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Evaluation of work zone safety using the SHRP2 naturalistic driving study data

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by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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DEDICATION

To my wonderful son Arnesh Goswamy Biswas and my husband Animesh Biswas.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

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I would like to express my sincere gratitude to my major professor, Dr. Shauna Hallmark for her encouragement, and generous support during the entire course. She is a great mentor who always motivate, support and encourage her students. She is a role model to me who constantly guide me to balance academics and life effectively. She has always inspired me with her positive, strong and effective work ethics as she commits herself to excellence in her everyday work. Without her supervision and guidance, this dissertation would not have been accomplished.

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ABSTRACT

Work zones provide challenging and hazardous conditions not only for vehicle drivers, but also for highway workers who are injured or killed by errant vehicles. Over, 96,000 work zone crashes occurred in 2015 which equates to a work zone crash every 5.4 minutes. Several factors have been noted as contributing to work zone crashes. Driver factors have not been as well studied as other factors. The main objective of this study was to evaluate safety in work zones utilizing the SHRP2, Roadway Information Database (511 data) to identify potential work-zones. The study looked into the effectiveness of each temporary traffic control device on drivers' change in speed on four-lane and multilane divided highways. The study also evaluated drivers' lane change behavior on freeways with lane closure.

The research team manually coded the locations of work zone features starting from first work-zone sign to the end of work-zone. The change in speed from a point upstream of the legibility distance of each work zone feature was compared to the speed just past the feature. Driver distraction and eye glance were also included. A linear mixed effects model was used to predict drivers' change in speed in the work zone. For work zones on four-lane divided highways, speed feedback signs, lane end sign, and changeable message signs were found to be effective in reducing driver speed before the merge point. Non-forward related glance was seen to increase driver speed inside the work zone. Work zone speed limit signs were seen to be more effective within half mile inside a work zone. Presence of static work zone signs were more effective when the cones were placed as channelizing device inside the work zone. Vertical panels as channelizing device were used to decrease driver speed more effectively compared to concrete and cones. The change in speed model for multilane work zones showed static work zone signs to be effective in the upstream portion of start of taper of a work zone. Work zone

speed limit signs are effective when placed within half mile upstream. Lane end signs are effective in all the sections of locations in the downstream model. Drivers reduced speed due to presence of any worker or equipment inside the work zone.

Driver's lane change behavior in work zones with lane closure on four-lane divided work zones were analyzed. It was seen that with presence of rear accommodating vehicle in the open lane, the drivers tend to merge early in a lane closure scenario in a four-lane divided (farther from work zone activity area). Similarly, presence of enforcement sign before merging, tends to increase distance of lane merge from the end of taper showing that the drivers merge early in a lane closure scenario in a four-lane divided. Non-forward related glance was associated with drivers merging early in a lane closure scenario in a four-lane divided. The study also showed that driver moving over to left from right lane closure were choosing to merge early than when they were moving from right lane closure to left lane. This phenomenon cannot be fully justified as the sample size of this study was small. Head to head configuration was associated with drivers merging late. Influence of distraction and cell phone use was seen on drivers' lane change behavior. When drivers were distracted, the arrowhead CMS sign was not seen to be effective, meaning that the drivers did not choose to merge early in work zones lane closure scenario. Similarly, when they were distracted by cell phone, the normal speed limit signs were not effective to influence the drivers to merge early for a lane closure ahead scenario.

Several different analyses were conducted in order to evaluate the data from different perspectives. The different models had different response variables (i.e. change in speed, lane merge distance). The change in speed model assume that a driver decelerating or decreasing speed when they encounter a work zone feature were interpreted as positive behaviors. However, they do not capture drivers who may have slowed their speed entering the work zone and then maintained their speed. As a result, they would not have needed to slow when encountering additional features. For the lane merge analysis, it was assumed that drivers merging earlier that is farther ahead of the activity area were showing safe driving behavior than the drivers merging at the vicinity of the activity area. Overall, this study was successful in identifying active work zones from the RID data and reduce valuable information from the forward videos to evaluate driver behavior in work zones.

CHAPTER 1. INTRODUCTION

1.1 Background

Work zones tend to provide an unconventional and abnormal highway environment for motorists who are instead accustomed to an unobstructed roadway. According to the FHWA, work zone is an area of a traffic way with highway construction, maintenance, or utility-work activities. Also, FHWA designates a work zone to be typically marked by signs, channeling devices, barriers, pavement markings, and/or work vehicles. It extends from the first warning sign or flashing lights on a vehicle to the "End of Road Work" sign or the last traffic control device (Burk, 2000).

Figure 1-1 A typical Work Zone. (Work Zone Safety, 2016)

A work zone may be for short or long-time durations and may include stationary or moving activities. Examples of work zones as listed by the FHWA can be the following: building a new bridge, adding travel lanes to the roadway and extending an existing traffic way, mobile highway maintenance. Short-term stationary utility work can be repairing electric, gas, or water lines within the traffic way. A work zone requires drivers to encounter various traffic control devices. The adjacent roadway which is usually free of fixed objects most of the time, is occupied by warning devices, protective barriers, equipment, and workers during a work zone. This reduces the normal roadway capacity as generally one or more lanes are closed during the construction or maintenance period. Work zones can also introduce conflict between road users, maintenance or construction activity and equipment (Ha et al., 1989). The adverse effect of these restrictions is increased delay and congestion.

Construction and maintenance activities are not expected to reduce soon. Thus, continuing research and innovations in work zone safety are mandatory as driving through work zones will continue to be an everyday driving experience.

1.1.1 Problem Statement

Work zone related crashes are a major concern. About 116 fatal occupational injuries at the road construction sites were recorded in 2014 (NWZSIC, 2015). Overall, about 579 people were killed in work-zones all over the country in 2013 which equates to one work-zone fatality every 15 hours and to 1.8% of all roadway fatalities nationally. About 47,758 injuries were estimated to have occurred in work-zones crashes during 2013. This equates to about 131 work-zone injuries per day (NWZSIC, 2015). Previous studies showed that work-zone crashes were more severe than other crashes (Rouphail et. al., 1988; Pigman et al., 1990, and AASHTO, 1987). According to the Fatality Analysis Reporting System (FARS, 2006), Florida fatal work-zone crashes have risen 334% since 1999, ranking Florida the second highest state in fatal work-zone crashes in 2004 after the state of Texas (FARS, 2006).

Work zones provide challenging and hazardous conditions not only for vehicle drivers, but also for highway workers who are injured or killed by errant vehicles. There are many well-recognized work zone related problems and challenges that are to be faced by transportation departments. In 2013, 67,523 crashes were estimated to have occurred in work zones nationwide.

More than 20,000 workers are injured in road construction work zones each year, some of which are traffic related and some of which are limited to hazards within the construction activity area (FHWA, 2016). Between 106 to 133 worker fatalities per year occurred in work zones from 2010 to 2013 (NWZSIC, 2015).

Transportation agencies and contractors have used numerous countermeasures to get drivers' attention and to reduce speeds to encourage safe work-zone driving. However, driver behavior in work-zones is not well understood and studies evaluating the effectiveness of these countermeasures have not shown a clear effect. The availability of Naturalistic Driving Study (NDS) data by the Second Strategic Highway Research (SHRP2) offers an opportunity for first-hand observation of driver behavior in work-zones. However, identification of an entire stretch of work zone with good upstream data for studies can also be a challenge sometimes.

1.2 Literature Review

1.2.1 Crash percentages and severities

It has been mentioned in several studies that the presence of work zones may lead to increased traffic accident risks (Meng et. al., 2010; Weng et. al., 2011). It was seen that crash rates at work zones on multilane highways in Virginia increased about 57 percent and on two-lane urban highways about 168 percent when compared with crash rates in the period before the onset of a work zone (Garber and Woo, 1990). Hall and Lorenz (1989) found that crashes during construction increased by 26 percent compared with crashes in the same period in the previous year when no construction was present. Similarly, Rouphail (1988) found that the crash rates during construction increased by 88 percent when compared to the "before" period of the long-term work zone, on the other hand the results from the same study indicated that the crash rates for short-term work zones were not affected by the road work.

It was reported that the proportion of severe crashes is higher in work zones than in non-work zones (Ha and Nemeth, 1995; Meng et al., 2010). There exist mixed results when it comes to severity analysis or crashes in work zones. Most crashes in work zones do not lead to fatalities. In 2013, approximately one quarter of work zone crashes resulted in injuries and less than one percent of which resulted in a fatality. Studies have found that work zone crashes were slightly less severe than all crashes (Rouphail, 1988; Nemeth and Migletz, 1978; Nemeth et al., 1983). On the contrary, studies by Pigman et al. (1990) and AASHTO (1987) concluded that work zone crashes were more severe than other crashes. Similarly, Hargroves (1981) studied the work zone crashes in Virginia in 1977 and concluded that the average work zone crash was slightly more severe than the average crash in terms of the number of vehicles involved and average property damage. But on the other hand, average work zone crash was slightly less severe than the average crash when compared by the percentage of PDO crashes and the number of persons killed or injured per crash.

1.2.2 Factors affecting safety on work zones

Meng and Weng (2011) evaluated rear-end crashes at work zone areas. Based on work zone traffic data in Singapore, the investigators developed three rear-end crash risk models to examine the relationship between rear-end crash risk at activity area and its contributing factors. They developed a fourth, rear-end crash risk model to examine the effects of merging behavior on crash risk at merging area. The model results indicated that rear-end crash risk at work zone activity area increases with heavy vehicle percentage and lane traffic flow rate. One of their interesting findings was that the lane closer to work zone was prone to higher rear-end crash risk. They also found that expressway work zone activity area had much larger crash risk than arterial work zone activity area. Encouraging vehicles to merge early, they suggested, could be the most effective method to reduce rear-end crash risk at work zone merging area.

One of the biggest challenges for traffic engineers is to find ways of improving safety without hampering traffic movement on the highways. Li and Bai (2008) in their study developed a set of Crash Severity Index (CSI) models to study work zone crash severity outcomes. The study made a comparative analysis of the characteristics of fatal and injury accidents that occurred between 1992 and 2004 in Kansas highway construction zones. The researchers found significant differences between fatal and injury accidents. Head-on collision was the main type of fatal accident and rear-end collision the dominant injury accident type. Fatal accidents involved trucks while light vehicles where mainly involved in injury accidents. In comparison to injury accidents, unfavorable light conditions and complicated road geometries were the major factors responsible for fatal accidents.

Harb et al. (2008) investigated freeway Work-Zone Crashes to help develop countermeasures that limit work-zones' hazards. Florida Crash Records Database for years 2002, 2003, and 2004 was utilized for this study. Conditional logistic regression along with stratified sampling and multiple logistic regression models were estimated to model work-zone freeway crash traits. According to the results, roadway geometry, weather condition, age, gender, lighting condition, residence code, and driving under the influence of alcohol and/or drugs were the significant risk factors associated with work-zone crashes.

Jin et al. (2008) statistically compared crash characteristics on highways between construction time and non-construction time. A paired t-test, a two-way ANOVA, and a Tukey test were used to compare crash rates during construction time and during non-construction time at the same 202 highway sections in Utah. It was found that the difference in mean crash rates between construction time and non-construction time was not statistically significant at the 95% confidence level, indicating that the trend of higher crash rates during construction time reported by previous work zone safety-related studies was statistically not supported by Utah's work zone crash records.

Khattak et al. (2002) investigated the effects of presence of work zones on injury and non-injury crashes. The study created a dataset of California freeway work zones that included crash data (crash frequency and injury severity), road inventory data (average daily traffic (ADT) and urban/rural character), and work zone related data (duration, length, and location). Crash rates and crash frequencies in the pre-work zone and during-work zone periods were compared. Crash frequencies were modeled using negative binomial models, which showed that frequencies increased with increasing work zone duration, length, and average daily traffic. The important finding from the study suggested that longer work zone duration significantly increased both injury and non-injury crash frequencies.

Venugopal et al. (2000) developed regression models predicting the expected number of crashes at work zones on rural, two-lane freeway segments. Crashes on approaches to and inside the work zones were analyzed separately. Negative binomial models were developed which indicated traffic volumes, length of the work zones, and type of work as well as duration of work zones as the significant factors. Moreover, shorter work zones had a larger number of approach crashes than longer work zones.

1.2.3 Characteristics of work zone crashes

Garber et al. (2002) investigated crash characteristics at work zones. This study investigated the characteristics of work zone crashes that occurred in Virginia between 1996 and 1999. Information on each crash was obtained from the police crash record. The results from this study indicated that the crashes occurring in the activity area was the predominant location for work zone crashes regardless of highway type. Further it was found that the rear-end crashes were the predominant type of crash. The results also indicated that the proportion of sideswipe same direction crashes in the transition area of a work zone with adjacent road was significantly higher than in the advance warning area. Work zone crashes was found to be involved with higher proportion of multi-vehicle crashes and fatal crashes than non–work zone crashes. Nemeth and Migletz (1978) studied the minor safety upgrading projects conducted at 21 locations on the rural Interstate system of Ohio. They analyzed in detail 151 accidents that were identified from traffic crash reports and construction diaries as construction related. Results showed that the most frequently occurring accidents were rear-ending and single vehicle accidents and fixed-object accidents.

1.2.4 Driver speed

Various factors affect the speed of vehicles passing through a work zone. These include the geometric properties of the roadway, such as number of lanes, lane width, horizontal and vertical curvature, lateral clearance; and traffic control devices and warning signs, such as variable speed limit (VSL) signs, speed monitoring and display, flaggers, and law enforcement (Noel et al. 1987).

Chitturi and Benekohal (2005) found out that the narrower the lanes, the greater the speed reduction. Huebschman et al. (2003) studied reduced speed limits in work zones and evaluated the effectiveness of a combination of fixed and dynamic signs advising motorists of work zone fines and enforcement activity. The study concluded that the dynamic signs had no significant effect. It indicated that the "Construction Zone Traffic Fines" panel sign resulted in a statistically significant reduction of the mean speeds of motorists in the heart of the work zone, where construction activity was underway, and workers were present. The study also indicated that the VMSs displaying the number of traffic fines issued to date in the work zone, and updates to this message, produced no meaningful reduction in the mean speeds of motorists. The authors had hypothesized that motorists who traveled through the work zone on a regular basis would notice the number of traffic fines had increased and would decrease their speeds to avoid paying traffic fines themselves.

Results of a study conducted by Migletz et al. (1999) suggest that average mean speeds decreased by 5.1 mph in work zones where the speed limit was not reduced. In work zones with reduced speed limit, the greater the reduction in speed limit, the greater the reduction in mean speed. Compliance with work zone speed limits was generally greatest where the speed limit was not reduced and decreased where the speed limit was reduced by more than 10 mph. Primary factor affecting compliance with work zone speed limits is the risk of collision or injury. Elements contributing to this risk may include traffic volume, roadway cross-section (lane and shoulder widths), road surface conditions, weather conditions, awareness of the posted speed limit, awareness of workers and equipment present in the work zone and their proximity to traffic, and advance notification of the upcoming work zone.

Benekohal et al. (1992) studied the speed of vehicles at different locations in a construction zone in Illinois. The work zone configuration was one lane closed in each direction on a two lane per direction highway. Speed data at various influence points within the construction zone were collected. A total of 151 free flow vehicles travelling through the study section during a weekdays were used in the study. Based on the speed profiles, drivers were categorized into four different categories. Category 1 indicated drivers with noticeably reduced speed at the first speed limit sign, category 2 indicated drivers that travelled faster than the speed limit and did not significantly reduced speed, category 3 ignored both the speed limit and construction activities, category 4 were other than 1, 2 and 3. Drivers showing speed change of less than 5 mph was not used in the criteria. The study evaluated the change in speed at many influence points within the work space. The result showed 63% of drivers reduced speed after passing first work zone speed limit sign (Category 1), only 11% reduced speed at near to the location of construction activities (category 2) and 11% did not reduce their speed limit at all (category 3). Drivers were found to decrease the speed limit to the lowest level near to the work space.

Finley et al. (2014) evaluated driver's speed at upstream as well as inside the work zones. All of the work zones used for the study had speed limit of 10 mph below the original posted speed limit with different work zone configurations such as lane shift, lane closure, and temporary diversion. Speed data were analyzed at different points. Speed characteristics at upstream of work zone showed that 85th percentile speed was greater than the posted speed limit. 85th percentile speed was within 5 mph in 82% of the sites and between 6 to 7 mph over the original posted speed limit. Variation in the speed upstream was found to be between 11.3 and 33.8 mph. They also found that 85th percentile speeds at the first work zone speed limit sign with a work zone condition visible were still 3 to 11 mph over the reduced speed limit. They also indicate that motorist only reduce their speed limit if they clearly perceive a need to do so.

1.2.5 Change in the speed for work zone signs

1.2.5.1 Changeable/variable message signs

Thompson (2002) investigated the effect of trailer mounted changeable message sign. The study found change in the mean speed during the activation-on compared with the time of activation-off of variable or changeable message sign. Mean speed reduced from 55 mph to 48 mph when the changeable message sign was on.

Dixon and Wang (2002) identified the potential of fluorescent orange sheeting, innovative message signs, and changeable message signs with radar for reducing speeds in highway work zones. The study investigates the immediate effect as well as several weeks after implementation. Changeable message signs with radar significantly reduce the vehicle speeds in the immediate vicinity of the sign and did not demonstrate a novelty effect. They found reduction in speed adjacent to the sign by 6-7 mph immediately adjacent to the change message sign with radar in upstream of work zone but its effect did not extent to work zone area.

Brewer et al. 2006 found 2 mph reduction in 85th percentile speed downstream of the location of portable changeable message sign. The study found orange-border speed limit signs to be less effective than changeable message sign in reducing 85th percentile speed. In addition, a study by Sorel et al. 2006 found reduction in mean speed of 3 to 10 mph due to changeable message signs. Wang et al. 2003 studied the effect of changeable message sign in addition to fluorescent orange sheeting and innovative message signs with radar. The signs were used for reducing speeds in work zones. Data were collected both from upstream and inside the work zone. Result showed changeable message sign with radar significantly reduced the vehicles speed on the vicinity of sign by 8 mph. On the other hand, fluorescent orange sheeting and innovative message signs were able to reduce speed by 1 to 3 mph and 0.2 to 1.8 mph respectively.

Bai et al. (2010) analyzed motorist responses to temporary signage in highway work zone to determine motorists' responses to warning signs in rural, two lane highway work zone. The study concentrated on two lane work zones on US 36 with duration of four days. Devices used were the following: Portable changeable message signs (PCM) off, PCM on with message 'Slow Down Drive Safely', Temp traffic sign (W20 – 1, 'Road Work Ahead'). Results indicated portable changeable message signs (PCM) to be the most effective reducing truck speed. Temporary traffic sign to be most effective in reducing passenger car and semi-trailer speed.

1.2.5.2 Speed limit and feedback signs

A study by Finley (2008) found, in general, the 85th percentile speed downstream of a reduced work zone speed limit sign decreased slightly (on average by 3 mph) though the operating speed was still 9 to 16 mph over the work zone speed limit. Finley et al. (2014) compared digital speed limit signs with static speed limit signs in work zone areas. The study found decrease in 85th percentile speed limit due to digital speed limit sign from 1.0 to 12.1 mph at different sites.

