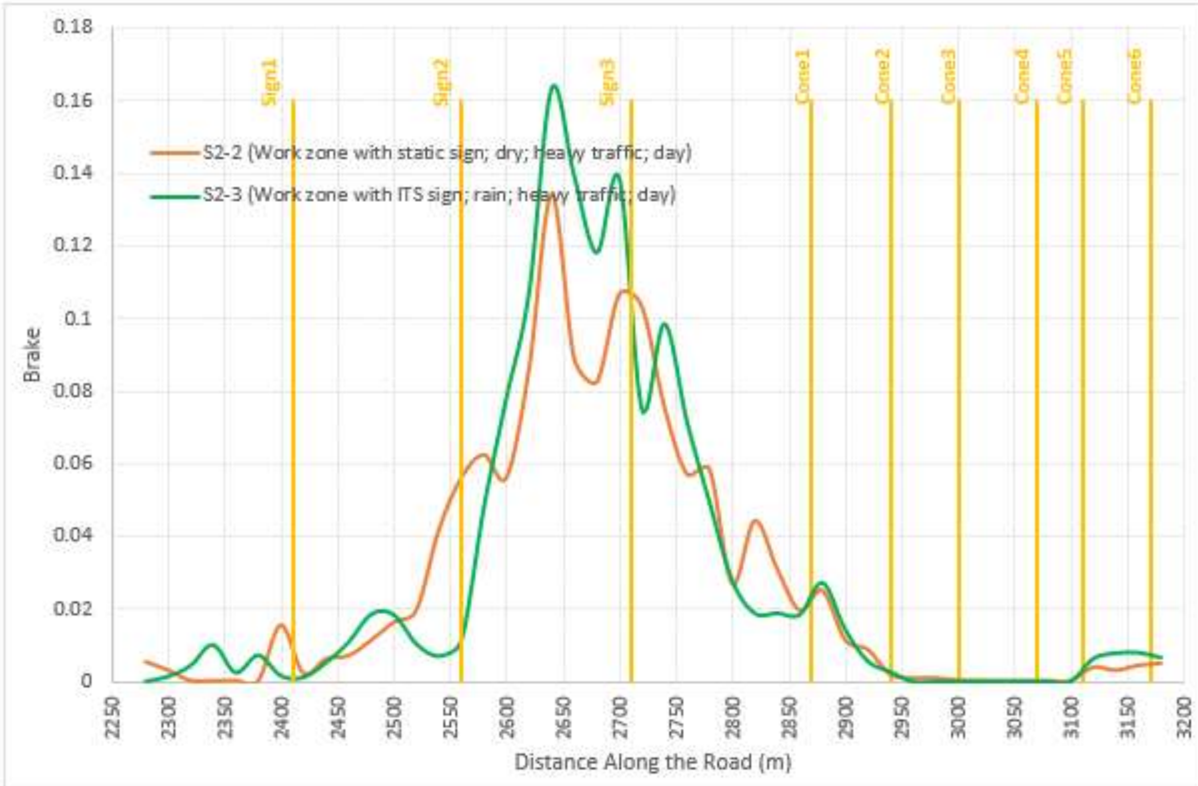


Figure 49: Brake use comparison between dry and rainy weather condition in work zone #3 with static warning

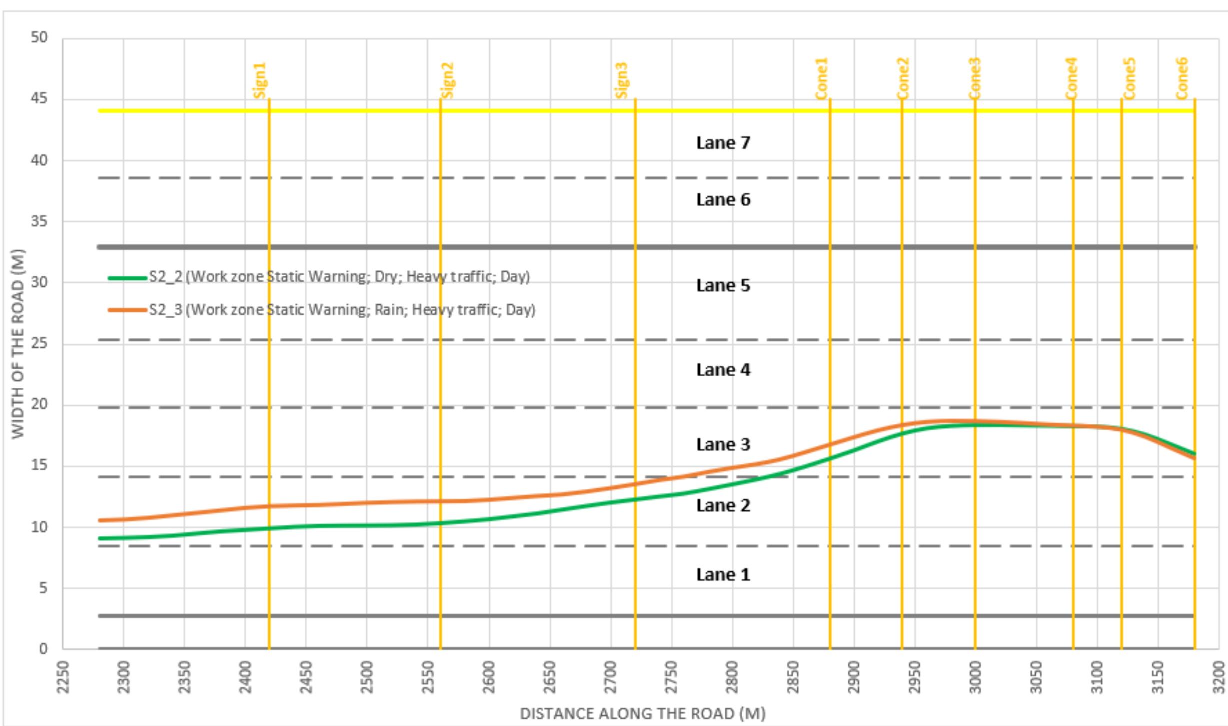


Figure 50: Lateral distance movement comparison between dry and rainy weather condition in work zone #3 with static warning

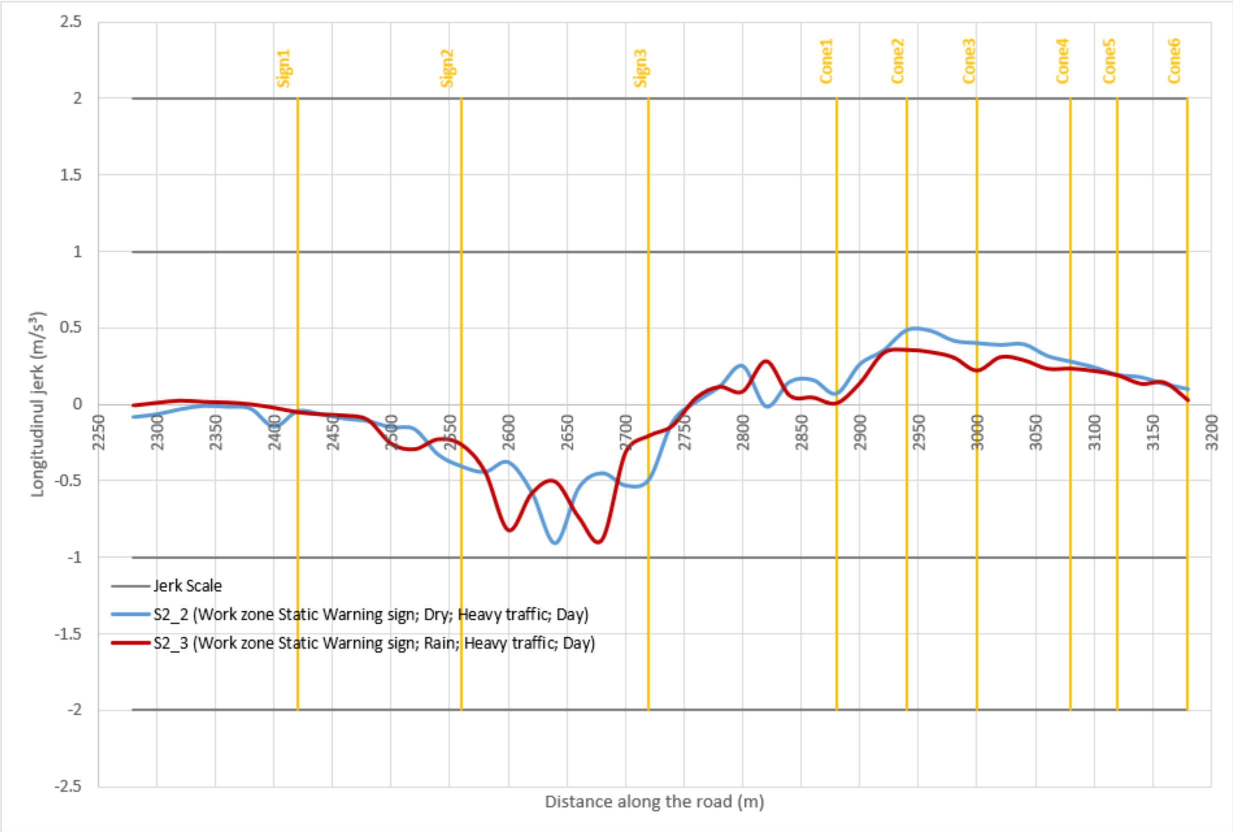


Figure 51: Vehicle jerk comparison between dry and rainy weather condition in work zone #3 with static warning

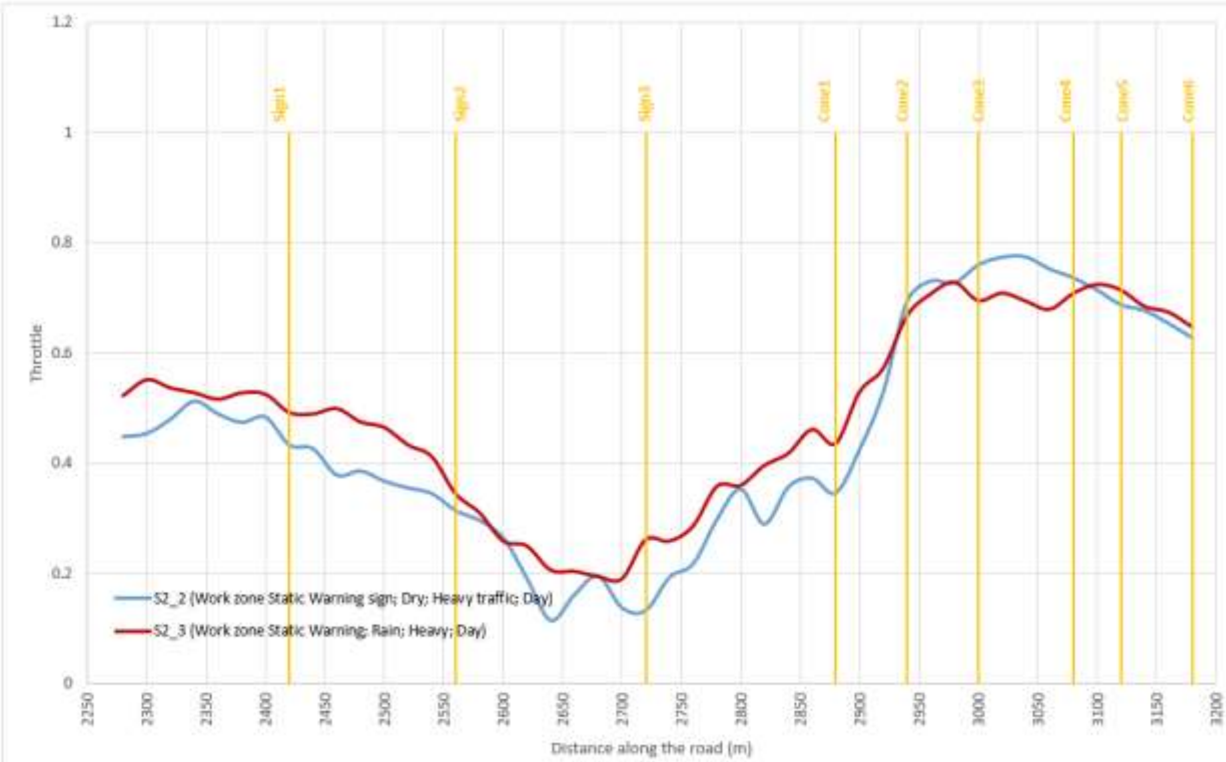


Figure 52: Vehicle throttle comparison between dry and rainy weather condition in work zone #3 with static warning

4.3.1.10. Visibility Condition Impact on Driving Behavior in Work Zone with Static Warning

The effect of visibility (daytime vs. nighttime) on driving behavior was evaluated by comparing two different scenarios, S2-3 and S2-5, in a work zone with a static warning. The participants drove the scenarios in *rainy* weather under *heavy* traffic conditions. **Figures 53** to **57** show and compare graphs of average speed, brake, lateral distance, jerk, and throttle of all participants in these scenarios when approaching and passing work zone #3. No significant change in driving behavioral parameters were observed between the daytime and nighttime driving conditions when the traffic volume was heavy.

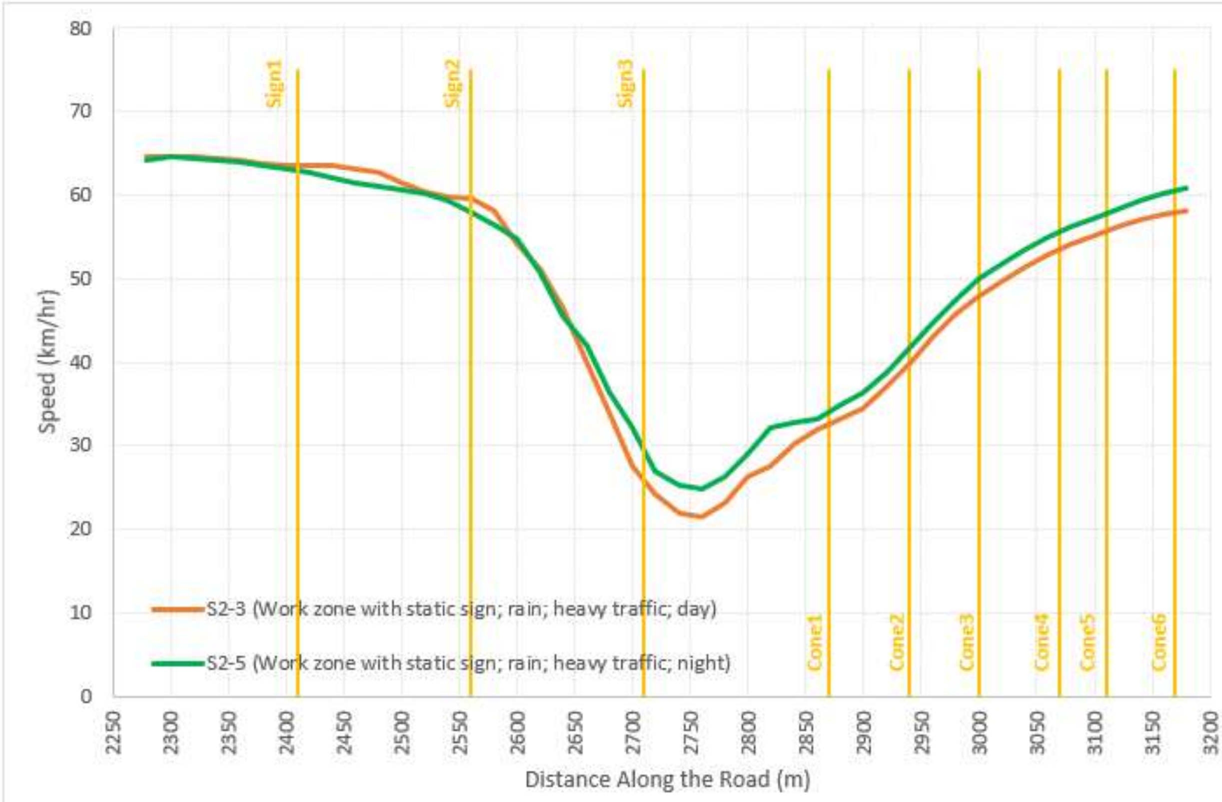


Figure 53: Mean speed comparison between daytime and nighttime in work zone #3 with static warning

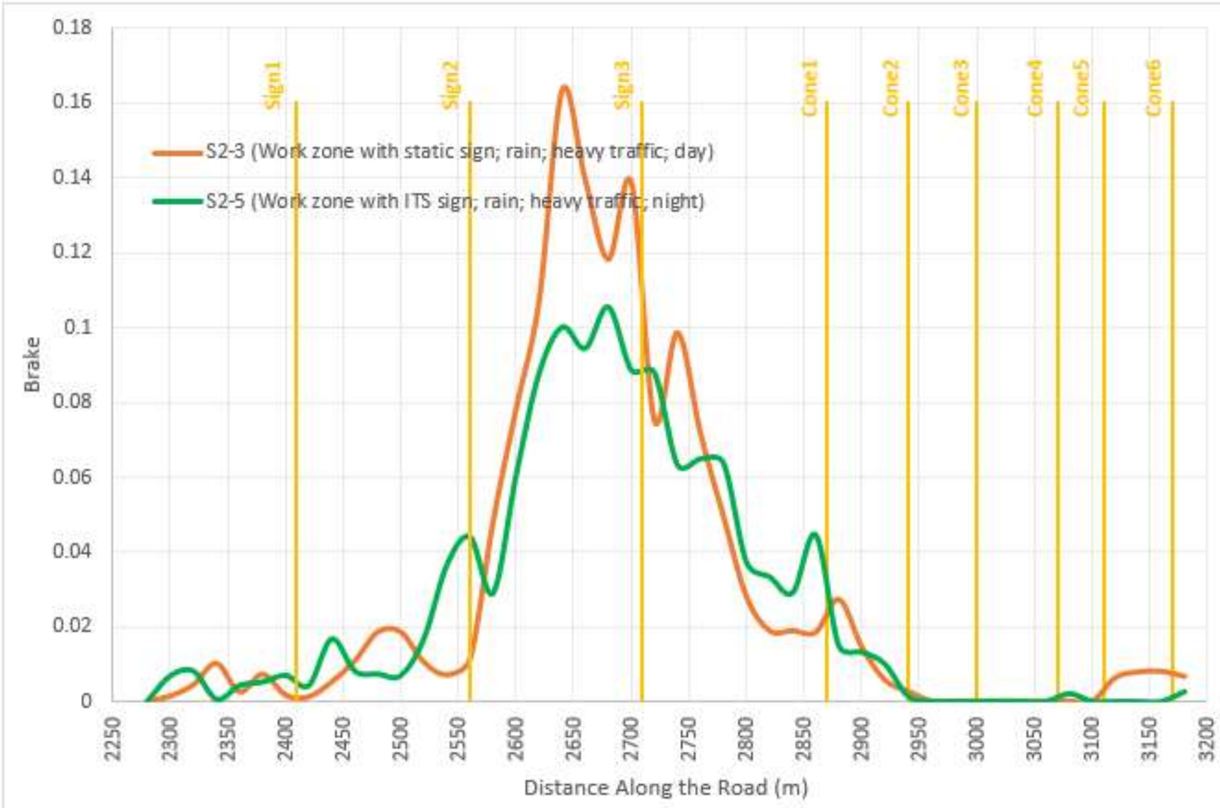


Figure 54: Brake use comparison between daytime and nighttime in work zone #3 with static warning