Brewer et al. (2006) evaluated the levels of driver compliance on three different work zone signs, speed display trailers, changeable message signs and orange bordered speed limit signs. Result showed that device that display the speed of vehicles has the most significant effect in reducing the speed compared to static speed limit signs. Similarly, McCoy et al. (1995) evaluated the effectiveness of speed monitoring display in a work zone on an interstate highway in South Dakota. Mean speed of vehicles were reduced by 4 to 5 mph. The sign was also able to reduce the percentage of vehicles exceeding the advisory speed limit by 20 to 40%. Maze (2000) also evaluated the effect of speed monitor display. The results showed decreased in the mean and 85th percentile speed but not statistically significant.

Richards et al. 1985 found that a Changeable Message Sign (CMS) showing a speed limit message reduced vehicles speed by an average of 3 mph. Both "Speed-Only Message" and "Speed and Information Message" reduced the mean speed in the range of 0 to 5 mph. Carlson et al. (2000) studied upstream and work zone area to find the effectiveness of speed display trailers. Four work zones with two lane highways and five work zones with multi-lane highway with single lane closure scenario were used for the study. LIDAR guns and piezoelectric sensors were used to track the speed of vehicles approaching to work zones. In work zones with lane closure operations, vehicles were found to reduce speed significantly higher between 2 to 7.5 miles per hour upstream and 3 to 6 miles with in the work zone. Other research studies have also shown reduced mean speed by 2 to 7 miles per hour due to speed display trailer (Saito et al. 2003; Carlson et al. 2000; Hall and Wrage, 1997; Jackels and Brannan, 1988; Richards et al. 1985). Meyer (2003) evaluated an effect of radar actuated speed display. The evaluation was done on a two-lane rural commuter routes on the west of Lawrence, Kansas and data were collected for about 8 weeks. Before and after data were compared to see an effect of speed displays on speed. Both mean and 85th percentile speed was significantly decreased by about 5 miles per hour. Percentage of drivers speeding above 5 mph dropped from 30% to less than 5%.

1.2.5.3 Enforcement signs

Benekohal et al. (2010) studied the effect of Speed Photo-radar Enforcement (SPE). The system reduced an average speed of free-flowing cars by 6.3-7.9 mph traveling on median lane and 4.1-7.7 mph traveling on shoulder lane. Due to SPE, free flowing trucks reduced speed in the median lane by 3.4-6.9 mph and in the shoulder lane by 4.0-6.1 mph. SPE was found to be more effective with the presence of police car. Benekohal et al. 1992 found that police patrolling by circulating in the 4 miles sections of work zone activity in work zone with 2 lanes in each direction with one lane closed in each direction, an average speed of cars and trucks in the work zone were reduced by about 4 to 5 mph. Finley et al. 2014 found that in the vicinity of law enforcement 85th percentile speed limit decreased by 14 miles per hours at all the sites. However, researchers also found the difference between stationary and circulating patrol car. Richards et al. 1985 found that stationary patrol car was able to reduce mean speed by 4-12 mph and circulating patrol car was able to reduce mean speed by 2-3 mph. In a different paper, Richards et al. 1985 also found a speed decrease of 9 to 15 mph due to stationary patrol car. Bai et al., (2009) investigated the drivers' acceptance of the proposed Emergency Flasher Traffic Control Device (EFTCD) by measuring the mean speed changes of vehicles with without

EFTCD and opinions. Area of focus was one lane two-way work zones in Kansas. Results showed that EFTCD was effective as motorist responded by reducing speed.

1.2.6 Daytime and nighttime work zones crash studies

The proportion of nighttime fatal work zone crashes was higher on urban roads compared to rural roads (Arditi et al., 2007). But nighttime construction is extensively conducted to mitigate congestion, for reduced exposure to the traveling public, to operate in cooler temperatures However, awareness about safety of workers in nighttime construction has been a major concern as nighttime construction may create hazardous work conditions (Arditi et al., 2007). Arditi et al. (2007) studied fatal accidents in nighttime and daytime highway construction work zones. The study investigated fatal accidents from the year 1996 to 2001 that occurred in Illinois highway work zones. The lighting and weather conditions were included into the study as control parameters to investigate their effects on the frequency of fatal accidents in work zones. Results suggested that nighttime construction was more hazardous than daytime construction. Pigman and Agent (1990) also found that crashes during darkness were more severe, whereas Nemeth and Migletz (1978) found that crashes during daylight hours were more severe than those at night or at dawn and dusk. Some studies concluded that nighttime crashes were especially concentrated at the transition area (Richard et al., 1981). Ha and Nemeth (1995) also found that night crashes were more likely to be crashes struck by fixed object and that single-vehicle crashes were more predominant at night.

1.2.7 Statistical approaches

Numerous studies have utilized various statistical approached to conduct studies based on the historical accident data, on the analysis of work zone crashes. Qi et al. (2005) conducted a detailed investigation of rear-end crashes occurred in work zones in the state of New York and developed the truncated count data models to study the relationship between crash frequency and work zone characteristics.

Wang and Abdel-Aty (2006) evaluated the generalized estimating equations with the help of negative binomial model with log link to model rear-end crash frequencies at signalized intersections. Kim et al. (2010) developed a modified negative binomial regression model to estimate rear-end crash risk using accident data from the state of Washington State. Srinivasan et al. (2007) modeled the location of rear-end crashes within work zones as a function of the lengths of different work zone segments, traffic volume, weather and other exogenous factors.

Harb et al. (2008) built a conditional logistic regression model to estimate work zone rear-end crash risk. Khattak et al. (2002) and Meng et al. (2010) analyzed the impacts of work zone characteristics on crash frequency based on the historical data. They found that traffic volume and road type are two important determinants of crash frequency in work zone.

Recent studies have attempted to exploit the vehicle trajectory data to estimate crash risk. Hu et al. (2004) proposed a probabilistic model for the prediction of traffic accidents using 3D model-based vehicle tracking. In their study, a fuzzy self-organizing neural network algorithm was applied to learn trajectory patterns.

Hourdos et al. (2006) used individual speeds and headways to detect crash-prone traffic conditions on a freeway in Minnesota. They also established a relationship between fast evolving real time traffic conditions and the likelihood of a crash. Oh et al. (2006) developed a methodology to identify the real-time rear-end collision potentials by using inductive loop detector data. Oh et al. (2009) and Oh and Kim (2010) developed methodologies to evaluate freeway safety performance and rear-end crash potential in real time based on the analysis of vehicular movements.

Although many researchers (Pigman and Agent, 1990; Garber and Zhao, 2002; Srinivasan et al., 2007) suggested that more concerns should be addressed on the activity area and merging area because of the highest rear-end crash potential, little efforts have been made to estimate rear-end crash risk at activity area and examine the effects of merging behavior at merging area by using the available traffic information. Furthermore, the effects of contributing factors like lane position and heavy vehicle percentage on the rear-end crash risk at work zone activity area have not been fully examined.

1.2.8 Voids in current work zone safety research

Several factors contribute to work zone crashes, but it is largely believed that the main contributors are inattentive driving, speeding, and other unsafe driver behaviors, such as following too closely. Several countermeasures have been utilized by agencies to get driver's attention and encourage safe work zone driving. However, there is limited information about which countermeasures are the most effective since driver behavior in work zones is not well understood for several reasons. The most common method of evaluation of crash causation is to analyze historical crash data. This historical crash data available to the states, only include reported crashes and the level of detail provided is dependent on the attending officer. As a result, whether a crash is coded as work zone related depends on the officer's interpretation.

In some cases, work zone traffic control may be present, but the work zone is not active during the time the crash occurred and the traffic control is unrelated to the crash. In other cases, the impact of the work zone extends well beyond the extent of the work zone (i.e. queuing or congestion) but since the crash does not happen within the confines of the work zone, it is not reported as such. Furthermore, little information can be obtained from crash reports as to what the driver was doing which resulted in the work zone crash. It is commonly believed that the driver is the major factor but information such as distraction or speeding are only estimating.

The naturalistic driving study data (NDS) collected by the SHRP 2 offers a rare opportunity for a first-hand view of work zone safety critical events. Using these data, actual driver behavior can be observed. Additionally, using forward roadway views, a researcher can decide as to whether the event was work zone related or not.

1.3 Research Objectives

The goal of this research is to investigate work zone safety using the unique SHRP 2 data. The main purpose of the project is to identify safe driving behavior and reduce work zone crashes. Thus, it was necessary to observe how drivers change speed in relationship to various work zone characteristics. It is assumed that reduction in speed has a positive safety benefit especially in work zones. Further the study was extended to investigate driver’s merge behavior for work zones that involved lane closure. The upstream distance at which drivers merge was modelled to better understand the factors affecting safer driver behavior in work zones. Work zones can become points of congestion that can lead to driver frustration and aggressive driver behavior. In work-zone configurations where lane drops are present, merging of traffic at the taper presents an operational concern. In addition, as flow through the work zone is reduced, the relative traffic safety of the work zone is also reduced as there is higher risk of rear end crashes. Improving work-zone flow-through merge points depends on the behavior of individual drivers. By better understanding driver behavior, in terms of when and why they merge with respect to the merge point (start of work zone), traffic control plans, work-zone policies, and countermeasures can be better targeted to improve safety and work-zone capacity. The study also investigated the relationship between driver’s distraction and eyes off the road. Longer glance away from the road signify unsafe driving behavior. The study will help to address the three research questions as outlined below. The models developed will help to address the three research questions outlined below.

1.3.1 First research objective: Change in speed in work zones on four-lane divided highways

Change in speed was used as a safety surrogate. Work zones provide various temporary traffic control (TTC) devices to alert drivers of an upcoming work zone. It was assumed that a reduction in speed in response to a work zone feature indicated that the driver was paying attention and modulated their speed accordingly. Additionally, a reduction in speed allows the driver more time to perceive and react to upcoming hazards. However, it should be noted that in some cases drivers are already traveling at an appropriate speed. Additionally, a driver may become more alert and thus better positioned to react after encountering traffic control but no exhibit and obvious change in speed.

The research analysis compared the change in speed from a point upstream of the legibility distance of an object/sign or work zone feature to the speed just past the feature. Separate models were developed for the area upstream and inside the work zone. A linear mixed effect model was developed to determine the mean change in speed associated with each object. Additional roadway, work zone, environmental, and driver data were obtained. Additionally, the models also investigated whether presence of workers or equipment in work zones. Some of the information included in the model are:

- Work Zone characteristics: work zone advance warning signs, presence of workers and equipment, type of work zone, channelizing devices. Etc.
- Driver demographics: gender, age, eye glance, distraction, vehicle type.
- Environmental characteristics: Time of a day, Weather, Pavement condition.

1.3.2 Second research objective: drivers' behavior in work zones on multilane divided highways

Given that the driving scenario is different on a four-lane divided highway compared to a multilane divided roadway, driver behavior in terms of speed selection might differ between these two roadways. The second objective is to expand the work from the previous research question to work zones on multilane roadways. Additional set of data on multilane roadways were reduced for this research objective. Similar work zone, driver and environmental characteristics were evaluated. A similar linear mixed effects model was fitted. Additional information related to level of service of the freeways were noted and added to the study.

1.3.3 Third research objective: driver lane change behavior in work zones with lane closure

The third objective of this research was to evaluate driver lane change behavior in work zones. Lane closures in work zones require drivers in the closing lane to merge into to the adjacent through lane before they enter the work zone area. A set of work zones with lane closure where drivers changed lanes to move over to the open lane were selected. The drivers' lane changing behavior in the work zone merging area can be characterized by the distance from the point of lane closure that a driver begins to merge. Lane change distance from work zones were categorized based on its closeness to work zone start of taper. It was assumed that it was less safe to change lanes closer to work zone than before a static lane merge sign. Three possible outcomes were used to evaluate the lane change behavior: Safe lane merge distance (when drivers merge before static lane merge sign), moderately safe lane merge distance (when drivers merge before the start of work zone) and unsafe merging distance (when drivers merge after the start of taper. An ordered logit model was fitted to evaluate the effects of different characteristics associated with merge distance.

1.4 Sources of data

1.4.1 Naturalistic driving study data

The naturalistic driving study data (NDS) collected by the second Strategic Highway Research Program (SHRP2) is the largest and most comprehensive NDS undertaken to date (in the United States or elsewhere). Data were collected from over 3,500 male and female volunteer passenger vehicle drivers, ages 16–98 with most drivers participating between one and two years. The majority of participants were in the study for 1 to 2years during a period from 2010 to 2013. Data were collected from sites located in six US states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington.

In-vehicle data were collected via a data acquisition system (DAS) and provided in a time series format reported at 10hz. Time series DAS data was collected from the GPS, video cameras, vehicle network, and vehicle sensors. Speed is one of the most important variables in the time series dataset. Several other vehicle variables were extracted such as acceleration, and braking; forward radar; and video views — forward roadway view, rear roadway view, driver face, and over the driver's shoulder. The NDS data file contains about 50 million vehicle miles, 5.4 million trips, more than 30 million vehicle-miles (48 million vehicle-kilometers) and 1 million hours traveled, about 2 petabytes of data. The SHRP NDS are stored at a secure data enclave at the Virginia Tech Transportation Institute (VTTI) which is in Blacksburg, Virginia (US). Global Positioning System (GPS) data were also collected and associated with the vehicle activity data so driving traces can be overlain with roadway or other spatial data.

The study was conducted from October 2010 to November 2013 (Dingus et al. 2014). Driver's vehicles were equipped with data acquisition system (DAS) with forward and rear radar, four video cameras, lane tracking system, and data storage system which collected information like speed, acceleration, pedal position, GPS data, forward, rear, shoulder and face video. The driving data for each driver are available in a comma separated-values (csv) file. Figure 1-2 below showing placement of various units as a framework of data acquisition system for SHRP 2 project.

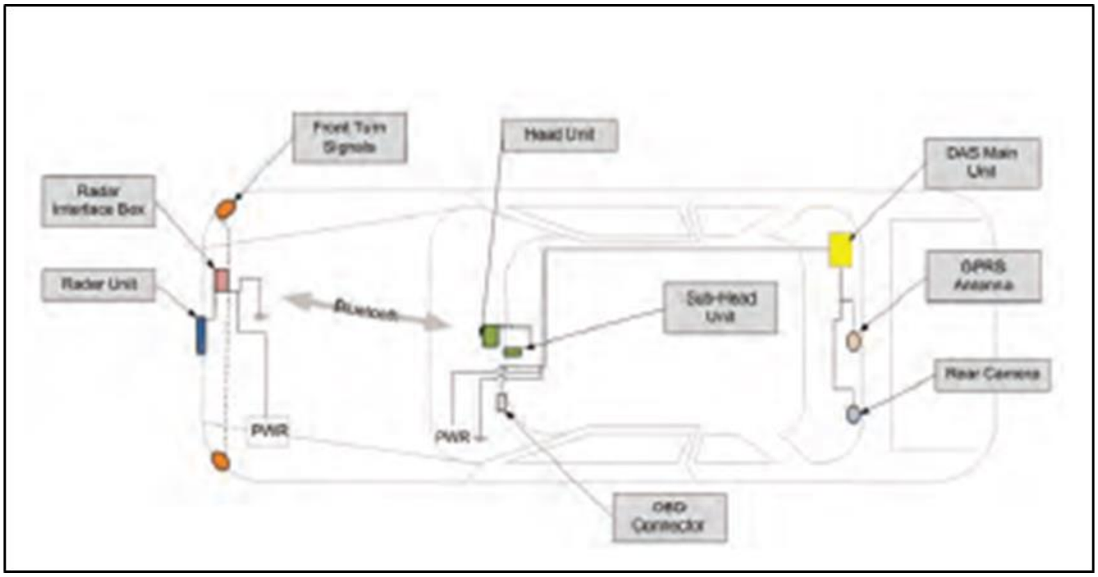


Figure 1-2 Framework of data acquisition system (Campbell, 2012)

1.4.2 Roadway Information Database

A Roadway Information Database (RID) was developed by Center for Transportation Research and Education (CTRE) at Iowa State University. The mobile data collection van was used to collect about 12,500 centerline miles in six different states where Naturalistic Driving Study sites. Data collected includes curve, barriers, intersections, highway lighting, medians, shoulders, rumble strips and different roadway signs. This allow researchers to use roadway information of the routes used in NDS trips. The driving data from NDS can be linked to the roadway database to get the roadway features. Roadway features collected includes Curve radius, number of lanes, roadway alignment, signing, intersection and types, lane width, grade, shoulder types, and lighting. The roadway data was collected using an instrumented mobile van driving at a posted speed limit (Smadi 2015). These data came from several sources including the NDS states'

Department of Transportation (DOT), Highway Performance Monitoring System (HPMS), covering most roadways for each study state. In addition to that, supplemental data such as 511 data, construction projects data, and traffic volume were also collected to further strengthen the database.

1.5 Study limitations

Although every attempt was made to account for issues in the data and to ensure sample size was adequate, several limitations were still present which may have influenced results. They are summarized below.

Sample size may have been an issue. Although over 1,000 traces were ultimately available, they represented several different work zone configurations. Since work zones are complicated with a number of varying characteristics, it was difficult to have enough samples to adequately represent all features. Additionally, driver distraction was of significant interest. Since there was no method to detect driver distraction or cell phone use in the raw time series data, it was difficult to ensure adequate samples of these behaviors were present. Further reduction of data was not feasible within time or resource constraints.

Work zones of three or more days were selected. This was to ensure there would be several time series traces through the work zone. However, the longer a work zone was in place, the more likely drivers were aware of the work zone conditions and reacted accordingly. For instance, drivers may have slowed before particular work zone features because they were anticipating changing conditions in the work zone rather than they were reacting to work zone features. Although it was possible to tell whether a driver had traversed the work zone before, this could not be accounted for in the models. Even with a sample of several hundred observations, the myriad of complex features in work zones makes it difficult to isolate the impact of a specific feature or set of features.

NDS data have a certain amount of noise. For instance, speed data have several fluctuations within short time periods that appear to exhibit acceleration/deceleration but in actuality are fluctuations in sensor measurements. As a result, trying to predict driver reaction can be challenging.

1.6 Study implications

Several factors have been noted as contributing to work zone crashes. Driver factors have not been as well studied as other factors. Driver factors have been difficult to determine from crash data. It has been largely believed, however, that the main contributors are inattentive driving, speeding, and other unsafe driver behaviors, such as following too closely. There is also limited information about which countermeasures, such as speed feedback signs or dynamic message signs, are effective.

The availability of naturalistic driving study data (NDS) collected by the second Strategic Highway Research Program (SHRP 2) offers an opportunity for a first-hand view of work zone safety and the observation of actual driver behavior. As a result, this study used the SHRP 2 NDS data to evaluate work zone and driver characteristics. This project utilized several crash surrogates, such as speed, lane change distance to assess driver behavior in work zones that may have a negative impact on safety.

The change in speed models for work zones on freeways, which will be among the first developed using the SHRP 2 NDS, will advance understanding by providing valuable insight into the effect that work zone attributes and countermeasures (i.e. speed feedback, changeable message signs, channelizing devices), driver behaviors and attributes (i.e. distraction, speed and age), and environmental factors (i.e. day vs night or weather conditions) have on drivers speed choice in a work zone. The results of these models can be used by States in their Strategic

Highway Safety Plans. The results can help agencies select appropriate countermeasures to reduce work zone crashes.

The lane change model will help gain insight into effects of work zone, driver, and other environmental characteristics on driver's decision of lane change prior to entering a work zone with lane closure.