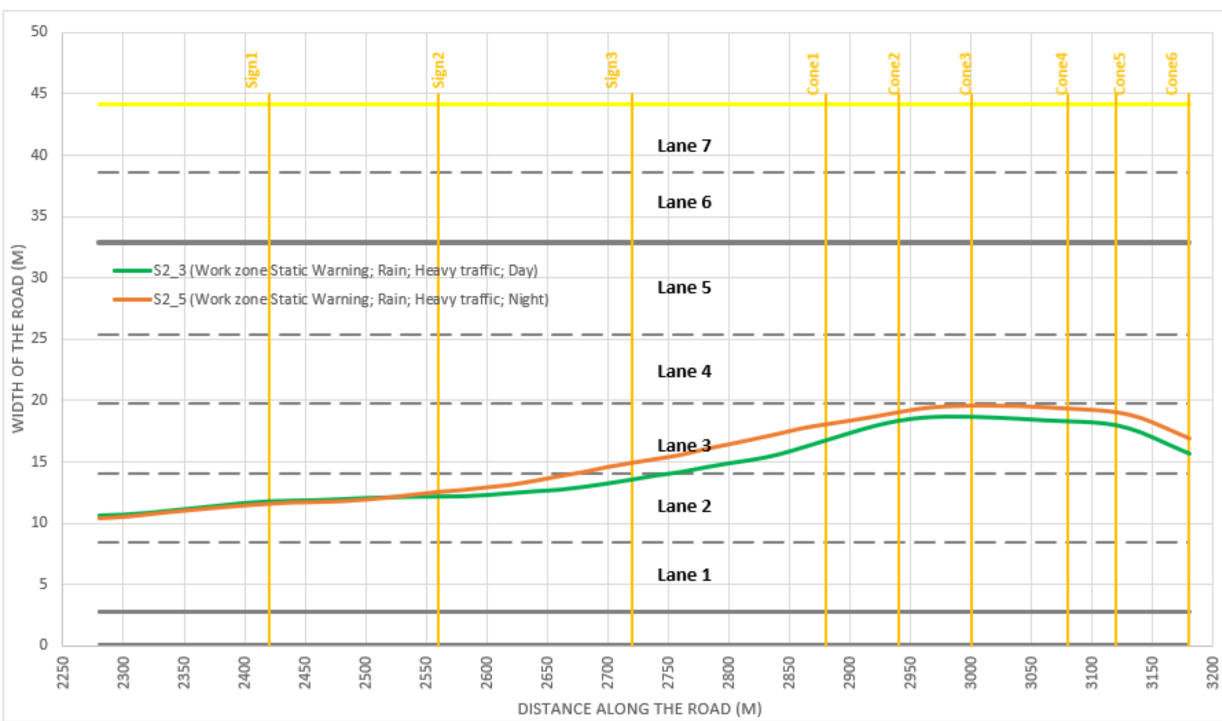


Figure 55: Lateral distance movement comparison between daytime and nighttime in work zone #3 with static warning

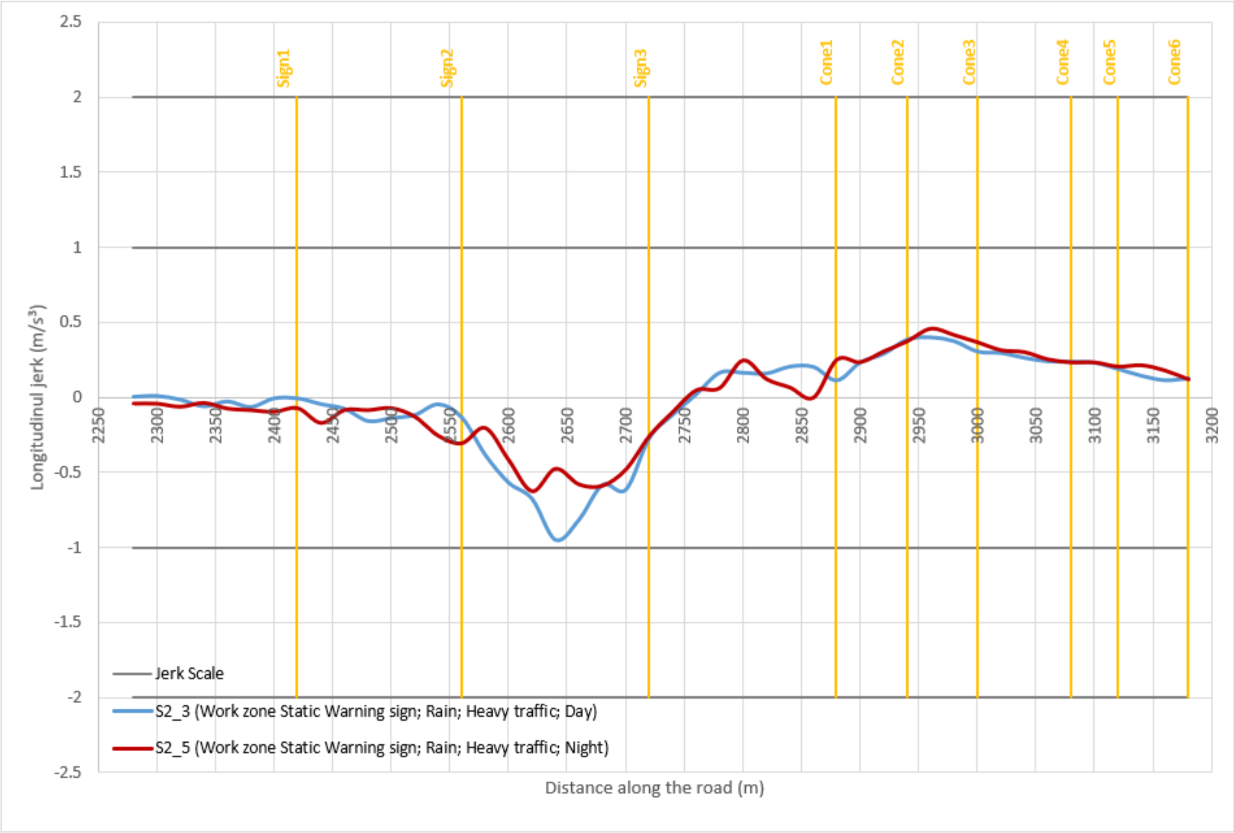


Figure 56: Vehicle jerk comparison between daytime and nighttime in work zone #3 with static warning