1.7 Organization of the dissertation

This dissertation contains seven chapters. Chapter 1 introduced the problem of work zone crashes. It also contained the review of existing literature in general related to work zones. Chapter 2 provides a detailed step by step process of identification of work zones. Chapter 3 provides procedure of data collection and manipulation method for the entire study. Chapter 4 addresses research objective of development of a conceptual model which will answer what work zone characteristics cause drivers to change Speed in work zones on four-lane divided highways. Chapter 5 is an extension of chapter 4 addressing the same objective of evaluation of driver's change in speed due to work zone characteristics on multilane divided highways. Chapter 6 addresses the research objective to answer how upstream signing/countermeasures impact lane change behavior of drivers in lane closure scenario in work zones. Chapter 7 provides summary, conclusions and main contributions of this dissertation, and limitations of the studies and recommendations for future research.

CHAPTER 2. IDENTIFICATION OF WORK ZONES USING SPATIAL DATA MINING AND DYNAMIC SEGMENTATION METHOD

This chapter provides a detailed step by step approach to identify work zones using RID and NDS data. Section 2.1 introduces big data usage for safety research and introduction to 511 data. Section 2.2 includes the detailed procedure of the selection using spatial software ArcGIS. Section 2.3 provides the process of selecting traces to be used for the study analysis depending on various factors including location, time of day, driver demographics and roadway level of service.

2.1 Introduction to study data

2.1.1 Using Big Data for Safety Research

FHWA's research program on roadway safety partnered with the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB) to launch the second Strategic Highway Research Program (SHRP2) in 2016. This program created two sets of highly unique big data: the NDS and the RID.

As mentioned earlier that NDS data recorded during the study on 3500 human participants include information on more than 5.4 million trips representing more than 30 million vehicle-miles (48 million vehicle-kilometers) and 1 million hours traveled. These data provide information on the driver and driving behavior, individual trip characteristics, including events (crashes and near-crashes), nonevent "normal" driving (exposure data), and continuous vehicle network data, such as accelerator and brake use, steering wheel angle, and speed.
Similarly, the RID contains geospatial data that provide the context for the driving study's trips, including roadway characteristics and features, crash histories, traffic volumes, weather, 511 information, work zones, and railroad crossings. The NDS and RID are geo-referenced and linkable, enabling driver behavior to be matched with the roadway and temporal elements, such

as surrounding traffic, work zones, and weather. These data provide decision makers with better information, resulting in a more efficient, reliable, and inherently safer experience for road users (Tang and McHale, 2016).

2.1.2 What is 511?

5-1-1 is a transportation and traffic information telephone hotline to inform drivers regarding road conditions and traffic. Currently 35 states in the United States participates in the 511 system. 5-1-1 services in the United States are organized by state or region. The 5-1-1 data served as the main source of data for finding out construction and maintenance events for this study. The University of North Dakota in the Summer 1995 introduced an Advanced Traveler Information System known by its phone number provided the proof of concept for statewide application across both North and South Dakota later adding Minnesota. This system proved that all Interstates, US, and state highways in a state could be covered and information about these roadways could be provided to travelers on demand 24/7. After more than 5 years of around the clock operations, the principles that established the operational and business rules of the above program were adopted by the FHWA as the initial guidelines of what later become 5-1-1. Eight states, from Alaska to Maine, pooled resources and expertise to develop the 511 voice-activated phone service for travelers. Led by the Iowa DOT, the multi-state consortium received $700,000 from the Federal Highway Administration to help pay for system design and software development. Each state also provided a 20 percent matching fund, boosting total funds to nearly $900,000. In addition to Iowa, the participating states in the consortium (as of 2011) are Idaho, Indiana, Kentucky, Louisiana, Maine, Minnesota, New Hampshire, Rhode Island, Sacramento Area Council of Governments, and Vermont (511 Guidelines, 2007). From the enormous amount of data feed every day to this system, make it a big data in the process.

2.2 Introduction to dynamic segmentation method

2.2.1 Introduction

Dynamic segmentation is the process of transforming linearly referenced data commonly known as events stored in a table, into a feature that can be spatially displayed. There are mainly two data requirements for performing dynamic segmentation. First; each event in an event table must include a unique identifier and its measurement along a linear feature and second; each linear feature commonly known as a route must have a unique identifier and a measurement system stored with it (Cadkin 2002).

2.2.2 Description of a route

A feature class is a table with a special field that can store a shape (i.e., geometry). A common geometry type can be point, multipoint, polyline, or polygon. In this study the 511 data was either a point or line feature. For linear features, the geometry type is polyline. A polyline is an ordered collection of paths that can be connected or disjointed. Each path is defined by a series of segments defined by x,y coordinate pairs. A route is simply any linear feature upon which events can be located. Examples of routes include city streets, highways. Events can be located along a route because the route feature has an identifier stored in a field and its geometry has a measurement system associated with it (Cadkin 2002).

2.3 Procedure of identification

Work zones of interest were identifies using 511 data to request any trips by NDS participants on these work zones from VTTI. Work zones were identified in all states except for Indiana as 511 data was not available for this state. A spatial buffer was created around each work zone. In some cases, work zones were located near one another and multiple work zones were included in a single buffer. The buffers were provided to VTTI for SHRP2 NDS forward videos. The following steps explains the step by step process of identifying work zones in details.

2.3.1 Step 1: Identification of potential work zones using 511 data

The supplemental RID data effort contains the 511 information. Data were obtained from each of the NDS states for each of the three years of study (from 2011 to 2013). The 511 files provided information mainly for locations and duration of any traffic event occurring in each of the states. The number of data points per year in each of the files was huge as 511 provides wide range of different real-time updates of a variety of events occurring on roadways. The resulting data from the five states of interest included around two million records.

There was no specific field in RID supplemental 511 data which could identify work zones, but the fields representing “event types” and “event description” provided information about any construction or maintenance activity. Thus, an attribute query was conducted in ArcGIS to select the work zones. Key words such as “construction,” “lane closure,” “road work,” or “maintenance” were used. This query was different for different states due to disparity in 511 data.

This study was aimed at identifying the long term (essentially more than 3 days) work zones that existed in the NDS states during the three-year study period. Thus, the attributes of interest for the study were the start and end dates of each of the alerts. Three days was used as a threshold because it was unlikely that a enough NDS time series traces (one trip through one buffer) would be available for short-duration work zones. Ultimately, 9,290 potential work zones were identified.

	ALERTID	FrMeasure	ToMeasure	SideOfRoad	Length	StartTime	EndTime	EventCateg	EventStatu	PointLine
	127046	98.2161	94.7659	Left Side Only	3.4502	2/19/2013	2013-02-20T05:00:00	Construction	Closed	Line
	127243	0	0.3774	Left Side Only	0.3774	2/22/2013	2013-02-23T12:30:00	Special Event	Closed	Line
	124714	0	0.0687	Right Side Only	0.0687	1/16/2013	2013-01-17T05:00:00	Construction	Closed	Line
	126472	134.4538	139.7084	Left Side Only	5.2546	2/8/2013	2013-02-08T18:30:00	Heavy Traffic	Closed	Line

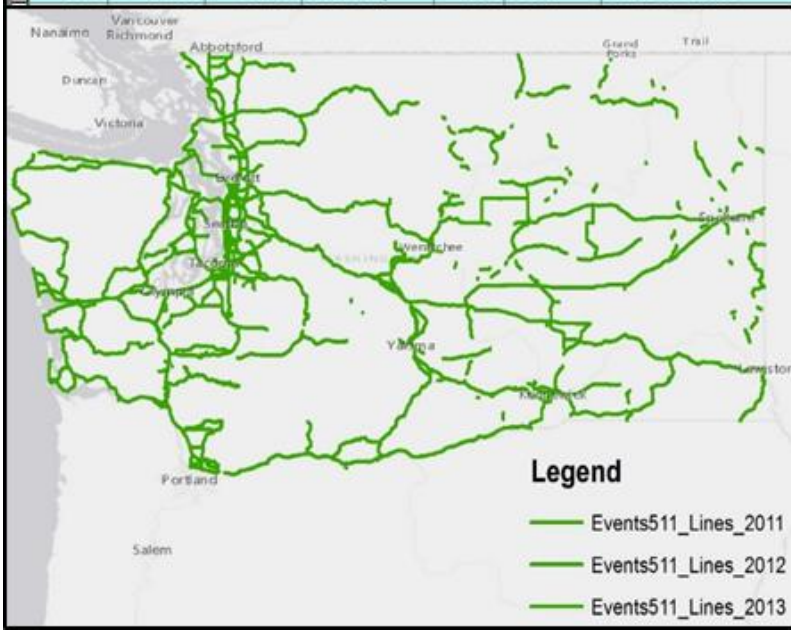


Figure 2-1 Data as Line links

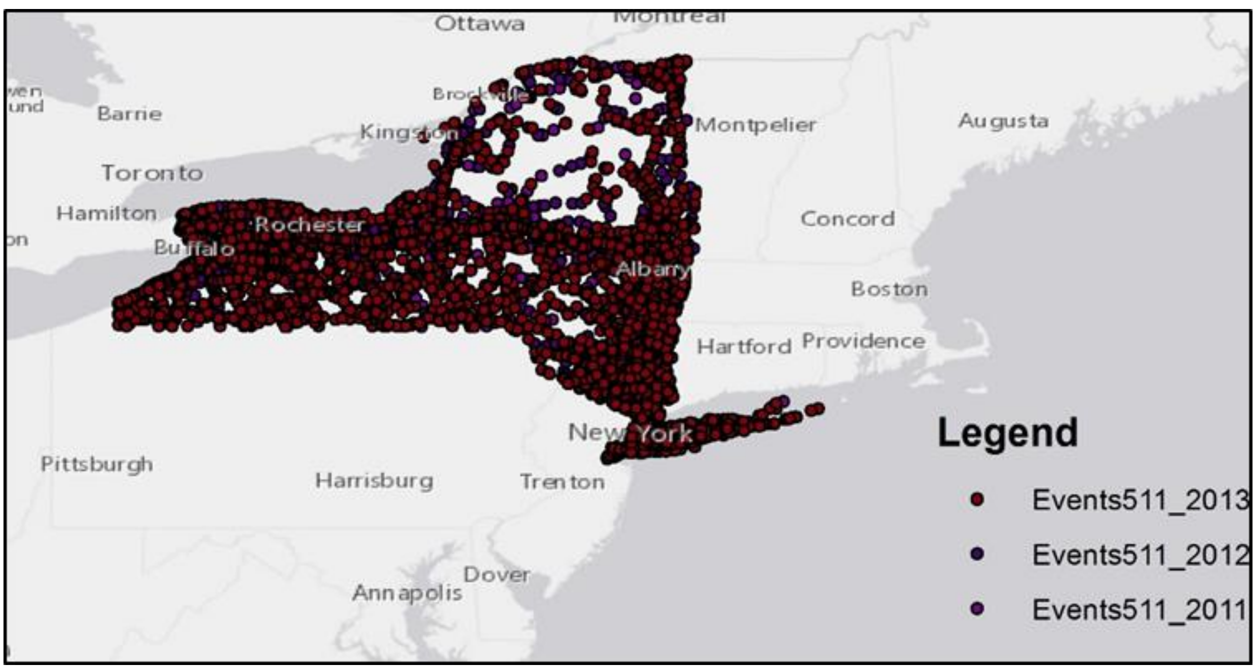


Figure 2-2 511 Data as Point Features

The 511 files sometimes represented “points” and other times “line features” in ArcGIS. For example, shows the 511 data which were obtained as “line features” for the state of Washington and Figure 2-2 shows the 511 data for the state of New York which was represented as “point features”.

Table 2-1 provides the information of the 511 files and the attributes that were queried in ArcGIS for identifying work zones for the five NDS States (WA, FL, NC, NY, and PA). 511 data for the state of Indiana was unavailable. Thus, the state of Indiana could not be included in the study.

Table 2-1 Information of the 511 Files and the Available Attribute Fields

NDS States	**RID 511 Files used:**	**Attribute query for Work zones in ArcGIS**	**Text search attribute for Work zone Configuration**
Washington (WA)	Point features: Events511_Points_2011, Events511_Points_2012, Events511_Points_2013	EVENTCATEG = 'Construction' OR 'Lane Closure' OR 'Maintenance'.	“HEADLINEDE”
	Line features: Events511_Lines_2011, Events511_Lines_2012, Events511_Lines_2013		
Florida (FL)	Point features: ATMSIncidents2011to2013	FDOT_EVENT_TYPE = 'Construction'.	“EVENT_NM”
North Carolina (NC)	Line features: TIMS_NC.	No field available to create attribute query	“REASON”
New York (NY)	Point features: Events511_2010, Events511_2011, Events511_2012, Events511_2013	EVENT_TYPE = 'Construction' OR 'Lane Closure' OR 'Maintenance'.	“EVENT_DESC”
Pennsylvania (PA)	Line features: Events511_Lines_2011-2013	CAUSE= “ROADWORK”	“STATUS”

2.3.2 Step 2: Determine the locations of potential work zone events and obtain the number of likely trips

RID contains spatial information about the roadway geometry and features of the NDS study sites or in other word “route”. The next step was to link the identified 511 events to the "route" data to exactly find out the spatial locations of the selected work zones. A link in RID "route "data can be defined as a segment of road having uniform characteristics and many such links can be grouped together to form a corridor. Each links has a unique "Link ID". When 511 events were provided as lines, it could be related to "links" in RID roadway geometry data. To locate the links that intersected with the 511 features, dynamic segmentation method was utilized.

In some cases, when the 511 data were in the form of a single point for each event, it did not indicate work zone extent. But when the 511 data were in the form of a line, it provided some indication of work zone boundaries Thus, when 511 events were provided as lines, dynamic segmentation method in ArcGIS was used to add "links" of each identified work zone. When 511 events were provided as a point, they were mapped to the RID, and the nearest corresponding "link ID" was extracted. When 511 data were presented as a point, dynamic segmentation was used to extract links two miles upstream and downstream of the point.

Dynamic segmentation method ensures accurate selection of "links" as opposed to conducting a "near table join" in ArcGIS. "Overlay Route Events" function in ArcGIS was used for this purpose. The "input events table" corresponds to the "Events 511 data table" created earlier. Figure 2-3 shows the dynamic segmentation process in ArcGIS. "Route" data layer from RID was used to display the route events of the final output file obtained from the dynamic segmentation process as shown in Figure 2-4. The outcome of this process provided information about the exact extents that corresponded to work zones with duration of three and more days.

Following that, the start and end dates were used to work zones that existed in-situ for more than three days were selected. These two processes narrowed down the extensive 511 data rows to the reasonable number of rows of three or more day's work zones. For example, there were about 1,022,354 total number of 511 events recorded in Florida in the years 2011 to 2013. The final number of work zones of three or more days in Florida were 568. A total of 9290 three or more days of work zones were identified for all the five states. Locations for these 9,290 potential work zones were sent to Virginia Tech Transportation Institute (VTTI), and the number of time series traces ("trip counts") and unique drivers and the drivers' age, gender and other demographic information for the links of interest were requested. Figure 2-5 shows the 9,290 potential work zones in the five states.

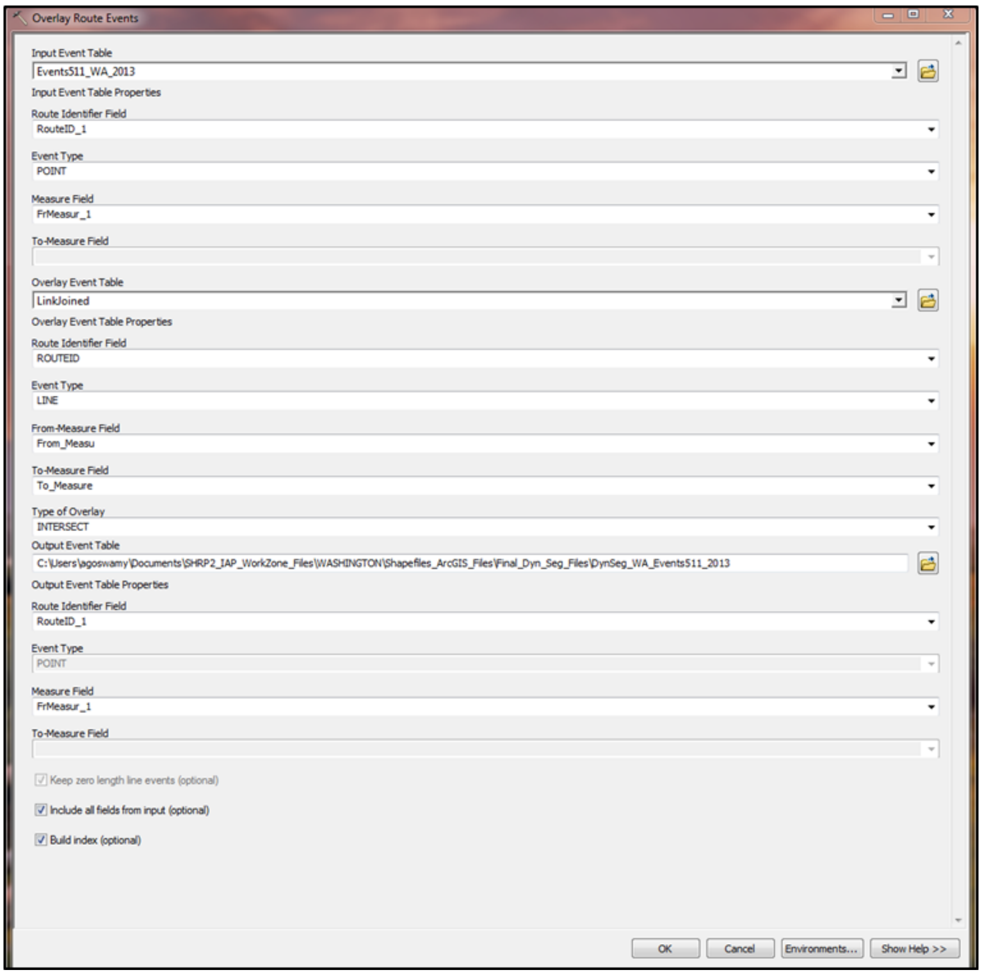


Figure 2-3 Dynamic Segmentation using overlay route events in ArcGIS

Thus, the potential work zones were evaluated based on “trip counts” to select work zones with high probability of subject drivers being present. Unique “work zone ID” was given to each potential work zone.