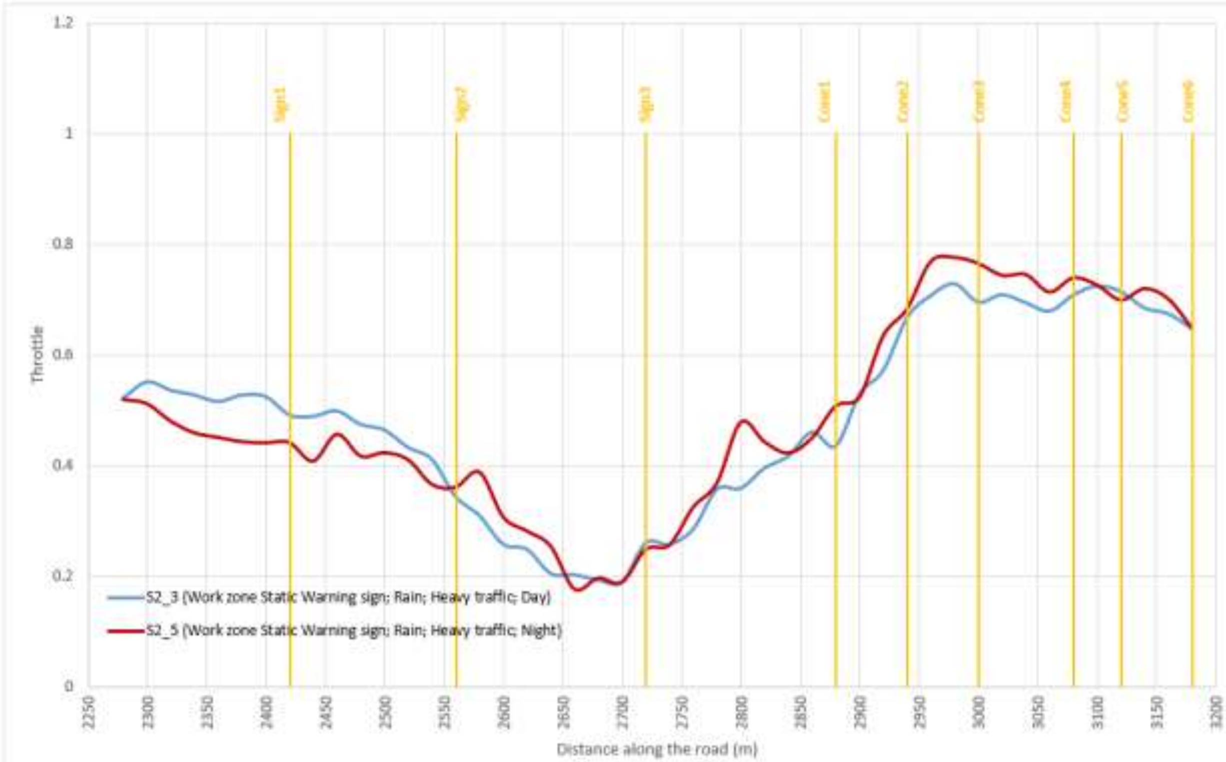


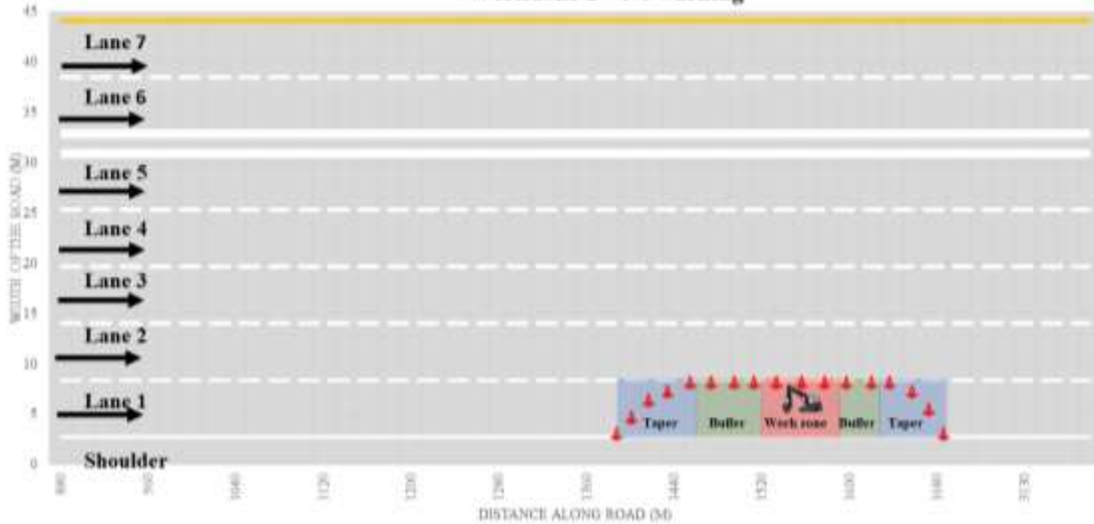
Figure 57: Vehicle throttle comparison between daytime and nighttime in work zone #3 with static warning

4.3.2. Work Zone #2 (Highway with 1 lane closed)

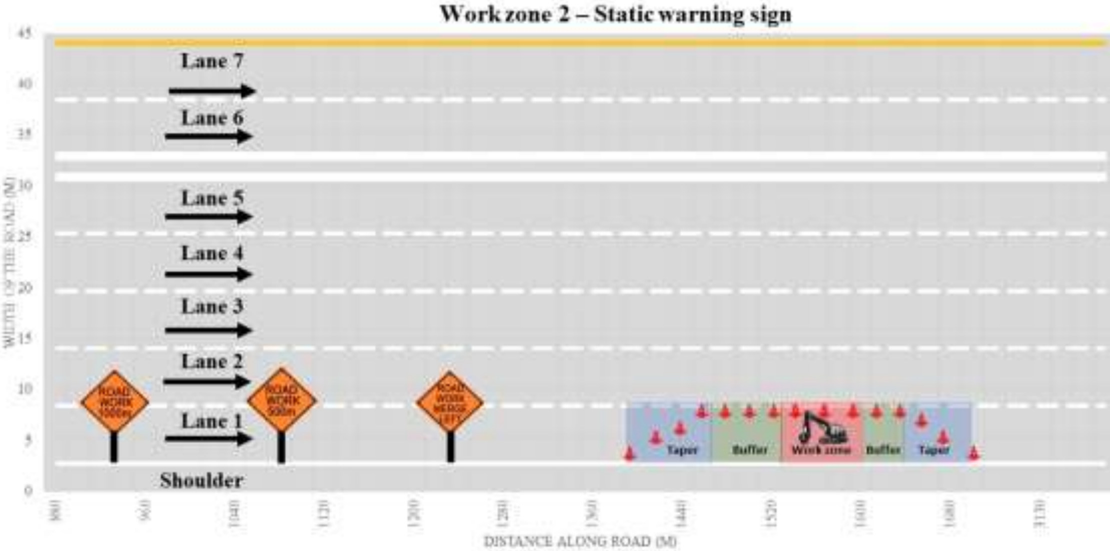
4.3.2.1. Aggregate Analysis

Figure 58 shows major points (signs, cones, start and end points, etc.) along the road where participants encountered the work zone under different scenarios with 1 lane closed on the highway. **Tables 8** and **9** present and compare the mean and variances (in parenthesis) of all participants' speeds and lateral distance, respectively, in each scenario for these 9 mileposts. A description of the study scenarios was presented earlier in **Table 4**.