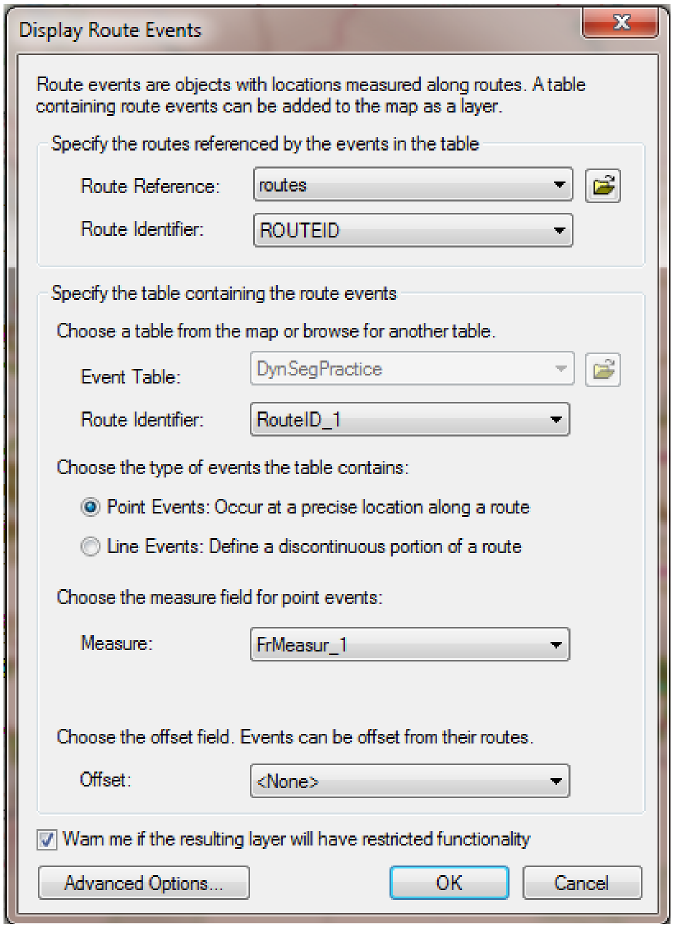


Figure 2-4 Display route events in ArcGIS.

Figure 2-5 Potential work zones selected in five NDS states

2.3.3 Step 3: Refine the extents of potential work zones

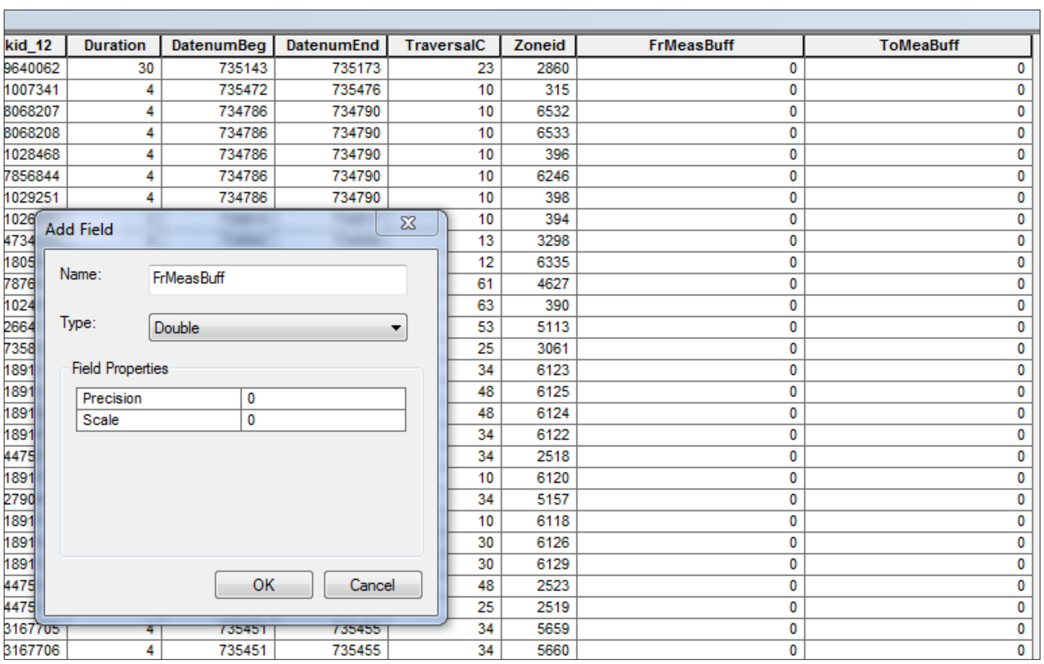
The potential work zones resulting from step 2 and information on "trip counts" was reviewed, and work zones with at least 15 potential trips were selected, resulting in 1,680 potential work zones. Table 2-2 provides the descriptive statistics of the total NDS trip counts and participants. To identify whether a SHRP2 participant traversed the link of interest during the work zone period, the work zones that indicated higher number of trip counts and participants on them will signify that the probability of one or more NDS drivers having driven the work zone is high.

Table 2-2 Descriptive Statistics of Trips and Participants for Potential Work Zones in each State

		Trip Counts			Participants		
	Total No. of Work Zones	Mean	Min	Max	Mean	Min	Max
North Carolina	90	500.9	32	7715	91.37	11	410
Florida	39	1026.13	34	9056	124.5	17	579
New York	1748	2033.86	31	23187	127.4	11	665
Washington	6984	2267.99	31	13097	193.1	11	665
Pennsylvania	429	307.25	31	11836	58.14	11	224

2.3.4 Step 4: Creating buffer for the potential work zones

This step included creating a buffer around each potential work zone to increase the likelihood that the actual work zone was included. Two new fields namely "FrMeasBuff" and "ToMeasBuff" were created for the 1,680 potential work zones to create a buffer of two miles upstream and downstream of the work zones (refer Figure 2-6). As dynamic segmentation was already applied on the potential work zones using "Routes" layer in RID. The information regarding the extents in the form of "From_measure" and "To_measure" of each of the "link Ids" of potential wok zone location was known. Thus, the buffer fields were calculated by subtracting two miles from the "From_measure" and similarly adding two miles to the "To_measure". That is FrMeasBuff = From_Measu-2*5280 and ToMeaBuff = To_Measure+2*5280. At the end of the step, work zones with all "link Ids" corresponding to the entire length of the buffered work zones were obtained (refer Figure 2-7).



kid_12	Duration	DatenumBeg	DatenumEnd	TraversalC	Zoneid	FrMeasBuff	ToMeaBuff
9640062	30	735143	735173	23	2860	0	0
1007341	4	735472	735476	10	315	0	0
8068207	4	734786	734790	10	6532	0	0
8068208	4	734786	734790	10	6533	0	0
1028468	4	734786	734790	10	396	0	0
7856844	4	734786	734790	10	6246	0	0
1029251	4	734786	734790	10	398	0	0
1026				10	394	0	0
4734				13	3298	0	0
1805				12	6335	0	0
7876				61	4627	0	0
1024				63	390	0	0
2664				53	5113	0	0
7358				25	3061	0	0
1891				34	6123	0	0
1891				48	6125	0	0
1891				48	6124	0	0
1891				34	6122	0	0
4475				34	2518	0	0
1891				10	6120	0	0
2790				34	5157	0	0
1891				10	6118	0	0
1891				30	6126	0	0
1891				30	6129	0	0
4475				48	2523	0	0
4475				25	2519	0	0
3167705	4	735451	735455	34	5659	0	0
3167706	4	735451	735455	34	5660	0	0

Figure 2-6 Linear buffer along work zones

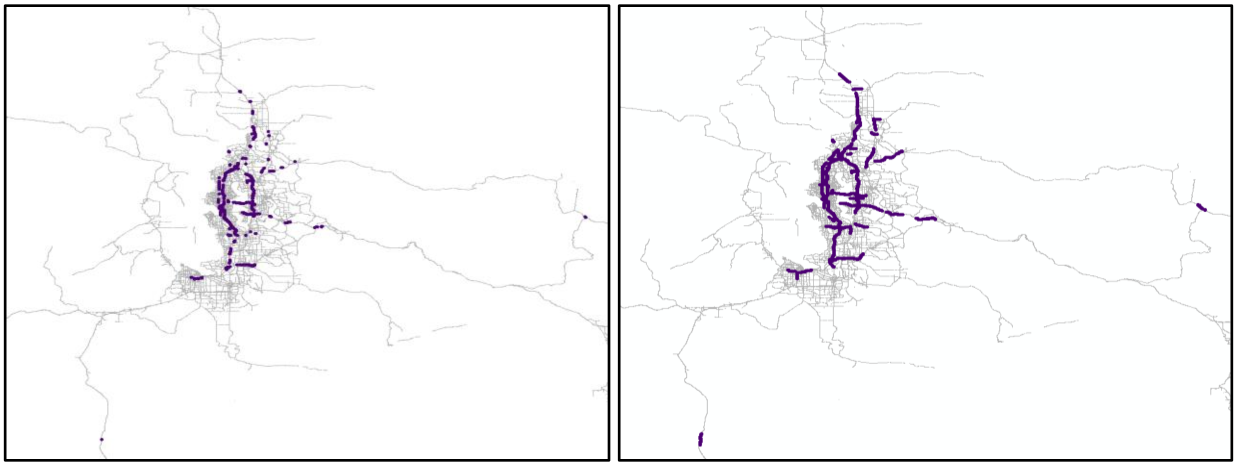


Figure 2-7 Work zones before and after adding buffer

2.3.5 Step 5: Confirm work zone presence and duration

A list of “link IDs” and work zone dates was submitted to VTTI. Several time series traces and associated forward videos were requested for each work zone. The forward video was reviewed to determine whether a work zone was actually present. The type of work zone and the work zone characteristics were also coded when a work zone was present.

In some cases, no work zone was present. In other cases, barrels were present along the side of the roadway, but the work zone was not considered to be active. These locations were excluded. Additionally, work zones that contained signals or other non-work zone-related interruptions in traffic flow were also excluded because predicting speed or reaction would have been difficult when external stimuli were present.

Time series traces sampled across the duration of the work zone were desired because exact start and end times were not known. Even if these times were recorded in maintenance or other records, work zones did not always start or end on time and records were not always updated. As a result, if a work zone was present at some points and not others within the start/end dates, as observed in the forward video, some attempt could be made to narrow the work zone duration.

The final and the most reliable step towards finding work zones of interest was manually going through NDS forward videos. A large amount of useful information was manually coded from the forward view video. The data coded from the video includes traffic condition, roadway characteristics, and other environmental factors. The data were manually coded from the forward video from each event, which was a very time-consuming process. A list of variables collected from the forward videos is shown in Table 2-3.

Table 2-3 Roadway Variables extracted from Forward Videos

Variable name	**Example**
Work zone (yes/no/possible)	yes
Type of roadway prior to work zone	2 lanes undivided
Median Type prior to work zone	Depressed median without barrier
ramp/exit (yes/no)	no
Bridge=1	yes
active work zone (yes, no, or only barrels)	no
Variable message sign presence (yes/no)	yes
Time stamp for first work zone sign	1520591
Time stamp for start of work zone	1525663
WZ configuration	head to head traffic with shoulder closed
Number of lanes closed	0
location of channelization(edge/median/both)	Both
Channelizing devices	concrete/jersey barrier
Work Zone Speed Limit	25
Presence of a worker on foot	no
Presence of an equipment	yes
Lane Shift	no
Time Stamp for end of work zones	1695634
Time stamp work zone termination sign	1716789
Residential/Highway	highway

2.3.6 Step 6: Request work zone data

After confirming the work zone presence and duration from step 4, a set of 240 work zones on four-lane, multi-lane or two-lane roadways with shoulder or lane closures were obtained. The beginning and end points of each work zone, initially identified, were adjusted based on a review of the forward video and corresponding spatial location from the time series data. A time series data is an excel file with once beginning and end points were established, 1 mile upstream and downstream of each work zone was determined using dynamic segmentation for the second time. All link IDs associated with the work zone and the upstream/downstream segments were extracted. Data were provided in terms of events. Each event included one trip by one driver through a work zone. A time series trace was provided for each event in the form of a CSV file with information including a time stamp (data were provided at 0.1 second intervals), position, speed, forward acceleration, lateral acceleration, wiper position status, brake status, lane position variables, etc. A video clip showing the forward roadway and a video clip showing a rear roadway view were also provided. A video clip of the driver face and hand position was accessible at the VTTI secure data enclave and was utilized to reduce driver characteristics. About 14,500 traces were obtained from all the 4-lane divided and multilane work zones locations.

2.4 Trace selection process

After obtaining the 14,500 traces from VTTI, it was seen that there were exceedingly greater number of traces in some work zone locations than other. Thus, it was necessary to find a good distribution of work zone traces for analysis.

2.4.1 Robust speed data

In some cases, speed was reported at less than 10 hz due to sensor issues. In order to detect a change in speed it was necessary to have consistent speed was the variable of interest, it was important to have consistently recorded speed data. Time series traces were only utilized if more than 90% of cells (representing 10 Hz [0.1 seconds]) for the speed variable were present. When speed was missing for an interval, speed was interpolated using nearest neighbor approach. About 50% of the entire number of traces obtained from VTTI had good data. This meant that the other half was not used. Data were requested early in the project and a number of lessons were learned as data were coded. As a result, in retrospect, the data request could have specified a threshold of percent of "good" speed data.

2.4.2 Location

Time series traces were spatially mapped in ArcGIS software using latitude and longitude. Sites less than 5 traces were excluded from analysis and about 10-15 traces were selected from sites with more than 30 traces available. Work zones on same locations but on different years were considered separate entities, thus traces were selected from them irrespective of location.

Traces were projected in ArcGIS to check details on location. Traces at a given location might have more than one work zones (i.e. different work zones along the same roadway) but it is given a same site number considering same exposure in terms of type of roadway prior to work zone, traffic volume, landscape etc. For example, there were more than 25 unique locations in the States of Washington, New York and Pennsylvania (Refer Figure 2-8 and Figure 2-9).

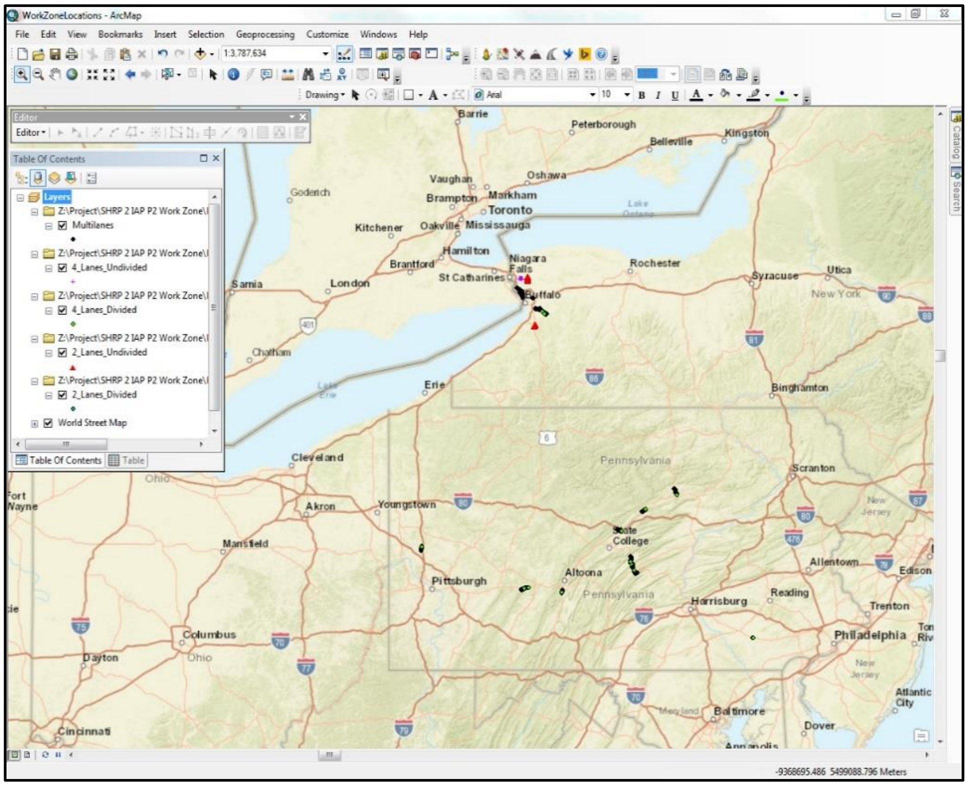


Figure 2-8 Sites in New York and Pennsylvania

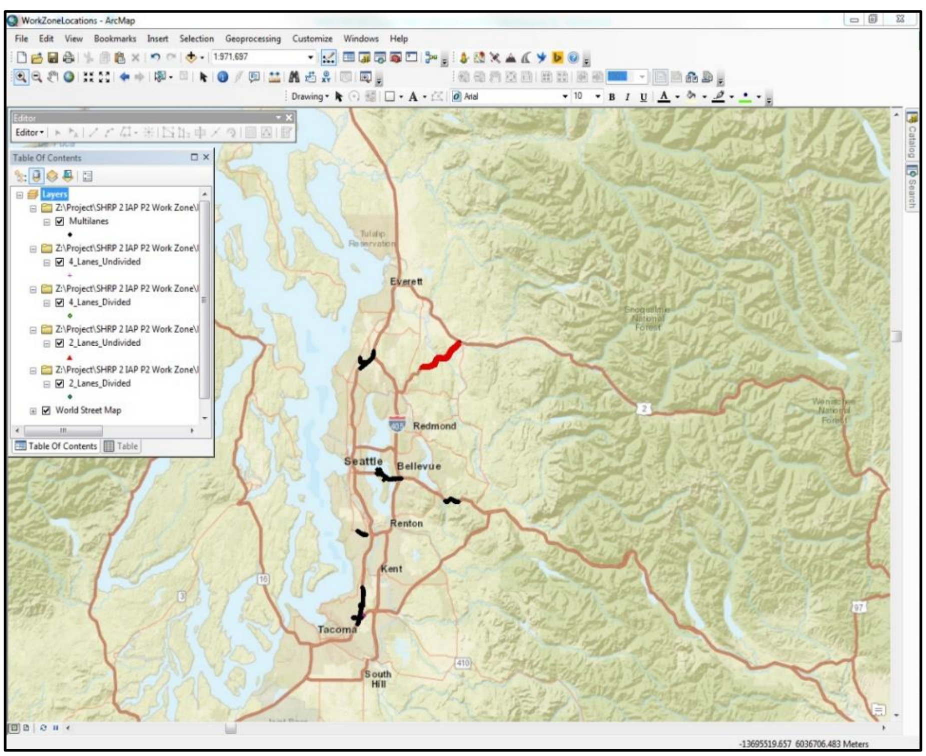


Figure 2-9 Sites at Washington

2.4.3 Driver Demographics

Information on driver age, gender, education level, number of driving years, etc. were obtained for each trace from VTTI. It was seen that a greater number of traces were driven by age group of above 25 and below 65. It was necessary to select traces from all age groups. Thus 10-15 traces that were selected from each work zone sites as mentioned in the previous paragraph, were drivers from different age groups.

2.4.4 Time of Day

Time of day was another factor for selecting traces. Information about time of day, date, month, and year was provided in each of the traces of drivers on work zones. Based on sunrise and sunset calculation for state, month, time of the traversal; well distributed day and night traces were selected.

2.4.5 Free flow condition with LOS A and B

The study only considered traces that were free of congestion. Each trace selected based on the above three criteria were visually inspected from the front videos. Highway capacity manual defines free flow as low-density roadway condition where drivers are not influenced by the presence of other surrounding vehicles and are able to travel freely at desired speed (HCM). The same concept was used by this study to define the flow of the subject vehicle. The headway between the subject vehicle and the front vehicle moving on the same lane was considered as a measure to define if the subject vehicle was moving freely. When the movement of the subject vehicle showed any sudden slow down (visually inspected as shown in Figure 2-10) due to the movement of front vehicles, was not considered as a free flow scenario assuming the speed of the subject vehicles was affected. The flow of the subject vehicle was visually inspected either from 2 miles upstream of work zone or first advance warning sign, whichever was farther, till the end of the work zone. If the subject vehicle was moving in a free flow during the entire region, then the trace was defined completely in a free flow condition. However, there were instances where the subject vehicle was not moving in a free flow for some period of a time at some section. For instance, a subject vehicle might not be in free flow for few seconds in advance warning area or inside the work zone area. In that scenario, the time stamp subject vehicle was not in a free flow condition was recorded and reduced in the time series data. This way data analyst can figure out the location on the traces where subject vehicle was in non-free flow condition. Figure 2-10 below shows snapshot from the front video with subject vehicle in two different traffic scenarios.

Figure 2-10 Free Flow Condition

CHAPTER 3. DATA COLLECTION AND REDUCTION

This chapter provides an overview of the extensive data collection and reduction process utilized in the study. Thus, the chapter lays the foundation for the discussion in the next few chapters. Section 3.1 provides description of different variables collected as part of the study.

3.1 Layout of a Work Zone

3.1.1 Background on MUTCD TTC layout

Temporary traffic control elements are described in Chapter 6 of the Manual on Uniform Traffic Control Devices (MUTCD). The point between the first work zone sign and merge point is referred to as the advance warning area and is characterized by various traffic control depending on the individual work zone such as reduced speed limit, changeable message signs, static signing, etc. The transition area is designated as the section of highway where road users are redirected out of their normal path using strategic use of tapers. Activity Area is the section of the highway where the work activity takes place, it comprises of the work space, the traffic space, and the buffer space. The termination area is the section of the highway where road users are returned to their normal driving path. The work zone proper was considered to have started at the beginning of the lane or shoulder closure until the transition away from the shoulder or lane closure at the termination area. Figure 3-1 illustrates the component parts of a TTC zone as provided in MUTCD.

The MUTCD also provides typical applications of the TTC devices that can generally be adapted to a broad range of road work conditions. In many instances, an appropriate TTC plan is achieved by combining features from various typical applications. Procedures for establishing TTC zones vary with road configuration, location of the work, work activity, duration of work, road user volumes, road vehicle mix (buses, trucks, cars, motorcycles, and bicycles), and road user speeds. The study sites were mostly on four-lane divided and multilane freeways with lane closure, shoulder closure or lane shift scenario. All the work zones were of longer duration of more than 3 days. The normal speed limits of most of the roadways used in the study was 55 to 70 mph.

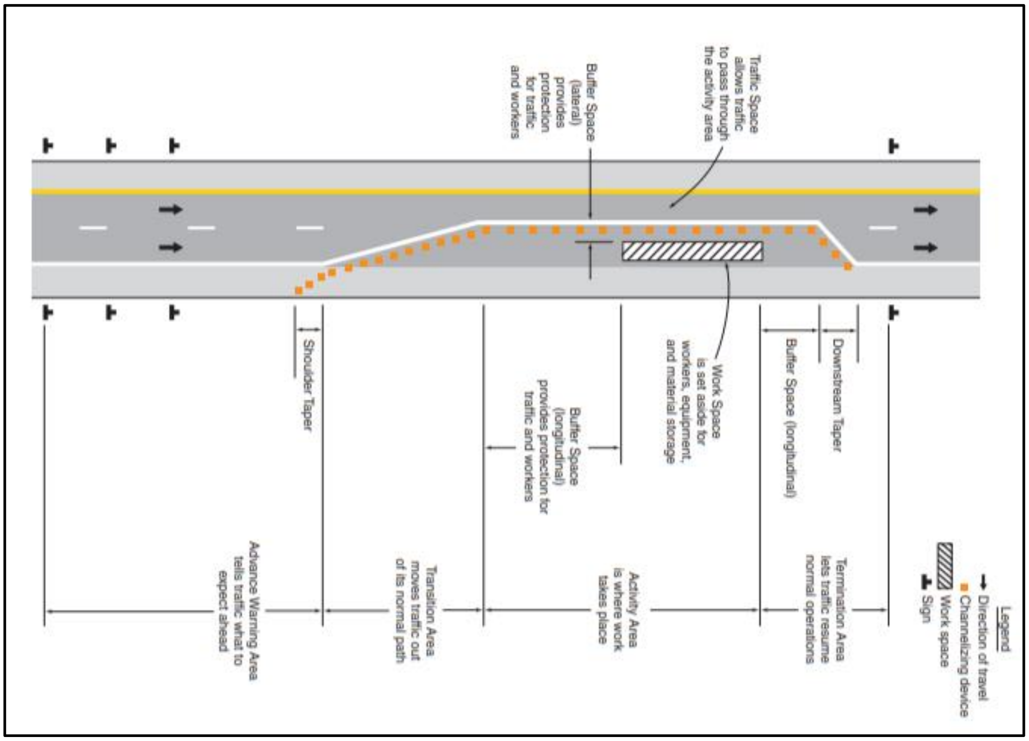


Figure 3-1 Component Parts of a Temporary Traffic Control Zone (source: MUTCD)

3.1.1.1 Lane closure on freeway guidelines

MUTCD also provides information about the work zone configurations for lane closure on divided highway. For the purpose of the study, as a considerable part of the study sites were mostly on divided freeways with lane closure. Chapter 6G of the MUTCD contains discussions of typical temporary traffic control activities. Chapter 6H presents diagrams of typical applications for a variety of situations of workzones. In general, the procedures illustrated represent minimum solutions for the situations depicted. Typical application 33 provided by

MUTCD serves as a close comparison. When work is being performed in the lane adjacent to the median on a divided highway. MUTCD suggests left lane closed signs and the corresponding lane reduction symbol signs shall be used, when a side road intersects the highway within the TTC zone, additional traffic control devices shall be erected, as needed, and all vehicles, equipment, workers, and their activities should be restricted to one side of the pavement. The figure below shows the TTC for Lane Closure on divided highways.

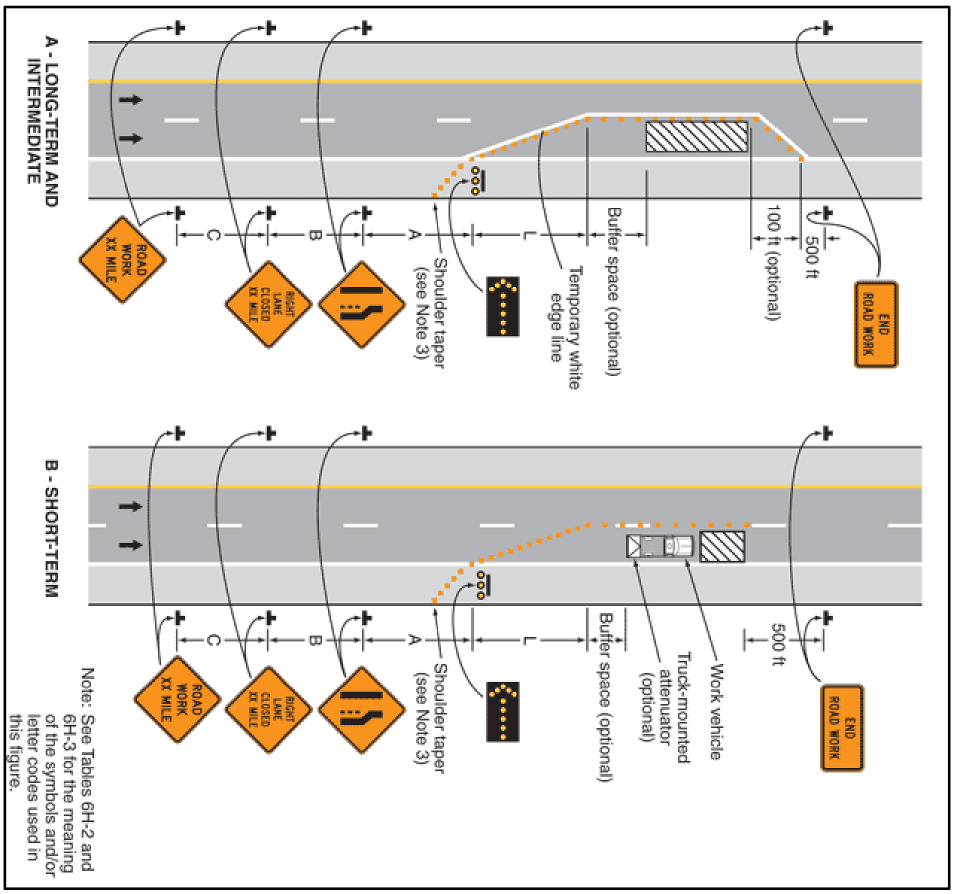


Figure 3-2 TTC for Lane Closure in Divided Highways

Shoulder closure guidelines

MUTCD also provides information about the work zone configurations for shoulder closure on freeways. SHOULDER CLOSED signs should be used on limited-access highways where there is no opportunity for disabled vehicles to pull off the roadway. Typical application 5 provided by MUTCD serves as a close comparison to the shoulder closure scenario for this study. Figure 3-3 shows the TTC layout guidance for shoulder closure on freeway by MUTCD.

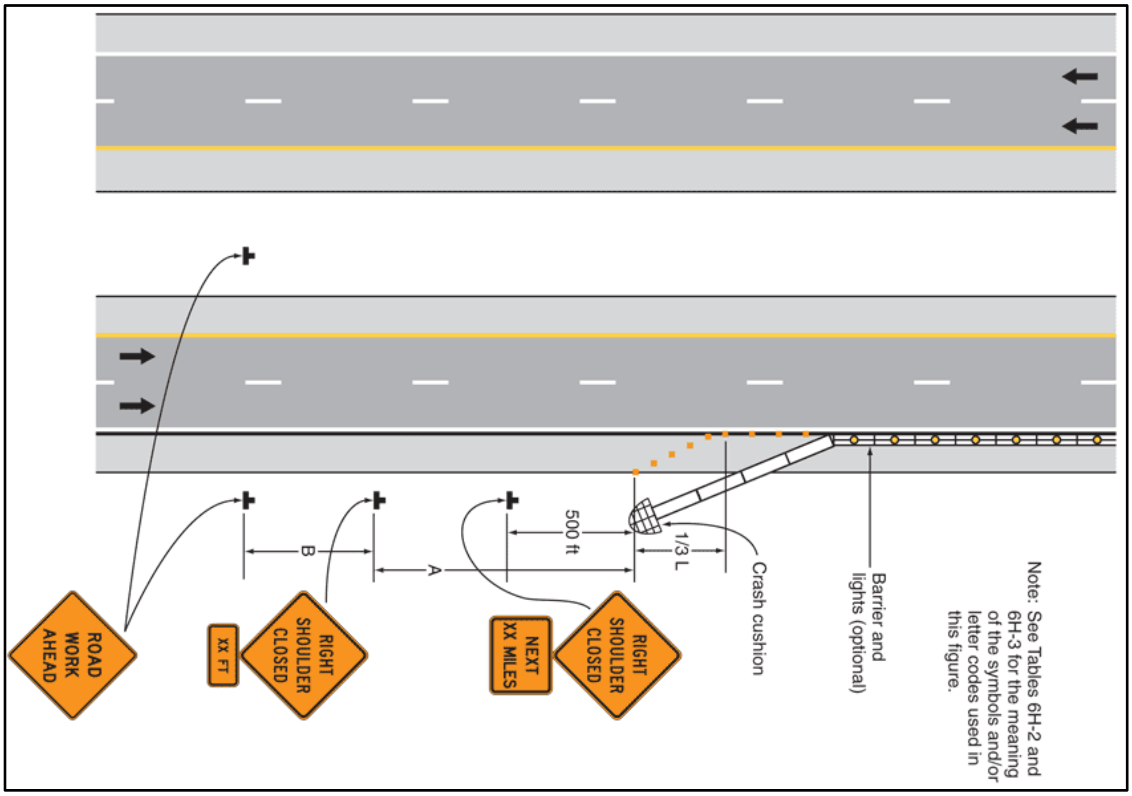


Figure 3-3 Shoulder closure on Freeway TTC layout by MUTCD

3.1.1.3 Head to head traffic/ median crossover scenario guidelines

MUTCD provides information about the head to head traffic scenario in work zones. Typical Application 39 shows the median crossover on a freeway. According to the layout channelizing devices or temporary traffic barriers shall be used to separate opposing vehicular traffic. An arrow board shall be used when a freeway lane is closed. When more than one freeway lane is closed, a separate arrow board shall be used. A typical layout of TTC on a work zone with head to head traffic/ median crossover scenario provided by MUTCD is in Figure 3-4.

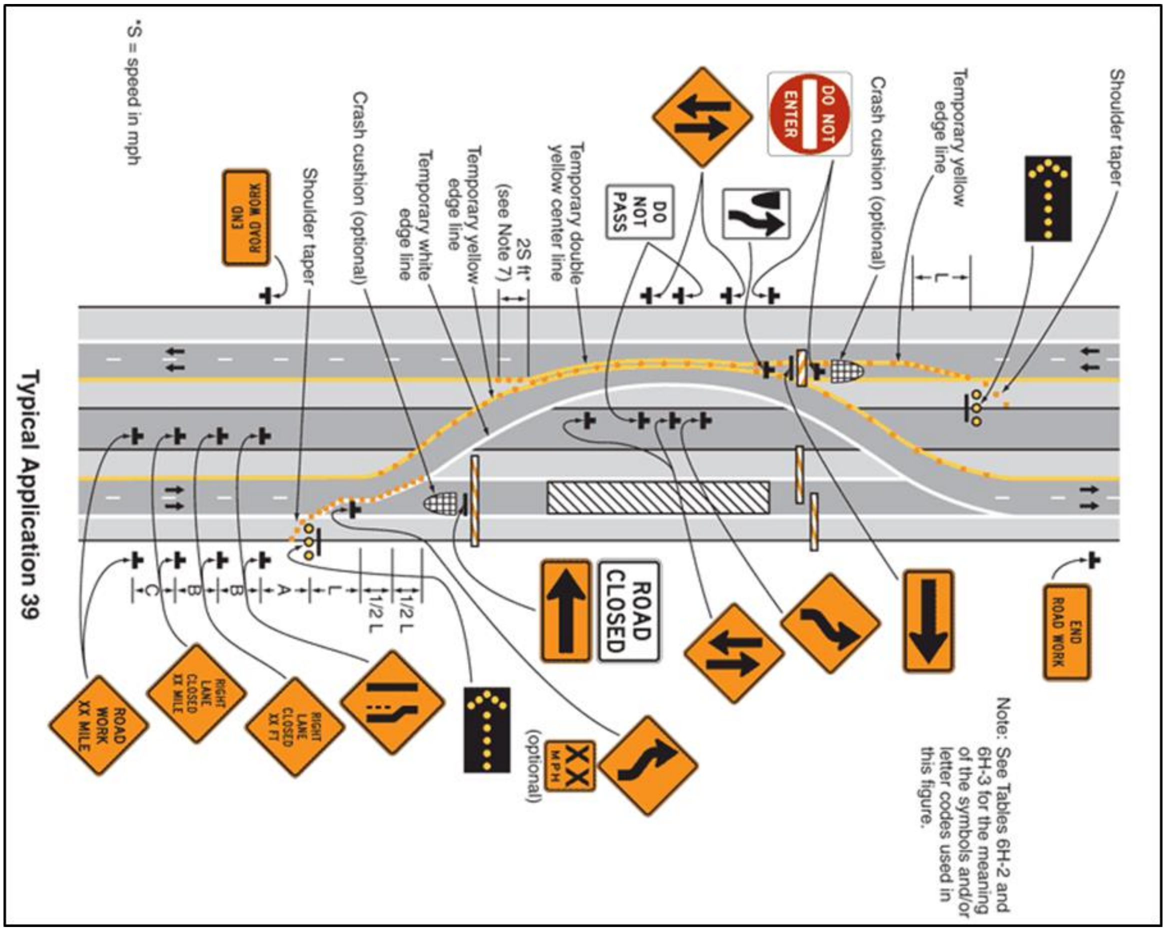


Figure 3-4 Median Crossover Guidance, MUTCD

3.1.2 Study TTC layout

A typical layout of a lane closure work zone on freeway for this study is provided in Figure 3-5. It illustrates the components of a lane closure work zone in the study. The start of the work zone influence area was indicated by the first work zone sign. This was any type of sign which alerted drivers to the presence of an upcoming work zone. In a few cases signs are placed several miles upstream of a work zone and may not have been captured since the requested video trace was typically 2 miles upstream of the merge point. The point between the first work zone sign and merge point was referred to as the advance warning area and was characterized by various traffic control depending on the individual work zone such as reduced speed limit, changeable message signs, static signing, etc. The start of taper (work zone merge point) is considered as the start of work zone for the study. The activity area was considered to have started at the beginning of the work zone merge point until the termination area.

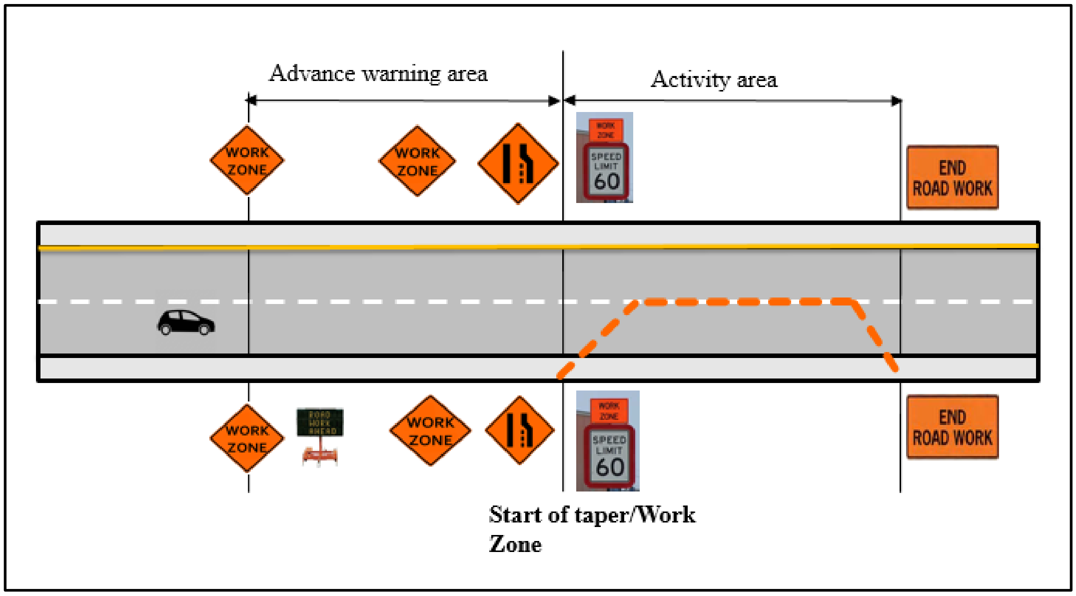


Figure 3-5 Study TTC Layout for Lane Closure

The shoulder closure work zones require a smaller number of TTC devices than the lane closure scenario. The two illustrations can be considered as basic versions of these two types of closures in work zones traces used in this study. Details about the different TTC devices used in the study sites will be discussed in detail in the later section of this chapter.