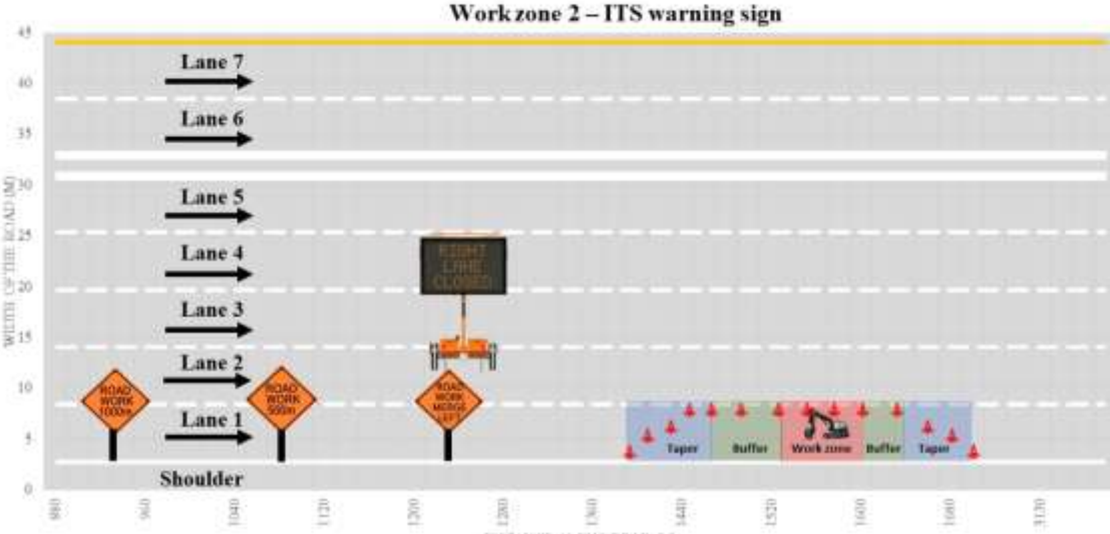
Work zone 2 – No warning



Work zone 2 – Static warning sign



Work zone 2 – ITS warning sign



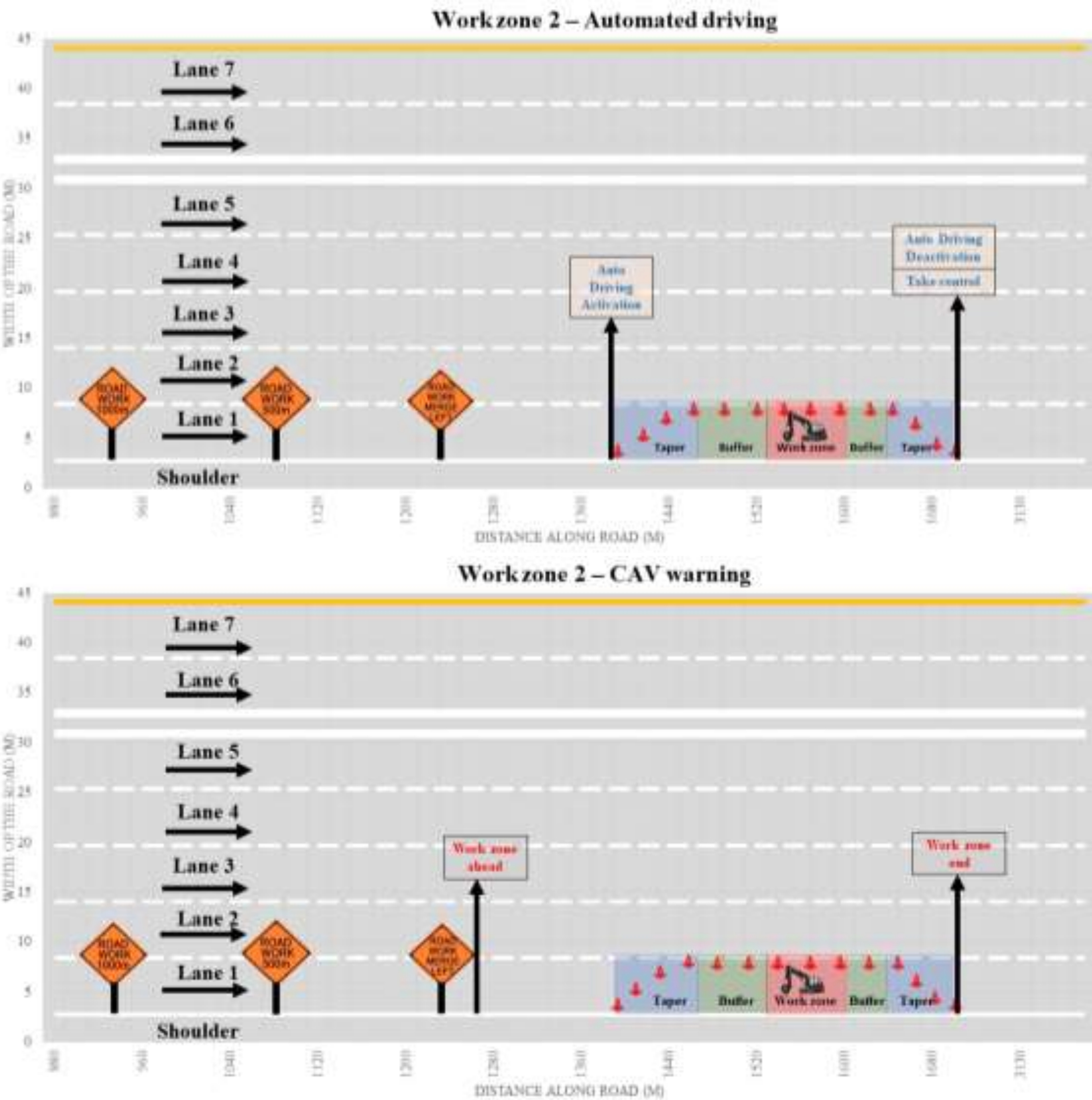


Figure 58: Work zone #2 illustration and critical points under various scenarios

Table 8: Mean (variance) speed in each scenario at 9 critical locations in work zone #2

Scenario \ point	Sign 1	Sign 2	Sign 3	cone 1	cone 2	cone 3	cone 4	cone 5	cone 6
S0	59.0	60.5	63.8	66.8	67.8	68.7	69.7	70.1	70.3
	(129.1)	(127.9)	(95.7)	(67.6)	(60.7)	(54.1)	(47.7)	(44.8)	(43.5)
S1_1	66.2	67.5	68.8	69.5	69.5	69.7	70.1	70.3	70.5
	(120.7)	(98.5)	(90.8)	(83.7)	(81.7)	(76.1)	(76.5)	(77.1)	(77.1)
S1_2	65.5	65.7	66.6	65.4	64.0	62.6	63.2	63.7	63.9
	(126.8)	(109.6)	(99.3)	(87.4)	(89.1)	(81.8)	(75.8)	(72.8)	(70.9)
S2_1	65.7	67.1	69.4	69.2	69.1	69.0	69.4	69.5	69.4
	(111.5)	(107.9)	(86.5)	(78.9)	(80.1)	(82.6)	(82.7)	(81.1)	(81.6)
S2_2	66.6	66.7	66.5	66.2	66.1	65.7	65.1	65.0	65.1
	(120.9)	(128.5)	(115.4)	(86.8)	(80.4)	(77.9)	(64.7)	(62.8)	(61.5)
S2_3	65.3	66.0	65.0	63.7	63.5	62.1	62.0	62.7	63.1
	(108.5)	(84.8)	(122.2)	(92.0)	(92.9)	(97.5)	(77.7)	(72.2)	(69.5)
S2_4	64.0	63.7	65.9	66.4	66.0	66.3	66.5	66.6	66.9
	(149.7)	(207.0)	(136.3)	(123.5)	(118.4)	(114.6)	(102.3)	(95.6)	(98.1)
S2_5	65.5	66.8	66.9	65.2	64.9	64.0	64.0	64.2	64.3
	(148.4)	(123.0)	(95.5)	(174.8)	(127.7)	(91.2)	(73.5)	(67.5)	(64.8)
S3_1	68.7	69.9	69.7	69.2	69.1	69.1	69.0	69.3	69.5
	(78.6)	(71.4)	(72.8)	(83.0)	(86.2)	(79.1)	(75.1)	(68.8)	(66.1)
S3_2	64.7	64.3	62.6	59.5	59.1	58.9	59.3	60.0	60.4
	(113.3)	(129.5)	(140.4)	(98.8)	(95.7)	(92.5)	(85.1)	(81.1)	(78.9)
S3_3	62.5	63.3	63.0	59.5	59.4	59.4	60.3	61.1	61.4
	(104.9)	(122.9)	(92.1)	(131.2)	(76.1)	(70.4)	(72.5)	(70.1)	(68.5)
S3_4	67.7	68.6	69.6	68.9	68.3	68.5	68.3	68.6	68.7
	(98.3)	(99.5)	(103.2)	(92.2)	(107.1)	(103.1)	(109.9)	(105.7)	(102.9)
S3_5	69.5	69.4	67.5	66.2	65.9	65.4	65.4	65.4	65.5
	(84.8)	(83.6)	(106.1)	(87.4)	(78.7)	(73.1)	(57.5)	(56.4)	(54.8)
S4_1	64.5	64.0	63.8	48.1	56.8	62.8	67.9	69.7	70.2
	(126.6)	(148.2)	(113.2)	(101.0)	(45.0)	(20.7)	(21.2)	(25.5)	(25.6)
S4_2	66.1	67.5	68.8	54.3	59.1	64.4	69.2	71.0	71.7
	(123.7)	(107.0)	(89.8)	(200.1)	(124.9)	(77.2)	(58.7)	(54.9)	(53.1)
S4_3	68.1	68.8	70.1	51.7	58.3	64.6	69.7	71.8	72.7
	(86.9)	(81.5)	(78.0)	(236.7)	(128.2)	(76.9)	(67.3)	(52.4)	(43.9)
S5_1	70.0	70.3	71.4	71.7	71.7	71.5	71.3	71.3	71.4
	(83.7)	(85.4)	(69.6)	(78.3)	(77.6)	(76.0)	(77.5)	(76.3)	(73.5)
S5_2	66.5	64.0	63.3	62.1	61.7	61.5	61.5	61.9	62.2
	(124.5)	(126.2)	(79.7)	(57.4)	(54.1)	(55.7)	(66.4)	(68.5)	(67.5)
S5_3	65.4	61.9	62.6	60.7	61.5	62.1	62.8	63.2	63.5
	(134.9)	(184.5)	(122.7)	(165.8)	(118.5)	(103.5)	(97.4)	(88.6)	(84.9)
S5_4	66.7	66.7	67.9	68.1	68.2	68.5	69.4	69.8	70.1
	(134.1)	(121.7)	(87.3)	(97.5)	(97.1)	(94.5)	(92.1)	(89.7)	(88.1)

Table 9: Average (variance) lateral distance of vehicle in each scenario at 9 critical locations in work zone #2