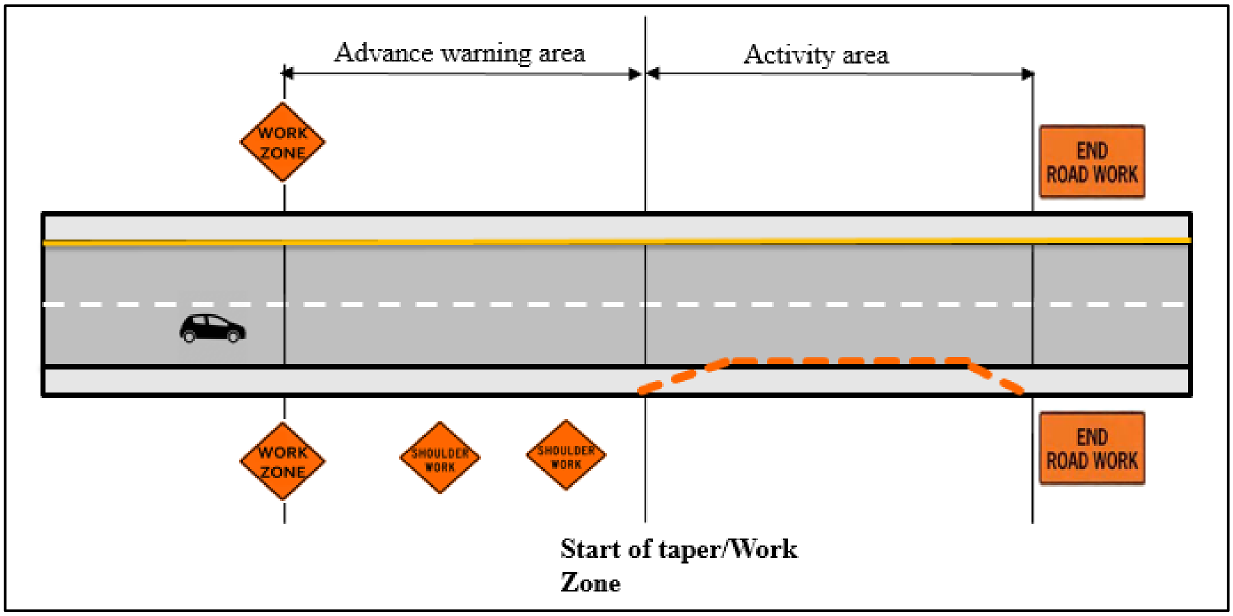


Figure 3-6 Study TTC Layout for Shoulder Closure

3.2 Data collection

Forward and rear videos of the selected time series traces were provided in the data request to VTTI. The forward roadway video was mainly used to identify and record Temporary Traffic Control (TTC) devices upstream and within the work zone. According to the MUTCD, TTC devices includes all signs, signals, markings, and other devices used to regulate, warn, or guide road users, placed on, over, or adjacent to a street, highway, pedestrian facility, or bikeway by authority of a public body or official having jurisdiction. A set of variables were manually coded starting from first work zone sign to the end of work zone for each individual time series traces. Even though multiple time series traces were available for each work zone, characteristics within a work zone can change from day to day and therefore had to be confirmed for every trace.

The coded information can be aggregated into three main categories. The first is TTC signs which include work zone signs (such as static, speed limit, lane merge, enforcement, etc.), presence of dynamic message sign (CMS) or other intelligent transportation system (ITS) countermeasures. The second category is channelizing/delineating devices for a work zone. These include the median type, lane shifts, temporary pavement markings, barrier, location of barriers glare screen, channelizing devices, location of these devices etc. All other variables can be grouped into the third category. For example, presence of worker and equipment, number of closed lanes, work zone configuration. Corresponding timestamps of each variable in each time series files were coded manually by the study team.

3.2.1 TTC Signs

The temporary traffic control signs encountered in corresponding work zones and spatially coded in the corresponding work zone included the following.

Standard static work zone signs: included all standard static work zone warning signs such as “Road Work Ahead” or “Begin Work Zone”, “End of Work Zone”, etc. In order to differentiate signs in different sections of work zones, work zone signs in the advance warning area were reduced as Type 1 and signs within the work zone starting from the first taper till the end of work zone were reduced as Type 2. Attempt was made to reduce the information inside the work zone signs too but due to the location of signs, time of a day (night time), weather (rainy) conditions and quality of the front video it was not always feasible to reduce the letters. Warning signs showing the change in the roadway alignment ahead like ramp merging from the right, lane shift, and narrow lane were also categorized under work zone signs. Overall, most of the work zone signs reduced were typically warning and guide signs to the upcoming change. Table 3-1 below shows the snapshot of some of the reduced work zone signs (such as static, speed limit, lane merge, enforcement, etc.).

1. Speed Limit: included regular posted speed limit signs, work zone specific speed limit signs (WZ), or speed feedback signs. Normal speed limit signs were existing regulatory

speed limit signs. For the upstream section, they served as the regulatory speed limit unless a work zone speed limit superseded the normal speed limit. Work zone speed limit signs were reduced as work zone type when they were placed additionally specific to work zone and usually provided in orange color background. The remaining type, feedback, displayed flashing numbers of individual vehicle speed usually with posted speed limit on the top. In addition, speed limit signs were also reduced as Trailer or Post mounted based on the placement of the signs.

2. Enforcement Signs: included signs which provided information on penalties for driver actions in work zones such as "Work Zone: Traffic Fines Double". Only enforcement signs relevant with the work zone were reduced in this study.

3. Lane Merge: indicated a lane merge was ahead for work zones where a lane was closed. The signs were only available at work zones with lane closure.

4. Variable Message Signs (VMS): Included signs with changeable digital text other than dynamic speed feedback signs. Table 3-2 provides snapshots of examples of variable/changeable/dynamic message sign (V/C/DMS) or other intelligent transportation system (ITS) countermeasures. It refers to the digital message signs placed on the side or overhead of the road showing information relevant to work zone ahead. It was further reduced as either "trailer" mounted on the side of the road or "over" mounted on the top of the road. If the sign was flashing it was coded as" active", otherwise it was coded as "not active". Similar to the normal work zone signs, an attempt was made to reduce letters displayed. But the letters were not always legible in the video due to time of a day, weather and quality of the video itself. In addition, the sign with digital arrow which inform drivers to merge on the moving lane was also reduced as VMS but tagged separately as arrow sign. First Sign: It was the first work zone related sign that a driver was presented with as they entered the work zone advance warning

area. It is the first sign that indicates work zone ahead. Any type of work zone sign can be the first sign. In this study, normal work zone signs and VMS or any of the signs discussed above were used as First Sign and was reduced accordingly.

Overlapping Effect: The study assigned legibility distance for each types of sign discussed above. In short, the legibility distance was defined as the distance from which the sign was legible (not visible). Due to multiple signs placed close to each other, there were numerous scenarios where, multiple signs were legible from a certain section. And it was difficult for the study to assign effect due a sign. Thus, when multiple signs were legible from a section, it was considered due to effect of multiple signs and was termed as overlapping effect. The overlapping was more dominant near to the start of work zone where multiple signs were placed close to each other.

Table 3-1 Examples of Standard Static Work Zone Signs

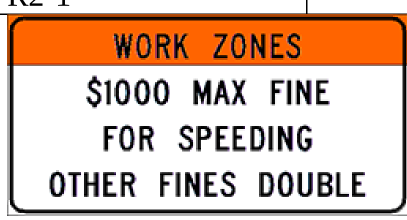
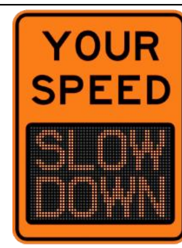
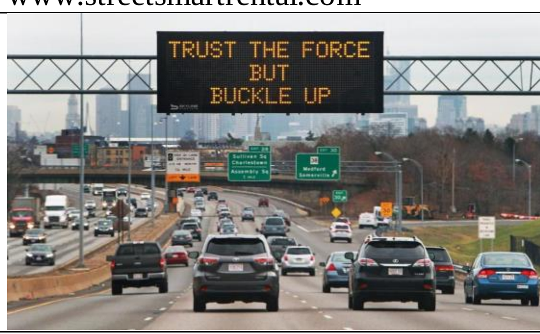
Type of Sign	Examples		
Static work zone			
	W21-5	W20-1	W20-5R-A
			
Work zone speed limit			 
	W3-5		
Regular speed limit			
	R2-1		
Work zone enforcement			  www.fhwa.dot.gov/publications/publicroads
Work zone closure			
	W4-2		

Table 3-2 Examples of Dynamic Message Signs

Type of Sign	Examples	
Dynamic arrow board	 	www.streetsmartrental.com
Trailer mounted changeable message signs	 www.mister-sign.info	 www.addco.com
Speed feedback sign	 www.streetsmartrental.com	 www.trafficalm.com
Overhead changeable message sign		www.bostonglobe.com

3.2.2 Channelizing/delineating devices

Channelizing devices are used to separate road users from work activities or other lanes of traffic. Channelizing devices include cones, tubular markers, vertical panels, drums, barricades, and temporary raised islands. This information was necessary to reduce to specify the effectiveness of each of these devices that channelizes the traffic inside the work zones. The frequently reduced channelizing devices were concrete or Jersey barrier, cones, barrels or pylons or vertical panels or combination of different devices. The location of the device was also reduced accordingly. Figure 3-7, Figure 3-8 and Figure 3-9 are examples of barrels, cones and vertical panels respectively.

Figure 3-7 Channelizing Device: Barrels

Figure 3-8 Channelizing Device: Cones

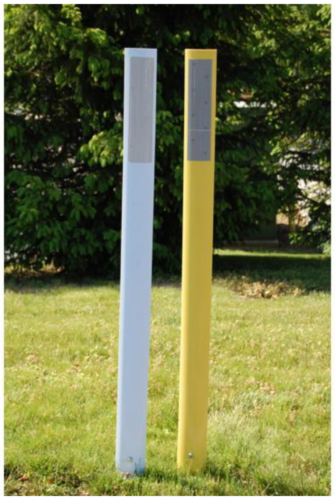


Figure 3-9 Channelizing device: Vertical panels

Median type prior to the work zone: In addition to the roadway features, the median type was reduced to check how the movement of vehicles were separated. The most frequently reduced median type was concrete median barrier, depressed median barrier, depressed median without barrier, flushed median with barrier, flushed painted median without barrier raised median without barrier, guardrail, road diet, and painted only median as a center line. Snapshot of each type of median were provided to the data reducers before start of the task to make uniformity in the data reduction.

Type of barrier: Type of barrier present in the median, such as like cable median, guardrail or concrete. Presence of glare screen: Indicated presence of glare screen on top of medians as noted in Figure 3-10.

Figure 3-10 Glare screen

3.2.3 Other work zone related variables

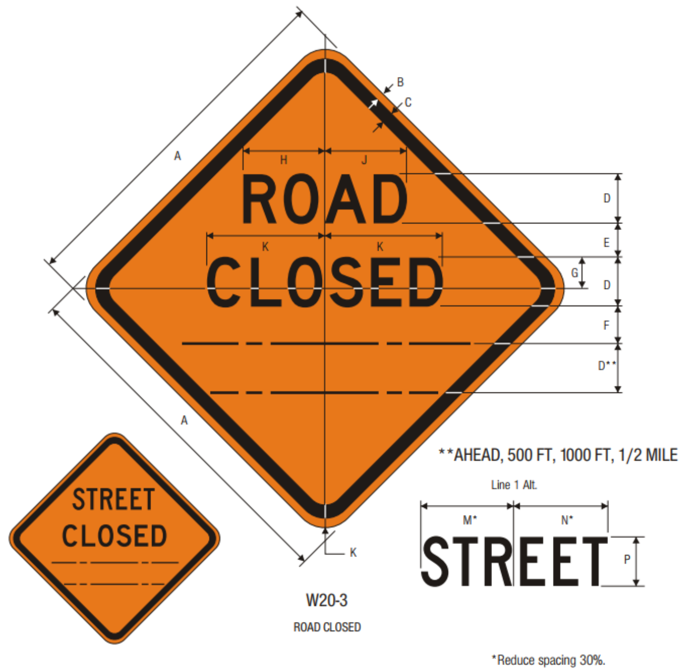
1. Rodway configuration prior to work zone: Coded as 2 lanes undivided, 2-lane divided, 4-lane divided, 4-lane undivided or multilane.
2. Work zone configuration: only active work zones were included as a result this was coded as single shoulder closure, both shoulder closure, or lane closure. The number of lanes were noted. Common work zone configurations were head to head traffic with or without shoulder closed, left or right lane closed, left or right shoulder closed or alternate left and right shoulder or lane closed
3. Other features: In addition to location and type of signs, presence of vehicles ahead, lane merge locations, presence and location of equipment and workers, time of a day, and weather information were also reduced.
   - Lane merge location noted from point vehicle started merging to the instant vehicle changed the lane till the vehicle aligned to the merged lane.

- Position: lane position of vehicle was noted as right, center, left, center right or center left lane.
- Vehicle ahead: presence of a vehicle ahead was noted if the subject vehicle was moving in the free flow in addition to its visibility to different signs. It was only reduced if the vehicle ahead was affecting the movement of subject vehicle or within 3 seconds gap size.
- Location of equipment and workers: Noted in terms of their location (inside work zone or near to the moving lane), device separating it with the moving lane and distance of equipment or workers from the moving lane to tentatively estimate the exposure for safety analysis.
- Time of a day: Indicated as night or day. Dawn and dusk was not categorized separately due to the limited sample size with in that category.
- Weather indicated if it was dry or rainy day.
- Level of congestion: Reduced using a protocol developed by VTTI. When LOS was lower than LOS C, time series traces were not included since it was felt most of the driver behaviors evaluated, such as speed, would be impacted by the behavior of surrounding vehicles. Events with congestion were utilized for the back of queue analysis.

3.2.4 Legibility distances of work zone objects

The legibility distances for TCD in each work zone were calculated to determine how far upstream a sign would have be visible to the average driver and therefore could have influenced driver behavior. This was referred to as the distance of influence for each sign. A legibility index of 30 per inch of letter height as a minimum ratio of one inch of letter height per 30 feet legibility distance was used according to MUTCD. Bertucci, 2006 mentioned that the minimum distance of the sign legibility depends on the time it takes to read the sign and the decisions and maneuvers required to comply with the sign. As the speed increases the rate of viewing distance decreases which means drivers need more distance to view the entire message at higher speed. In addition, legibility depends on the sign placement if it is perpendicular or parallel. Overall, legibility distance is a complex phenomenon where drivers should have suitable time to detect it, read and at the end react to the displayed message based on the surrounding traffic scenario. The distance differs by the types of work zone signs and the speed of the moving traffic.

Static Work Zone Signs: With some exceptions, MUTCD describes warning signs as diamond-shaped with a black symbol or message on an orange background. According to MUTCD, the sizes of main signs include 24”by 24”, 30”by 30”, 36”by 36” to 48”by48”. Generally, the letter sizes in the static work zone ahead warning plaques (assuming 36” by 36” plaque sizes) vary between 5 to 6 inches (Refer Figure 3-11). Thus assuming 6-inch letter height the legibility distance was 180ft for static work zone signs. For CMS signs the legibility distances were 600 ft. for both nighttime conditions and normal daylight conditions.



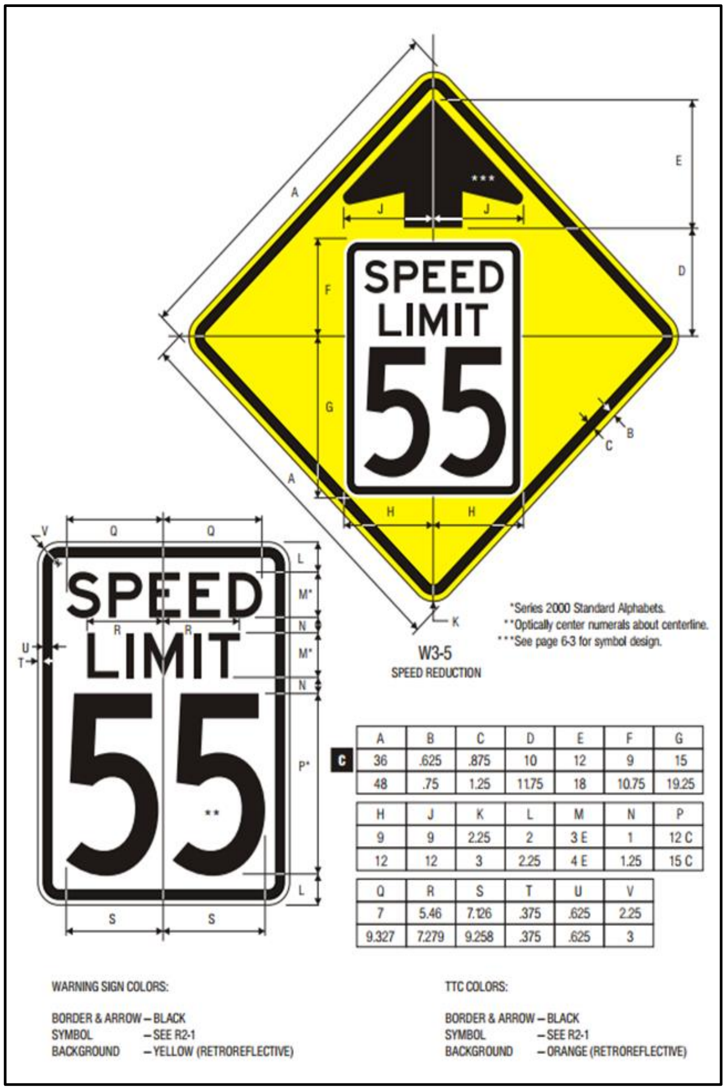
C	A	B	C	D	E	F	G	H	J	K	L	M
	36	.625	.875	5 D	3.5	3.75	3.25	8.375	8.875	12.313	2.25	10
	48	.75	1.25	7 D	4.75	5.25	4.5	11.688	12.438	17.25	3	14

N	P
9.625	5 C
13.5	7 C

TTC SIGN COLORS:
LEGEND — BLACK
BACKGROUND— ORANGE (RETROREFLECTIVE)

Figure 3-11 Static Work Zone Sign Plaque

Speed limit signs: given that there are different kinds of work zone speed limit signs, assuming the average letter height of speed limit letters to be 15 inches, the legibility distance was calculated as 450 feet. If there was any speed limit sign before the work zone speed limit sign in a trace, then it was considered as a normal speed limit otherwise work zone speed limit. For simplicity, legibility distance of lane merge Sign was assumed to be 450feet. Literature showed anything between 90-900 feet is advisable.



	A	B	C	D	E	F	G
C	36	.625	.875	10	12	9	15
	48	.75	1.25	11.75	18	10.75	19.25

H	J	K	L	M	N	P
9	9	2.25	2	3 E	1	12 C
12	12	3	2.25	4 E	1.25	15 C

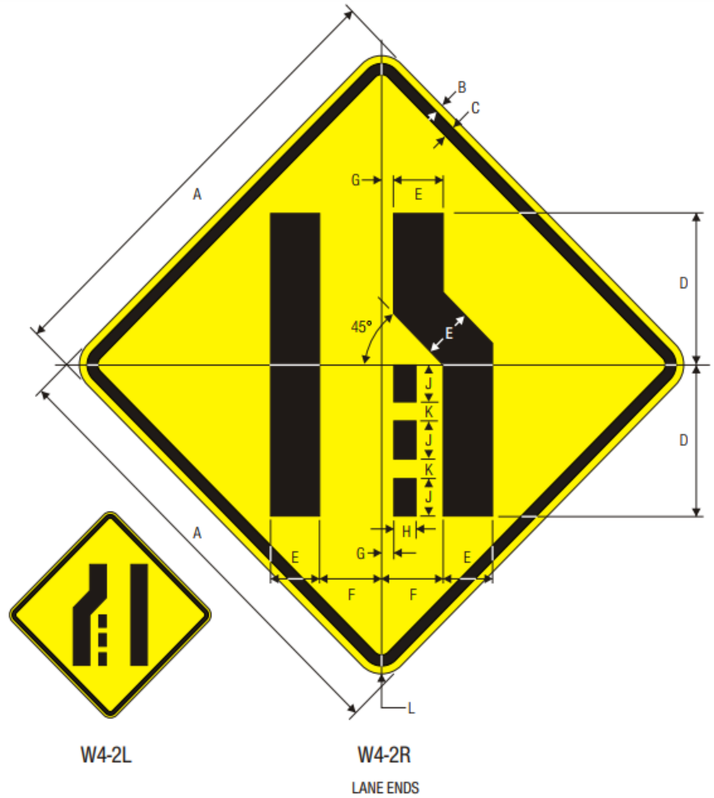
Q	R	S	T	U	V
7	5.46	7.126	.375	.625	2.25
9.327	7.279	9.258	.375	.625	3

Figure 3-12 Speed Limit Sign Plaque

Changeable Message Signs: A general guidance on displaying the message on Dynamic Message Sign (DMS) or Changeable Message Board (CMS) discussed that DMS used on roadways with speed limits of 55 mph or higher should be visible from half mile under both day and night conditions. The message should be designed to be legible from a minimum of 600 ft. for nighttime conditions and 800 ft. for normal daylight conditions (DMS). MUTCD also recommend changeable message signs should be legible from at least 600 feet for nighttime and 800 feet for daylight conditions.

A research study by Perez et al. 2016 showed that mean legibility distance for speed limit signs were close to 1,250 feet though the type and placement of speed limit signs was different. Signs were placed overhead rather than on the side of road. In addition, research showed double the legibility distance for symbols than that of the alphanumeric signs (Jacob et al. 1975). Research studies have also found that increase in the letter height does not linearly or proportionally increase the legible distance. For instance, double the letter height does not double the legibility distance (Allen et al. 1967). Garvey and Mace, 1996 found that increases in letter height greater than about 8 inches resulted in non-proportional increases in the legibility distance. Usually, FHWA provides legibility distance based on the character height that is required for certain speed (Portable Changeable Message Sign Handbook).

Lane Merge Sign: The study by Paniati, 1988 used FHWA sign simulator to show a legibility distance equivalent to 90 meters (295 feet) for the lane merging sign (W4-1) (closest to lane drop sign that they included in the test). Another study by Zwahlen et al. 1991 did actual field tests and found legibility for W4-1 to be close to 900 feet which is significantly larger compared to that from the previous study. Legibility distance for majority of symbols were found to be twice that of the alphanumeric signs (Jacobs et al., 1979). Height of lane merge sign was taken to be 10 inches as the double line part is important to recognize (refer Figure 3-13). Based on legibility index of 30, it is legible from 300 feet apart. As symbols were assumed to have double legibility distance, required distance for lane merge sign is equal to around 600 feet. For being on the conservative side this legibility distance was taken same as speed limit sign which is 450 feet.



	A	B	C	D	E	F	G	H	J	K	L
C	30	.5	.75	10	3.375	4.188	.875	1.5	2.5	1.25	1.875
	36	.625	.875	12	4	5	1	1.75	3	1.5	2.25
	48	.75	1.25	16	5.375	6.688	1.25	2.375	4	2	3

Figure 3-13 Lane Merge Sign

Finally, based on findings from various research studies and using own engineering judgement this study used various distance as legibility distance for different types of work zone signs. For Static work zone signs: General guidance for selecting letter height is based on legibility index which is 30 per inch of letter height as a minimum ratio of 1 inch of letter height per 30 feet legibility distance. Thus assuming 6-inch letter height the legibility distance is 180ft. For DMS signs, the legibility distances were chosen to be 600 ft for nighttime conditions and 800 ft for normal daylight conditions. For simplicity and being on the conservative side, both nighttime and daytime legibility distances were taken to be 600ft. Similarly, for arrowhead VMS signs the legibility distance was chosen to be same as 600 ft. as VMS text message boards to be on the conservative side. For Speed limit and speed feedback signs, given that there are different kinds of work one speed limit signs, assuming the average letter height of speed limit letters to be 15 inches, the legibility distance was calculated as 30X15= 450ft. For Lane merge signs, since the calculated distance are so different from each other, to be on the conservative side, legibility to that of speed limit sign was used. Table 3-3 below shows the summary of the legibility distance used for different types of work zone signs in this study.

Table 3-3 Legibility distances of Work Zone Signs

Types of Work Zone Sign	Legibility Distance, in feet (in meter)
Static Work Zone Sign with 5" letter height	180 (54.86)
CMS Signs	600 (182.88)
Arrowhead VMS	600 (182.88)
Speed Limit Signs (Normal, Work Zone, Feedback)	450 (137.16)
Lane Ends	450 (137.16)

3.2.5 QAQC of the reduced data

The data were reduced by multiple researchers and over a period of time, there were inconsistencies and irregularities in the coding. Efforts were made to reduce these human errors from the traces that were finally used in analysis. The coded time series traces (0.1 secs apart) for 343 traces of work zones on 4 lane divided roadways were stacked together and the dataset represented a combined file of multiple time series files with other variables associated to the time stamps. Similarly, about 511 traces of work zones on multilane roadway were stacked together. Driver characteristics (e.g., age, gender, etc.) provided for each driver by the VTTI were linked to these datasets. Mismatch between variable of different traces were identified and efforts were made to minimize errors. For example, for "median type" some traces were coded upstream of work zone and some for entire trace and some for a certain portion of it. For other variable such as, work zone configuration, channelizing device, weather/lighting conditions different names of subcategories were used by different coders. Some traces from each of the two datasets were spot checked with the available forward videos. Missing information in variable in the datasets were imputed from available information of traces from same work zones.

3.3 Driver demographics

Driver characteristics including age, gender, and other socioeconomic characteristics were provided by VTTI along with the time series traces. Driver distraction and kinematic driver characteristics were initially reduced for a 134 time series traces. Later it was decided that having VTTI reduce the additional data was more time and cost efficient. Due to the cost of reducing driver face video, a total of only 1,099 traces were reduced. Characteristics reduced include behaviors such as hands on wheel, impairments (i.e., drowsiness, intoxication), seat belt use, driving action (i.e., failure to yield), and speeding (exceeding speed limit or driving too fast for conditions). Driver distraction was also coded in the form of secondary tasks, including non-driving-related glances away from the driving task.

3.4 Driver eye glance and distraction

Drivers glance location and any visual distractions were manually coded at the secure enclave at VTTI. This was coded from 2 miles upstream of the start of the work zone through 1.5 miles into the work zone. Approximately 115 traces were coded by the team at Iowa State, while the remaining 984 traces were coded using the same protocol by the team at VTTI.

For each trace, drivers' glance and visual distraction were coded at 15 Hz. Glance locations can be seen in Figure 3-14 and included: Forward, left, right, up, down, over the shoulder (not shown, but glance beyond the b pillar), center console, steering wheel, rear view mirror, other (used when blinks, squints, or closed eyes that last more than 10 frames.), missing (used when the eyes are obscured or obstructed for more than 10 frames or when video is missing).

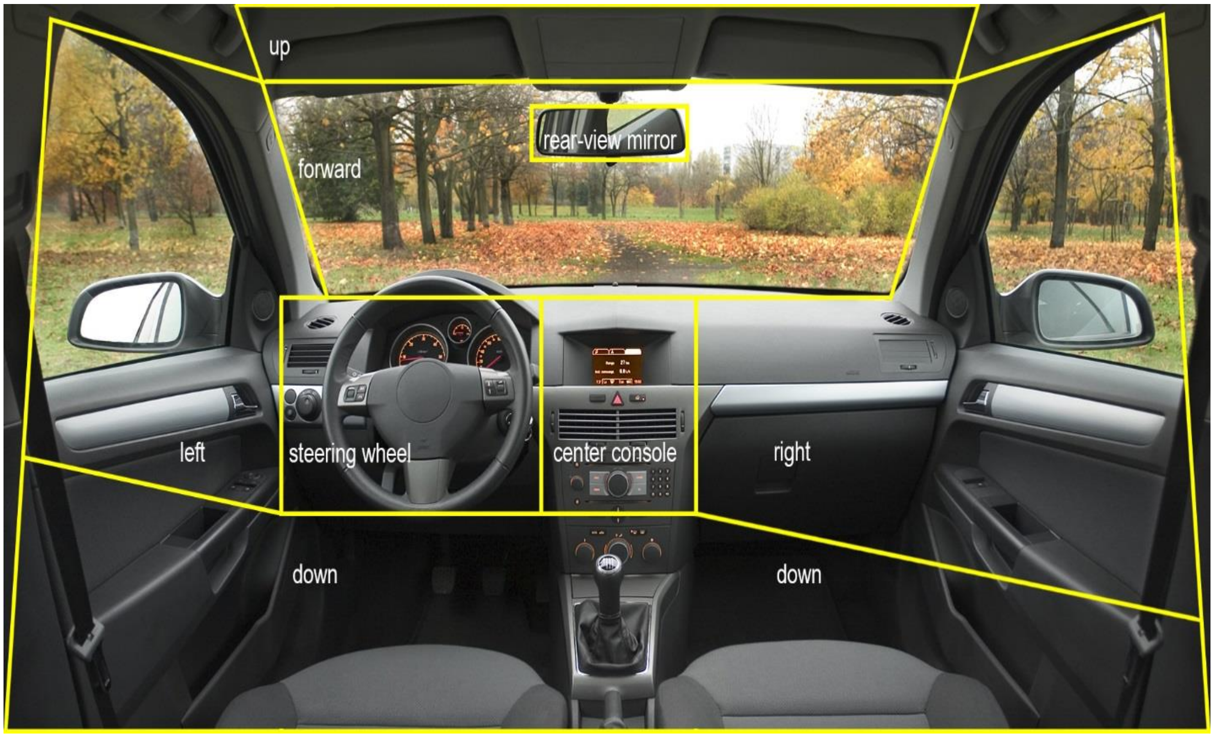


Figure 3-14 Glance Locations

Visual distractions were only coded when they were associated with a glance away from the forward view. For instance, if a driver was looking forward but talking to a passenger, that was not coded as a distraction. However, if they looked to the right at the passenger while talking to them, that was coded as a distraction. The distractions were coded as follows: Passenger, route planning (locating, viewing, or operating), moving or dropped object in vehicle, animal/insect in vehicle, cell phone (locating, viewing, operating), ipod/mp3 (locating, viewing, operating), in-vehicle controls, drinking/eating, smoking, personal hygiene, other task.

In addition, as the use of cell phones in work zones was a particular research question the use of cell phones outside of just visual distractions was also included. VTTI coded the timestamp for the beginning and ending of a cell phone conversation. If the start or end occurred outside of the time frame we requested, we asked the beginning/end timestamp of the coding period be used. Distractions caused by the cell phone that were not associated with a glance away from the forward roadway were also included. This included tasks such as reaching, adjusting the charger, texting, etc. Hands free usage was not able to be determined as cell phone records were not available for all traces.

Coded glance data were grouped for forward, left, right and rear-view mirror and was named as forward roadway related. And all other glances were grouped together as not roadway related. Similarly, for distraction category for cell phone use was separated out and all the other distractions were grouped together. Glance and Distraction was coded mostly by VTTI. About 134 (12%) traces were coded by a member of the research team. Effort were spending to organize these two databases. This distraction and glance data exist separately from the time series traces with speeds. The timestamps in the distraction/glance data do not exactly match with the timestamps of the time series speed data. Thus, an R code was written to join them (provided in Appendix 2). Driver distraction in the baseline events was coded manually at the VTTI secure data enclave. Weather and road surface conditions were coded time stamps nearest to each other.

3.5 Cell phone distraction

VTTI coded about 1003 work zone traces on both four lane and multilane work zones for both visual and cognitive distraction for cell phone usage. The cell phone usage was coded by several tasks across an event id. So, an event id with a cell phone use can have more than one task of cell phone. The different tasks can be listed as below.

- Confirmed - Hands-free cell phone use
- Dialing/Texting/Manipulating phone
- Reaching for phone

- Suspected - Hands-free cell phone use
- Talking on phone - Hand Held

The total number of events with cell phone distraction among the 1003 traces were 167. The data represented about 76 males and 91 females being distracted by cell phone during driving in the work zones. The distribution of age among the cell phone users in the work zones were as follows: 70 drivers of age 24 yrs. or younger, 86 drivers of age 25-64 yrs., and 11 drivers of age 65 yrs. up. As one trace can contain a cell phone task multiple times, the count of cell phone usage type across 167 Event IDs exceeds 167. It was seen that drivers were more prone to dialing, texting and manipulating a phone in work zones compared to other cell phone tasks coded by VTTI.

Table 3-4 Count of Cases with Cell Phone Tasks across All Traces.

Cell Phone Tasks	**Count**
Reaching for phone	179
Dialing/Texting/Manipulating phone	219
Confirmed - Hands-free cell phone use	24
Suspected - Hands-free cell phone use	2
Talking on phone - Hand Held	52

3.5.1 Relationship between cell phone distraction and glance

It was necessary to look at the relationship between drivers' non-forward related glance (eyes off the road) and type of cell phone distraction in work zones. The average total percentage non-forward glance in all the events of cell phone use taken together, Dialing/Texting/Manipulating phone is the maximum followed by reaching for phone. Other tasks like hands free and hand-held usage had less average non-forward glance. On the contrary, the average time they were distracted during those tasks shows that they were cognitively distracted on average for 152/182 and 84 secs during hands free and hand-held cell phone usage.

Table 3-5 Percentage of Non-forward Glance and Distraction

Cell Phone Tasks	Avg Percent Non-Forward	Avg Total Secs Distracted	Avg Total Secs Non-Forward
Dialing/Texting/Manipulating phone	59%	17	10.4
Talking on phone - Hand Held	6.2%	83.6	3.1
Reaching for the phone	33%	3	0.82
Confirmed - Hands-free cell phone use	8%	182	7
Suspected - Hands-free cell phone use	3.6%	152	5.4

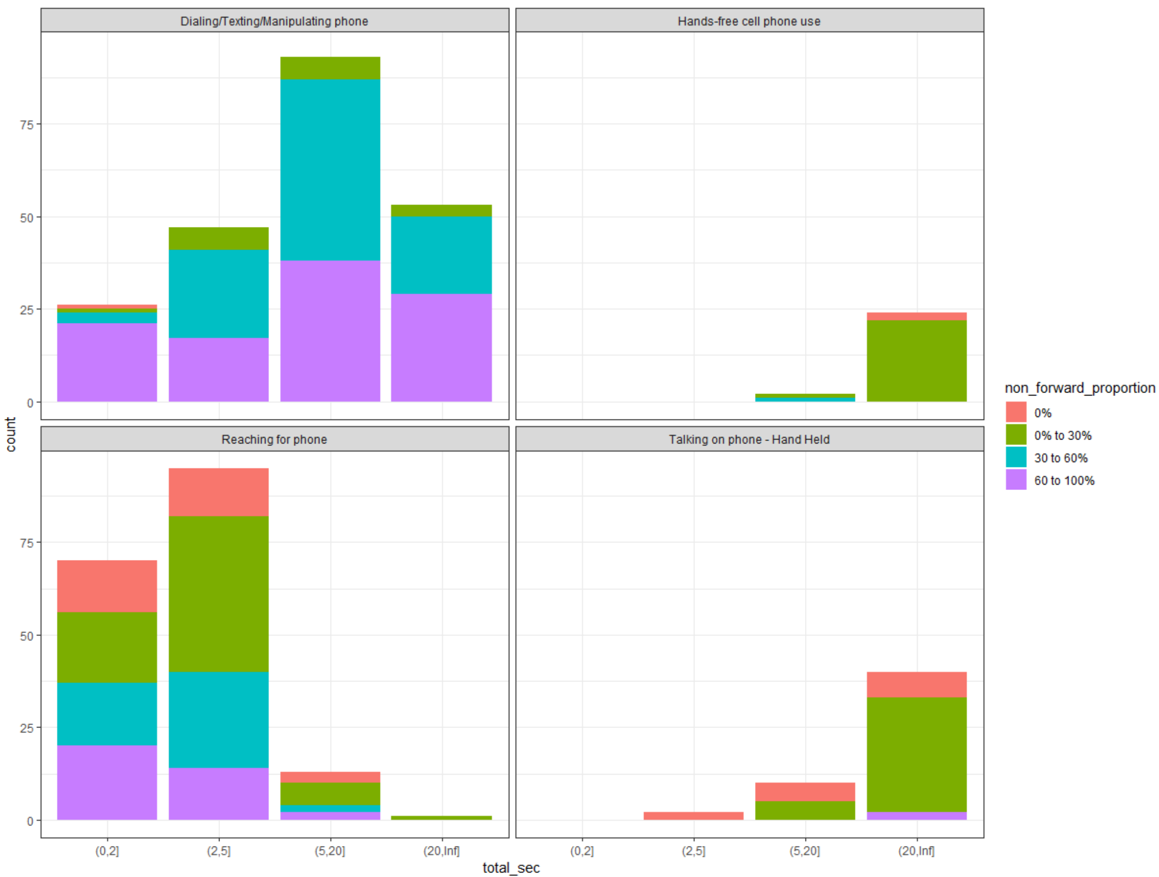


Figure 3-15 Total sections of cell phone distraction and Percentages of non-forward Glance

Total Secs of Cell Phone distraction verses non-forward glance percentages were plotted, and the following observations were made (refer Figure 3-15):

- Confirmed and suspected Hands free were grouped together.
- The pattern of non-forward glance is very different for Reaching for phone and texting/dialing/manipulating phone.
- Drivers were mostly distracted for more than 5 sec during Dialing/Texting… compared to reaching for phone.
- We have only 14 cases of more than 5 secs non-forward glance for reaching for phone, we can ask VTTI about this.
- Drivers had more than 30% of non-forward glance for dialing and texting compared to reaching for phone
- Drivers distracted for more than 20 secs when talking on phone hand held or hands free had less than 30% non-forward glance.

CHAPTER 4. CHANGE IN SPEED MODELS FOR WORK ZONES IN FOUR-LANE DIVIDED HIGHWAYS

This chapter focusses on the analysis of speed change of drivers on four lane divided work zones. Section 4.1 introduces to the objectives of the study. Section 4.2 discusses the final data used for the study. Section 4.3 Focusses on the statistical methodology. The study utilized linear mixed effects model for the purpose of the analysis. Section 4.4 discusses the results, conclusions and limitations of the study.

4.1 Objectives

One of the objectives of this study was to investigate the effectiveness of different temporary traffic control (TTC) devices on driver behavior on work zones situated on four lane divided highways. Several scenarios such as lane closure, shoulder closure and median crossover (lane shift) were investigated. Speed is a major contributing factor in most types of crashes including work zones. Several countermeasures have been utilized by agencies to get driver's attention and encourage safe work zone driving. However, only a few have been evaluated and as noted in the previous chapters, the impact is not conclusive for countermeasures such as dynamic message, speed feedback, or static speed limit reduction signs. So, this study takes on the responsibility to evaluate by how much a driver changes their speed for a particular TTC device.