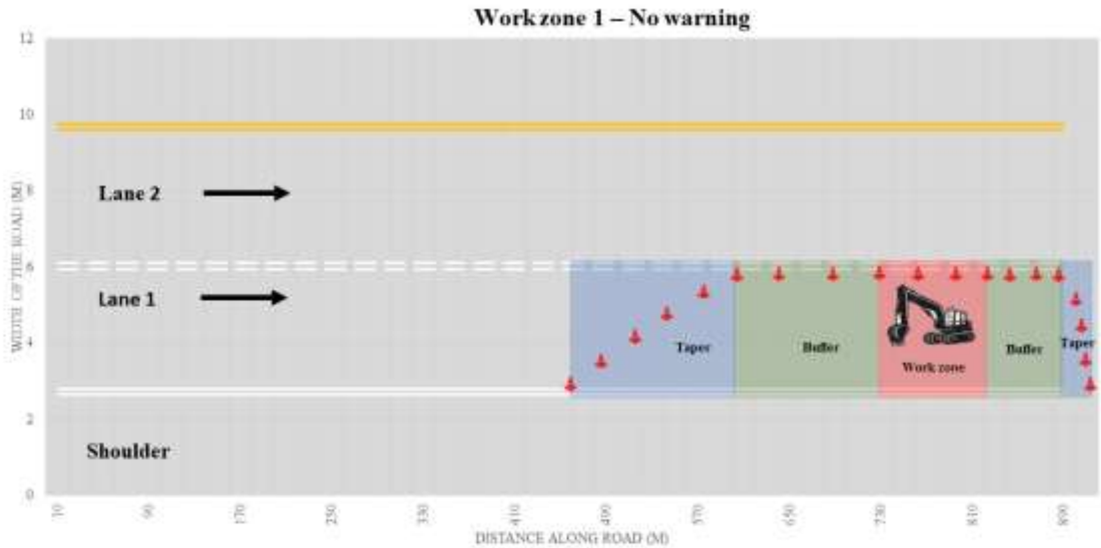
point / Scenario	Sign 1	Sign 2	Sign 3	cone 1	cone 2	cone 3	cone 4	cone 5	cone 6
S0	5.42	4.97	7.8	8.68	9.56	9.78	9.4	9.57	9.89
	(0.45)	(0.66)	(9.02)	(7.99)	(8.31)	(7.97)	(8.11)	(8.69)	(9.93)
S1_1	5.45	5.02	9.96	12.4	14.01	14.81	14.62	14.85	14.76
	(0.81)	(1.12)	(11.07)	(12.35)	(12.34)	(13.77)	(14.48)	(17.29)	(20.47)
S1_2	5.57	5.31	9.12	12.39	14.26	14.96	15.13	15.3	15.18
	(0.4)	(0.95)	(9.94)	(11.49)	(14.26)	(18.15)	(21.01)	(23.31)	(26.6)
S2_1	5.28	5.47	9.95	12.87	14.6	15.28	15.42	15.65	15.7
	(0.49)	(0.82)	(10.11)	(16.81)	(15.85)	(16.86)	(19.5)	(22.14)	(26.52)
S2_2	5.57	5.17	8.98	11.81	13.5	14.02	14.02	14.07	13.94
	(0.36)	(1.2)	(10.49)	(7.89)	(10.3)	(14.56)	(16.88)	(18.41)	(20.66)
S2_3	5.68	5.32	9.47	12.32	14.06	14.69	14.8	14.97	14.94
	(0.67)	(0.95)	(15.88)	(13.94)	(15.83)	(17.38)	(21.66)	(23.14)	(26.88)
S2_4	5.54	5.3	9.81	12.55	14.33	15.01	15.03	15.22	15.37
	(0.41)	(1.32)	(14.46)	(13.24)	(12.4)	(14.43)	(16.57)	(17.88)	(21.36)
S2_5	5.74	5.3	9.2	12.17	14	14.64	14.82	15.18	15.3
	(0.53)	(0.62)	(9.99)	(15.39)	(14)	(16.67)	(21.03)	(23.87)	(27.3)
S3_1	5.42	5.52	11.03	13.95	15.57	16.27	16.33	16.45	16.5
	(0.33)	(0.95)	(13.61)	(12.43)	(14.23)	(20.46)	(24.13)	(25.11)	(27.25)
S3_2	5.66	5.19	10.38	12.65	14.01	14.46	14.59	14.88	15.05
	(0.55)	(0.8)	(8.28)	(10.66)	(9.98)	(9.58)	(12.13)	(16.07)	(20.22)
S3_3	5.68	5.3	10.15	12.9	14.36	14.74	14.64	14.75	14.74
	(0.58)	(0.59)	(10.5)	(13.03)	(13.09)	(14.88)	(16.42)	(17.25)	(19.1)
S3_4	5.76	5.34	9.86	12.28	13.67	14.15	14.23	14.42	14.53
	(0.33)	(0.96)	(7.15)	(8.59)	(7.59)	(7.7)	(9.99)	(12.06)	(15.18)
S3_5	5.8	5.17	10.46	13.49	15.36	16.05	16.28	16.5	16.45
	(0.33)	(0.78)	(14.66)	(19.36)	(22.97)	(25.97)	(28.57)	(31.27)	(35.22)
S4_1	5.51	5.2	9.69	15.5	16.45	16.73	16.68	16.74	16.79
	(0.79)	(1.03)	(9.69)	(19)	(17.45)	(17.52)	(18.62)	(18.87)	(19.05)
S4_2	5.51	5.14	10.24	16.28	17.57	17.99	18.14	18.24	18.32
	(0.36)	(0.56)	(14.04)	(24.38)	(26.69)	(26.74)	(27.24)	(27.76)	(28.54)
S4_3	5.67	5.48	9.81	15.36	16.77	17.14	17.09	17.21	17.25
	(0.43)	(0.86)	(13.22)	(29.85)	(21.36)	(20.51)	(22.19)	(21.49)	(21.27)
S5_1	5.56	5.86	12.67	15.33	17.06	17.55	17.56	17.78	17.85
	(0.43)	(1.8)	(15.53)	(19.24)	(20.41)	(22.28)	(26.69)	(30.71)	(33.43)
S5_2	5.7	5.51	10.85	13.47	14.9	15.35	15.26	15.28	15.16
	(0.51)	(1.34)	(7.21)	(14.74)	(13.9)	(13.45)	(14.99)	(16.58)	(19.51)
S5_3	5.63	5.8	10.33	13.32	15.13	15.69	15.86	16.11	16.09
	(0.56)	(1.51)	(11.93)	(13.16)	(14.34)	(16.26)	(18.77)	(21.16)	(23.8)
S5_4	5.6	5.66	11.18	14.03	15.65	16.12	16.07	16.27	16.2
	(0.42)	(1.22)	(9.04)	(10.88)	(10.27)	(11.01)	(11.31)	(12.9)	(16.53)

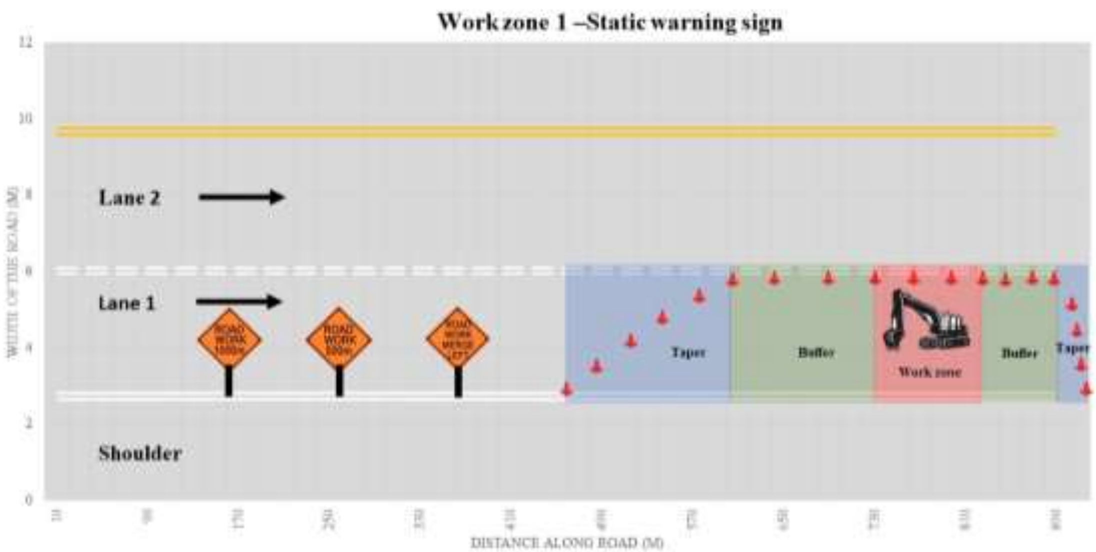
4.3.3. Work Zone #1 (Arterial with 1 lane closed)

4.3.3.1. Aggregate Analysis

Figure 59 shows major points (signs, cones, start and end points, etc.) along the road where participants encountered the work zone under different scenarios in an arterial with 1 lane closed.

Tables 10 and **11** present and compare the mean and variances (in parenthesis) of all participants' speeds and lateral distance, respectively, in each scenario for these 9 mileposts. A description of the study scenarios was presented earlier in **Table 4**.





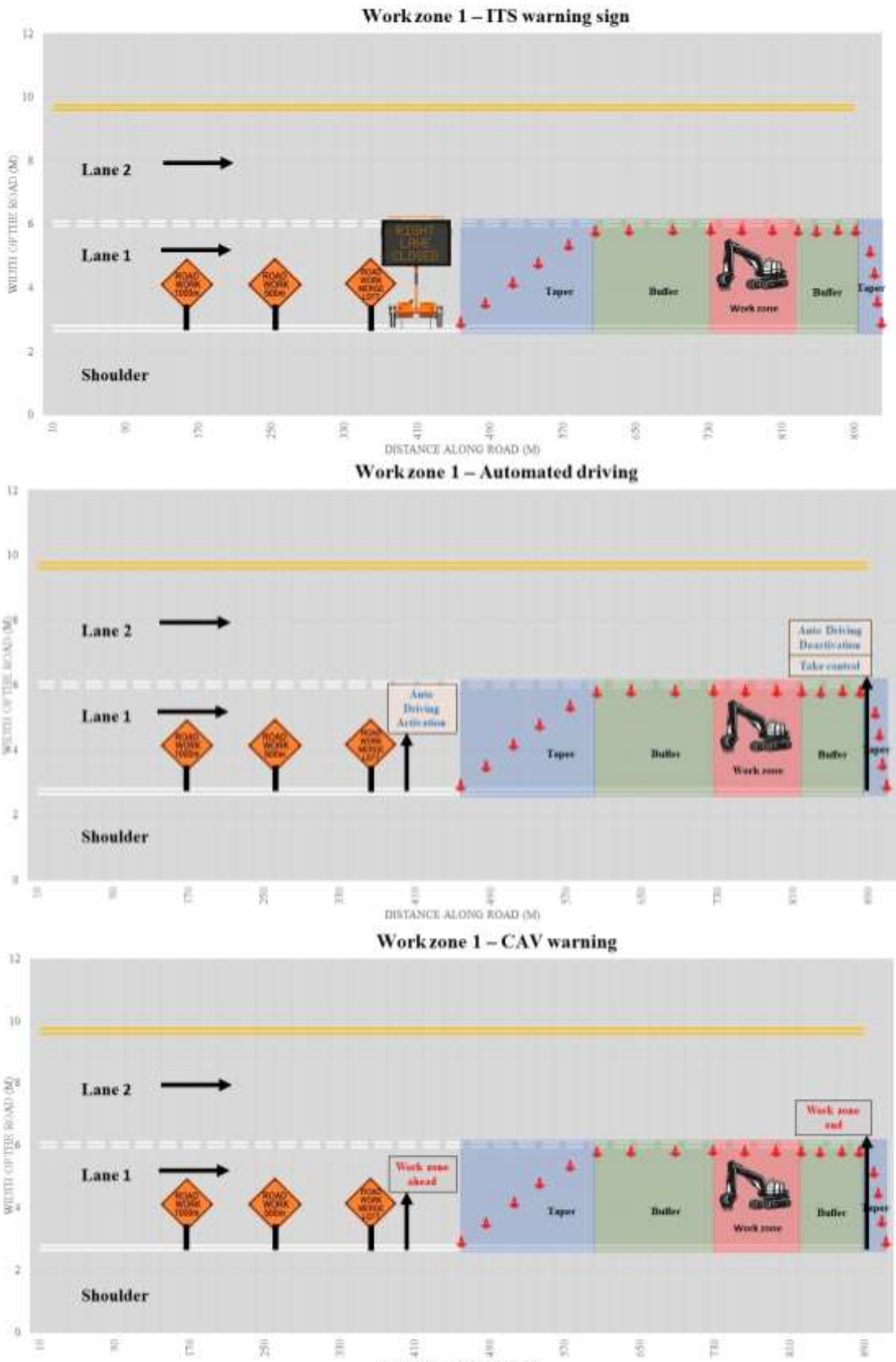


Figure 59: Work zone #1 illustration and critical points under various scenarios

Table 10: Mean (variance) speed in each scenario at 9 critical locations in work zone #1

point / Scenario	Sign 1	Sign 2	Sign 3	cone 1	cone 2	cone 3	cone 4	cone 5	cone 6
S0	39.4	48.9	53.0	57.2	60.0	62.1	62.8	62.5	62.0
	(49.5)	(53.4)	(58.2)	(63.2)	(70.3)	(68.4)	(70.2)	(88.2)	(97.8)
S1_1	48.2	56.5	59.0	60.1	60.0	59.5	59.9	59.1	58.3
	(24.3)	(43.3)	(62.1)	(93.5)	(98.3)	(118.3)	(138.8)	(126.0)	(127.4)
S1_2	47.8	55.3	56.8	55.9	58.0	58.0	58.4	56.2	55.6
	(41.0)	(55.6)	(124.1)	(197.3)	(89.5)	(90.2)	(91.3)	(121.5)	(137.7)
S2_1	47.4	56.2	59.0	59.1	60.7	59.9	60.3	59.6	59.2
	(43.3)	(51.4)	(72.7)	(134.1)	(91.6)	(110.6)	(105.7)	(99.2)	(100.5)
S2_2	47.7	56.0	57.6	56.6	57.0	56.8	57.1	55.4	54.9
	(34.2)	(38.8)	(67.0)	(96.5)	(93.9)	(109.2)	(105.2)	(120.7)	(119.2)
S2_3	47.1	53.4	55.2	56.5	59.2	57.8	57.7	55.5	54.5
	(49.9)	(126.9)	(137.5)	(161.2)	(93.8)	(103.3)	(104.9)	(127.4)	(154.6)
S2_4	46.6	55.0	57.3	58.1	59.3	58.7	58.5	58.7	58.8
	(74.6)	(104.0)	(135.2)	(217.5)	(176.6)	(181.6)	(199.0)	(213.4)	(201.1)
S2_5	47.8	56.1	57.7	58.7	60.9	61.0	61.3	60.6	60.4
	(30.1)	(57.6)	(129.5)	(134.7)	(82.6)	(90.0)	(88.7)	(97.5)	(96.4)
S3_1	48.3	56.6	58.3	61.3	61.6	60.3	60.7	59.9	59.5
	(38.0)	(60.4)	(100.1)	(71.5)	(73.3)	(116.9)	(122.8)	(151.6)	(155.1)
S3_2	47.0	53.0	54.6	55.8	57.3	58.1	56.8	53.2	53.3
	(55.3)	(128.9)	(202.9)	(206.3)	(85.6)	(98.2)	(178.3)	(252.1)	(218.1)
S3_3	46.6	53.2	54.4	53.8	56.9	57.1	57.7	57.1	56.0
	(43.3)	(97.5)	(133.2)	(222.8)	(105.0)	(122.9)	(128.4)	(150.2)	(180.7)
S3_4	46.5	55.0	57.6	58.0	60.5	60.8	61.2	60.9	61.1
	(35.7)	(52.9)	(79.5)	(96.6)	(74.0)	(86.2)	(94.2)	(98.1)	(97.6)
S3_5	48.1	56.4	58.3	59.1	60.8	60.3	60.2	60.3	60.1
	(36.9)	(41.9)	(71.4)	(93.4)	(66.3)	(57.6)	(73.3)	(77.9)	(81.1)
S4_1	46.4	53.7	56.6	47.0	45.4	45.5	45.7	45.8	46.4
	(26.5)	(35.6)	(81.7)	(56.6)	(8.8)	(11.78)	(14.8)	(19.6)	(20.1)
S4_2	48.0	54.8	58.4	48.8	44.9	44.9	44.9	44.9	44.9
	(38.1)	(74.1)	(85.7)	(51.8)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
S4_3	47.3	55.2	59.2	48.7	45.4	45.4	45.4	45.4	45.4
	(39.3)	(48.7)	(66.1)	(79.5)	(14.6)	(12.9)	(10.7)	(10.6)	(10.6)
S5_1	48.1	56.6	58.5	58.9	60.3	60.2	60.6	60.8	60.8
	(36.8)	(40.4)	(52.1)	(90.5)	(66.6)	(92.3)	(89.1)	(83.8)	(83.8)
S5_2	48.2	55.5	56.8	54.3	57.5	57.0	57.1	55.6	55.1
	(32.6)	(51.1)	(87.3)	(192.2)	(51.9)	(57.7)	(76.9)	(108.0)	(108.8)
S5_3	47.7	55.4	56.4	55.2	57.1	56.5	57.1	56.7	56.1
	(47.6)	(73.1)	(102.6)	(162.9)	(89.3)	(112.5)	(110.0)	(123.4)	(138.4)
S5_4	47.8	56.8	58.0	59.8	60.0	59.5	60.1	60.0	59.6
	(50.8)	(62.6)	(114.0)	(119.9)	(149.4)	(156.6)	(156.6)	(180.1)	(185.3)

Table 11: Average (variance) lateral distance of vehicle in each scenario at 9 critical locations in work zone #1

Scenario \ point	Sign 1	Sign 2	Sign 3	cone 1	cone 2	cone 3	cone 4	cone 5	cone 6
S0	4.20	4.06	4.03	3.85	3.86	4.22	4.20	4.10	3.97
	(0.62)	(0.54)	(0.53)	(0.78)	(0.71)	(0.66)	(0.79)	(0.73)	(0.76)
S1_1	4.74	5.15	5.90	6.80	7.86	7.73	7.83	7.79	6.59
	(2.11)	(2.61)	(2.47)	(0.8)	(0.1)	(0.1)	(0.12)	(0.17)	(0.6)
S1_2	4.86	5.21	6.08	6.80	7.92	7.74	7.92	7.73	6.39
	(2.62)	(2.47)	(2.15)	(0.97)	(0.1)	(0.14)	(0.09)	(0.15)	(0.6)
S2_1	4.92	5.33	5.98	6.79	7.92	7.82	7.93	7.81	6.97
	(2.38)	(2.28)	(2.29)	(0.9)	(0.14)	(0.17)	(0.11)	(0.14)	(0.43)
S2_2	4.75	5.06	5.60	6.68	7.89	7.87	7.82	7.81	6.96
	(2.16)	(2.58)	(2.42)	(1.08)	(0.16)	(0.16)	(0.2)	(0.13)	(0.48)
S2_3	4.72	5.37	6.06	6.68	7.89	7.77	7.87	7.85	6.77
	(2.07)	(2.55)	(2.56)	(0.82)	(0.1)	(0.13)	(0.08)	(0.11)	(0.54)
S2_4	5.08	5.59	6.03	6.75	7.80	7.72	7.86	7.86	6.94
	(2.16)	(2.39)	(2.04)	(0.87)	(0.12)	(0.15)	(0.19)	(0.12)	(0.62)
S2_5	5.25	5.71	6.20	6.83	7.80	7.75	7.79	7.79	6.73
	(2.75)	(2.95)	(2.49)	(0.85)	(0.16)	(0.2)	(0.18)	(0.15)	(0.56)
S3_1	5.64	6.28	6.46	7.24	7.87	7.83	7.82	7.80	6.84
	(2.66)	(2.07)	(1.44)	(0.27)	(0.17)	(0.13)	(0.14)	(0.15)	(0.36)
S3_2	5.00	5.65	6.30	6.97	7.90	7.80	7.87	7.82	6.68
	(2.62)	(2.44)	(1.78)	(0.81)	(0.1)	(0.14)	(0.14)	(0.13)	(0.81)
S3_3	4.94	5.43	6.22	6.86	7.87	7.81	7.86	7.73	6.82
	(2.22)	(2.38)	(2.1)	(1.2)	(0.09)	(0.1)	(0.1)	(0.12)	(0.5)
S3_4	5.48	5.91	6.64	7.11	7.77	7.67	7.76	7.88	7.02
	(2.74)	(2.2)	(1.15)	(0.37)	(0.15)	(0.19)	(0.18)	(0.17)	(0.46)
S3_5	5.14	5.82	6.32	6.97	7.71	7.74	7.79	7.74	6.59
	(2.69)	(2.85)	(1.97)	(0.62)	(0.22)	(0.16)	(0.18)	(0.19)	(0.49)
S4_1	4.98	5.29	5.73	6.88	7.73	7.69	7.67	7.72	7.68
	(2.49)	(2.95)	(2.76)	(1.71)	(0)	(0)	(0)	(0)	(0.01)
S4_2	5.32	5.77	6.22	7.48	7.76	7.67	7.68	7.72	7.70
	(2.49)	(2.51)	(1.66)	(0.54)	(0)	(0)	(0)	(0)	(0)
S4_3	5.76	6.25	6.56	7.62	7.76	7.67	7.66	7.72	7.69
	(3.06)	(2.54)	(1.5)	(0.21)	(0)	(0)	(0)	(0)	(0)
S5_1	5.51	6.00	6.22	6.77	7.82	7.83	7.84	7.76	6.55
	(2.71)	(2.42)	(1.94)	(1.22)	(0.23)	(0.14)	(0.19)	(0.14)	(0.5)
S5_2	5.18	5.54	5.92	6.72	7.96	7.75	7.88	7.80	6.61
	(2.18)	(2.62)	(2.36)	(0.96)	(0.11)	(0.15)	(0.23)	(0.19)	(0.53)
S5_3	4.96	5.32	5.95	6.89	7.82	7.85	7.84	7.76	6.69
	(2.11)	(2.74)	(2.12)	(0.67)	(0.13)	(0.14)	(0.14)	(0.27)	(0.66)
S5_4	5.07	5.55	6.06	7.02	7.72	7.75	7.76	7.82	7.00
	(2.59)	(2.95)	(2.24)	(0.49)	(0.18)	(0.11)	(0.13)	(0.1)	(0.24)

5. Conclusion

Work zones are essential for maintaining and upgrade any highway system. However, work zones can also pose an increased risk of crashes due to reduced road capacity, lane or ramp closure, altered traffic flow, and lane configuration changes. Commercial Motor Vehicles (CMVs), with their larger dimensions, heavier weight, lower acceleration/deceleration rate, harder maneuverability, and bigger blind spots, have shown higher risk of crashes in work zones compared to passenger cars.

Driving simulator are proven to be safe and effective method in safety research studies. The research investigated various work zone warning systems, including static signs, ITS application, connected & autonomous vehicles (CAV) and autonomous vehicles (AV) technologies in a simulated environment to evaluate the effectiveness of these methods on the driving behavior of CMV drivers and enhancing highway safety. The research recruited more than 50 drivers to test 20 different driving scenarios in a driving simulator environment to log and evaluate their driving records under various warning systems in the work zone. Within these 20 scenarios, three work zones were incorporated into the simulated network, each designed to represent different times of day, weather conditions, and traffic patterns. Each of these 20 scenarios took 5 – 7 minutes for the participant to complete and the whole experiment was nearly 2 hours for participants. Subjects were reimbursed for their time of driving.

Around 61% of the participants were male, and 33% of the total participants were within the age range of 26 to 33 years old. Among all, 31.6% reported having substantial prior knowledge about CAV technologies, while 26.3% had never heard about CAVs before. Moreover, 56% of participants regarded CAV features as beneficial for enhancing their driving safety. Similarly, 67% expressed the belief that CAV technology could serve as a valuable tool for promoting safe driving practices. When it came to encountering work zones, a third of the participants stated they would re-route to avoid the work zone, while 54% mentioned that they would adhere to their usual route but would take more caution.

Longitudinal and latitudinal driving data analysis results showed that the signs and warnings are all effective when compared to no sign/warning scenarios, where CAV mode generated the smoothest driving pattern, such as change in vehicles' speed when approaching a work area and change in lateral position of the vehicles when a lane change was required due to lane blockage.

While static sign showed more of a reactive behavior of the drivers, ITS systems and CAV modes made the drivers proactive by alerting them about the event downstream. Average lane change and speed reduction took place in an earlier point in the ITS scenario compared to static sign scenario. AV technology had the fastest return to normal driving conditions upon passing the work zone. Adopting CAV and AV technologies in CMV would be a major step toward highway safety in general and specifically around work zones. Under heavy traffic condition where lane changing is challenging for human-driven cars, the role of CAV and AV becomes more important to control and maneuver the car along the road with a work zone. This help traffic flow, reduction of sudden brakes, and improve throughput under reduced capacity conditions. The research finding is another proof of CAV applications in enhancing driving safety in work zones that shows the superiority of in-vehicle safety messages compared to the generic public messages by roadway traveler information systems.

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Appendix A

Pre-simulation survey questions

1. Please select your subject number
2. What is your gender?
   a. Male
   b. Female
3. What is your age group?
   a. 18 – 25,
   b. 26-35,
   c. 36-45,
   d. 46-55,
   e. 56- 65,
   f. More than 65
4. What is your ethnicity?
   a. American Indian or Alaska Native,
   b. Asian,
   c. Black or African American,
   d. White,
   e. Other
5. What is your present educational status?
   a. High School or less,
   b. Associate degree,
   c. Undergraduate student,
   d. Graduate
   e. Postgraduate
6. Are you currently employed?
   a. No,
   b. Part-time,
   c. full-time
7. What type of driving license do you have?
   a. Permanent license for regular vehicles-class C,
   b. Permanent license for all types of vehicles class A,
   c. Learner's Permit,
   d. Don't have a license
8. How many years do you drive commercial motor vehicle?
9. What is your annual household income?
   a. $20,000,
   b. $20,000 - $29,999,
   c. $30,000 - $49,999,
   d. $50,000 - $74,999,
   e. $75,000 - $99,999,
   f. More than $100,000
10. What is your household size?
    a. Only me

   b. 2
   c. 3
   d. 4 and more.
11. Do you drive a car?
   a. yes,
   b. no
12. How many cars does your household own?
   a. 1
   b. 2
   c. 3 or more
   d. None
13. What year and model of car do you drive if applicable?
14. Are you familiar with Connected and Autonomous Vehicles (CAVs)?
   a. Yes
   b. No
15. Does your personal car or CMV has CAV functions?
   a. Personal Car
   b. CMV
   c. None
16. If answer for 15 is yes , does your personal car or CMV inform you about any of the following? Check all that apply
   a. Incident Warning
   b. Forward Collision Warning,
   c. Curve Speed Warning,
   d. Pedestrian Warning,
   e. Autonomous Mode,
   f. None
17. Would you trust CAV applications?
   a. Yes
   b. No
   c. Some of them.
18. Do you use any app (like "Waze") while driving which alerts you about incidents or other information?
   a. Yes,
   b. No,
   c. Not applicable
19. Do you use any special app or platform for work zone information?
20. What is your primary strategy before start your route?
   a. Check the full Route via Google map or other platforms
   b. Check information through traffic alerts
   c. Use any social media platform (if yes please provide the platform name)
   d. Just put the addresses in GPS and start driving
   e. Something else (Please name the method here)
21. If you see any work zone in your route what is your regular reaction? (Chose all the answer match with you)
   a. Get frustrated

    b. Reduce your regular speed
    c. Try to speed up to cross the work zone fast
    d. Drive in regular pattern

22. If you come to know there will be a work zone in your route what will you do?
    a. Re-route
    b. Drive same route with more precaution
    c. Drive as you always drive.
23. Which kind of work zone sign make you more aware?
    a. Regular Static signs
    b. Digital Signs
    c. Prior Information through any app.
24. Do you think any mobile app with all necessary information (number of lane close, work zone length, time) about work zone will be helpful?
    a. Yes
    b. No
    c. May be
25. What information you want in any app regarding work zone or any other to drive any commercial vehicle safely?

Appendix B

Post-simulation survey questions

1. Please select your subject number
2. Which ITS function you liked for work zone safety?
    a. Dynamic Lane Merge System
    b. Portable Changeable Message Sign
    c. Queue Warning System
    d. None.
3. What was your reaction on encountering a CAV application?
    a. It was distracting,
    b. It helped for safe driving
    c. Ignored it
4. When autonomous mode was activated, you were?
    a. Distracted,
    b. Bored,
    c. Attentive
    d. Did not liked it
5. Which Automated mode do you liked?
    a. Automated Enforcement
    b. Voluntary automated driving
    c. Involuntary automated driving
    d. Entrance and exit warning
    e. None
6. After this experience, do you think CAV application will help you to drive safely?
    a. Yes,
    b. No
    c. Maybe
7. Would you pay to add any of these applications to CMV?
    a. Yes,
    b. No,
    c. Maybe
8. Which function you will prefer to have in your CMV?
9. Please check the intensity of any symptom which applies to you now.
    a. General discomfort, Fatigue,
    b. Headache, Eyestrain,
    c. Blurred Vision,
    d. Salivation increase/decrease,
    e. Sweating,
    f. Dizziness,
    g. Nausea
    h. None
10. Will you return for another simulation run using the driving simulator?
    a. Yes,
    b. No.