In this case, the change in speed from a point upstream of the legibility distance of a sign or work zone feature was compared to the speed just past the feature. The intent was to determine whether drivers slow down for a feature (TTC device). In some cases, a driver may slow within the legibility distance in response to the feature but may then increase speed again. For instance, a driver may slow when presented with a speed feedback sign but then may speed back up. Change in speed was assumed to suggest a sustained response. A linear mixed effects model was used to analyze drivers' change in speed in the work zone. Any work zone related object within 2 miles upstream of the taper point to a distance 1 mile inside the work zone (downstream) was included.

4.2 Description of data

The previous chapter 3 demonstrated that work-zones can be successfully located in the SHPR 2 RID data using the 511 data and then matched to work-zones identified in the SHRP 2 NDS data. It should be mentioned here that due to the time and resources needed to manually code work zone characteristics or all the TTC devices from 2 miles upstream of the start of taper point (start of work zone) to a distance 1 mile inside the work zone (downstream), only 343 traces were reduced which corresponded to four-lane work zones. This number was further reduced by the number of traces which could realistically be reduced for driver distraction and glance location and ultimately resulted in 264 traces over 42 unique work zones and 157 unique drivers. In a few cases signs are placed several miles upstream of a work zone and may not have been captured since the requested video trace was typically 2 miles upstream of the merge point. As mentioned earlier that the point between the first work zone sign and merge point was referred to as the advance warning area and was characterized by various TTC devices on the individual work zone such as reduced speed limit, changeable message signs, static signing, etc. Legibility of these signs was based on letter or symbol size with a general guide of legibility index of 30 per inch of letter height. For instance, a 6-inch letter height is visible for 180 feet. The legibility bands or buffer are represented in Table 3-3 in chapter 3. The legibility distance of other two work zone features that is presence of worker or equipment was selected to be 180 feet same as static work zone signs. Finally, each row of the dataset contained change in speed for each object (TTC signs, worker or equipment) in a work zone trace along with the associated work zone, roadway and driver characteristics. There can be multiple observations from the same event or trace id. Similarly, there can be multiple traces driven by a same driver in a work zone.

4.2.1 Calculation of change in speed

Effectiveness of three types of work zone features were studied in this chapter, first the advance warning signs, second the presence of equipment and third the presence of workers. Change in speed was calculated for each work zone feature in the influence areas for each time series trace. Essentially speed is measured just before the calculated legibility distance for each sign and then measured again just past the sign. The buffered distance for each sign includes the calculated upstream legibility distance plus a distance of 100 meters upstream to ensure the first speed measurement is taken at a point where the driver would not have been influenced by the sign.

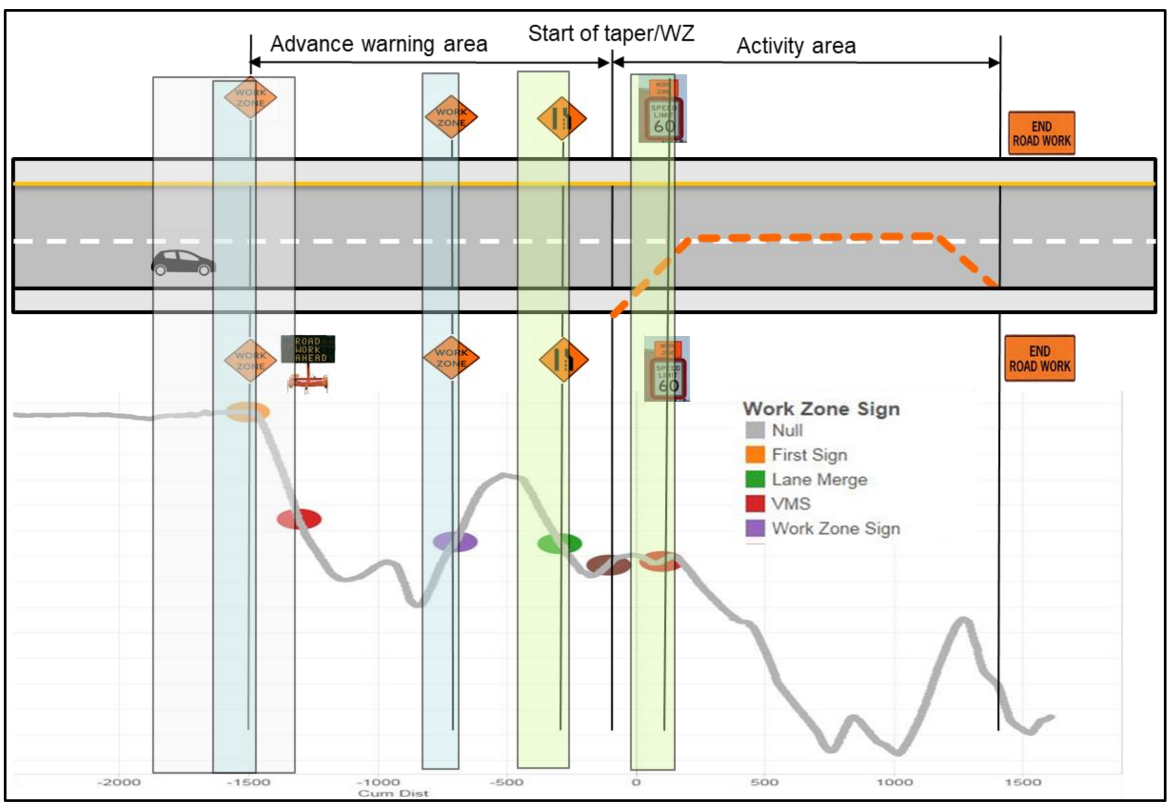


Figure 4-1 Buffered Legibility bands for TTC devices

The second speed measurement is taken at a point which is more than 50 meters downstream of the sign which accounts for a driver slowing after they have passed the sign. Using the time stamp, the approximate location for each feature was coded and then using time stamp and speed, a vehicle's position in relation to work zone features was determined (i.e. 100 feet upstream of a lane closure sign). Since a driver's position in relation to work zone features were important, legibility distances of each work zone sign were calculated to determine the area within which the sign would be visible to the driver. It was assumed that a driver would react to a sign within this distance. The upstream speed for each object was taken 100 meters upstream of the start of the legibility distance and the downstream speed was taken 50 meters downstream of the object. It was assumed that drivers upstream of that point had not yet seen the object and were not influenced by the object. The downstream distance accounts for a driver slowing after they have passed the object. Change in speed was the upstream speed minus the downstream speed. Figure 4-1 shows a schematic of a time series trace overlain with the legibility distance for various objects.

4.2.2 Numerical variables

The different work zone signs such as CMS, enforcement, lane end, normal speed limit, speed feedback signs, static work zone signs, work zone speed limit sign, etc. were used as categorical variables in the models. Status of CMS sign whether it was active or not was also taken as a categorical variable. Apart from these types of work zone closures such as lane closure, shoulder closure, etc. were taken as categorical variables.

Driver gender was considered as a categorical variable. Age was categorized into three groups, less than twenty-five were grouped as one category, more than equal to twenty-five and less than sixty-five as another category and above and equal to sixty-five as the third category. Other characteristics specific to each object were also summarized.

Also, apart from these, indicator variables for cell phone use or distraction was created which indicated if the driver was on cell phone or was distracted at all for the period of buffered legibility bands. Similarly, an indicator variable was created for non-forward related glance. A long glance away was calculated if the driver was looking away from the forward direction for more than 2 seconds and was engaged in any activity.

Some of the variables are not relevant before the merge point. For example, equipment, worker and channelizing devices are present only in the active work zone area after the start of taper or merge point. The location of a work zone object within the work zone was important since drivers may be more likely to slow for a speed limit sign near the begin of the work zone than some distance upstream where they perceive no need to slow. Channelizing devices taken as categorical variables also indicated presence and absence of any type during the legibility band of any sign or equipment or worker.

Each row represented change in speed (mph) and other summarized characteristics of the same trace for different bands along the length of the work zone. A linear mixed effects model with traces and driver as the random effects was used for the analysis. Variables for both before and after merge point are presented in Table 4-1.

4.2.4 Determining study sections

The portion of a trace before the start of taper or work zone is designated as an upstream section and the portion of the trace after the start of work zone is designated as the downstream portion (refer Figure 4 2). It should be noted here that the upstream portion started from 200 meters before the first sign and the downstream portion ends 100m after the end of work zone. Attempts were made to include location within one model for both the upstream and downstream portions, but the models became increasingly complicated and began to lose practical significance. As a result, separate models were created for the study sections before and after the merge point (start of work zone).

Table 4-1 Descriptive Statistics Before and After Work Zone Point

	Before Merge Point				After Merge Point			
Variables	**Mean**	**Std. Dev**	**Min**	**Max**	**Mean**	**Std. Dev**	**Min**	**Max**
Female	0.55	0.50	0	1	0.60	0.49	0	1
Twenty-Four Younger	0.14	0.34	0	1	0.17	0.37	0	1
Twenty-Five to Sixty-four	0.60	0.49	0	1	0.60	0.49	0	1
CMS ALL	0.12	0.32	0	1	0.20	0.40	0	1
CMS Status (Active)	0.04	0.20	0	1	0.13	0.34	0	1
Enforcement Sign	0.05	0.21	0	1	0.01	0.10	0	1
Equipment	NA	NA	NA	NA	0.29	0.45	0	1
Lane End Sign	0.11	0.31	0	1	0.02	0.12	0	1
Normal Speed Limit	0.06	0.24	0	1	0.02	0.13	0	1
Speed Feed back	0.02	0.14	0	1	0.02	0.15	0	1
Static WZ Signs	0.47	0.50	0	1	0.18	0.39	0	1
WZ Speed Limit	0.17	0.37	0	1	0.24	0.43	0	1
Worker	NA	NA	NA	NA	0.03	0.18	0	1
Percent Glance	71.88	42.17	0	100	75.26	40.69	0	100
Less Than Half the Time Forward	0.02	0.14	0	1	0.01	0.08	0	1
Percent Cell Phone	2.44	15.36	0	100	1.81	13.25	0	100
Cell Phone Use	0.02	0.16	0	1	0.02	0.13	0	1
Two Sec Glance Away	0.01	0.08	0	1	0.00	0.06	0	1
Lane Closure	NA	NA	NA	NA	0.52	0.50	0	1
Head to Head	NA	NA	NA	NA	0.08	0.28	0	1
Shoulder Closure	NA	NA	NA	NA	0.36	0.48	0	1
Barrels	NA	NA	NA	NA	0.43	0.50	0	1
Cones	NA	NA	NA	NA	0.05	0.21	0	1
Concrete	NA	NA	NA	NA	0.41	0.49	0	1
Vertical Panels	NA	NA	NA	NA	0.11	0.31	0	1
Channelization on Both Sides	NA	NA	NA	NA	0.10	0.29	0	1
Equipment Inside Barrier	NA	NA	NA	NA	0.29	0.45	0	1
Worker Outside Barrier	NA	NA	NA	NA	0.03	0.17	0	1
Following Car	0.10	0.30	0	1	0.17	0.38	0	1
Lane Change	0.03	0.16	0	1	0.01	0.07	0	1
Rainy	0.07	0.26	0	1	0.07	0.26	0	1
Night	0.22	0.41	0	1	0.17	0.38	0	1
Lane Shift	NA	NA	NA	NA	0.07	0.26	0	1

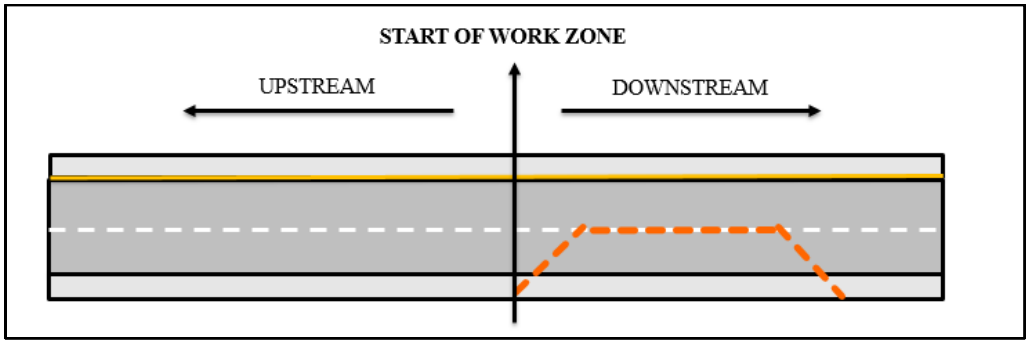


Figure 4-2 Study Sections for a Trace

Additionally, due to vastness of the areas of the upstream and downstream portions of the work zone traces, attempts were made to disaggregate these portions further to be included in the models. Distance of all objects were plotted against their calculated change in speed (Refer Figure 4-3). For most of the objects or work zone features a change in slope can be observed around 1250 meters (three quarters of a mile approx.). Thus, this point was chosen as a division for the location variable for the upstream section. Similarly, a cut off was considered at 800m (half mile approx.) for the downstream portion (Refer Figure 4-4).

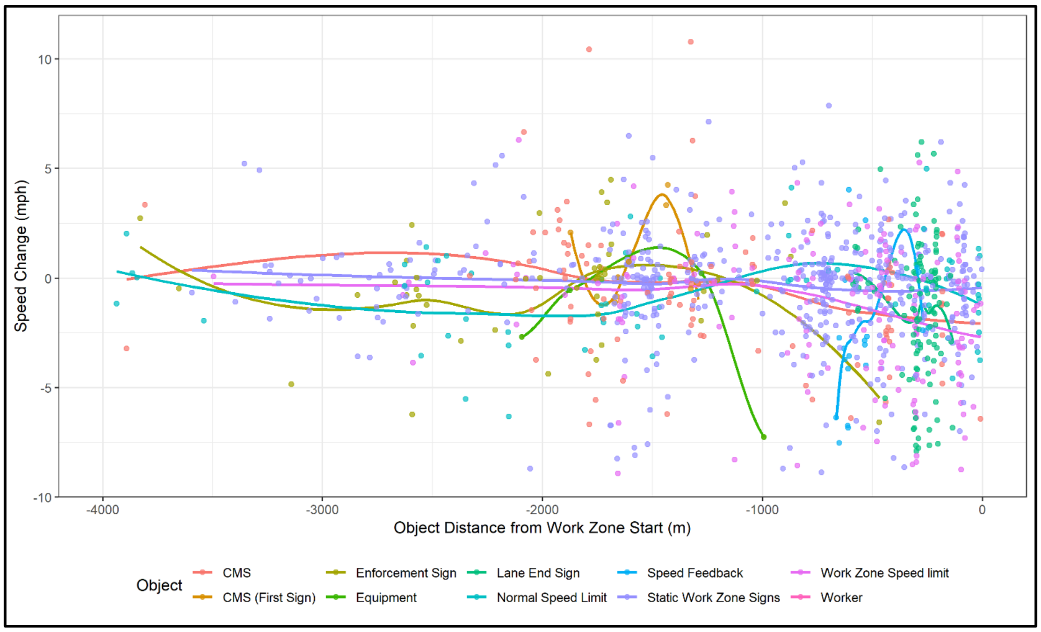


Figure 4-3 Upstream Portion of Work Zone

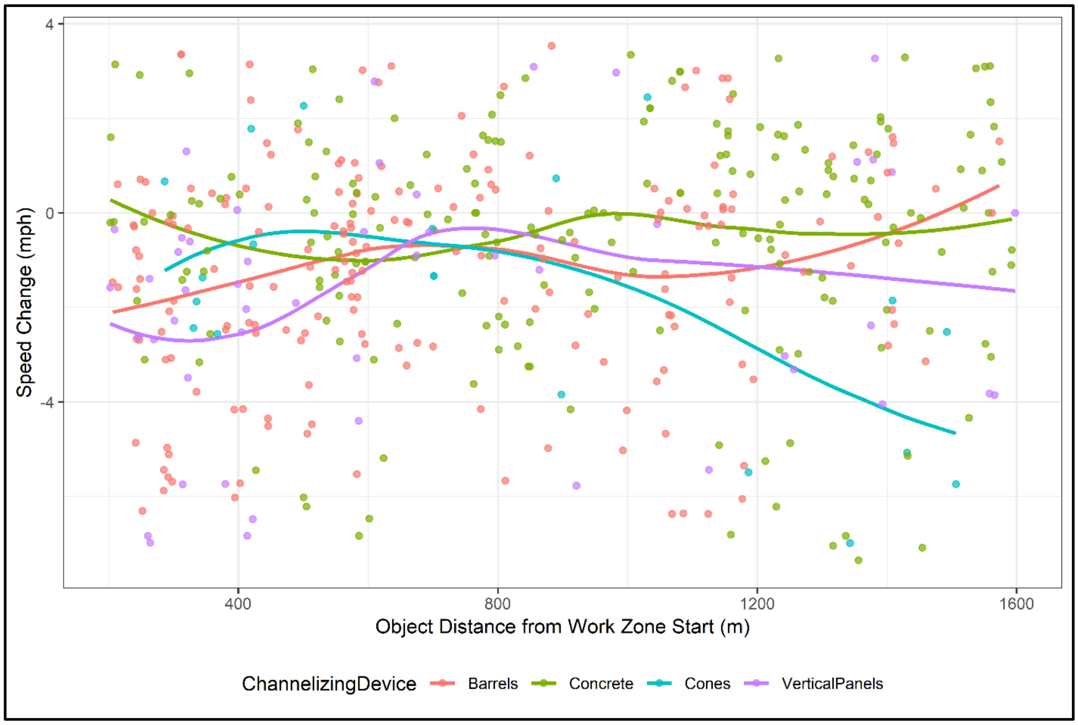


Figure 4-4 Downstream Portion of Work Zone

4.3 Statistical methodology

The main objective of this analysis was to predict how drivers change speed in relationship to different work zone features. It is assumed that reduction in speed has a positive safety benefit. In many cases drivers have already slowed to a safe speed and as a result, there is no further need for the driver to react. A model to estimate speed as a function of work zone characteristics was first attempted but speed is highly correlated to distance from the taper point. Additionally, location of many work zone features is also correlated to distance from the taper point. A change is speed was utilized since it could isolate the impact of individual features.

Two separate models for four lane divided roads were developed using a linear mixed effects (LME) models, which account for some dependency in the observations. In these two models, random effects for trace, driver, and work zone were introduced to deal with the dependency of the observations from the same trace, driver and work zone. More specifically, an LME model consists of the sum of two terms, a fixed effects part and a random effects part. The former is constituted by the variables of interest while the latter models the dependency of the variables. The random effect part will consist of two sources: within and between trace variability. The j-th observation from the i-th observation in any of the two models looks like

$$y_{ij} = \beta_0 + x_{1,ij}\beta_1 + x_{2,ij}\beta_{2,} + \cdots + x_{k,ij}\beta_k + u_i + \epsilon_{ij}.$$

Where y is the response, $\boldsymbol{x}_{ij} = (1, x_{1,ij}, x_{2,ij}, \ldots, x_{k,ij})$ is the vector of explanatory variables, $\boldsymbol{\beta} = (\beta_0, \beta_1, \beta_2, \ldots, \beta_k)$ is the vector of coefficients, u_i is the random effect for trace (between trace error), and ϵ_{ij} the error (within trace error).

The random effects u_i is normally distributed with mean zero and variance σ_u^2, while ϵ_{ij} are normally distributed with mean zero and variance σ_ϵ^2. The relation between these variance components goes as follows.

$$cov\left(y_{i_1 j_1}, y_{i_2 j_2}\right) = \begin{cases} \sigma_u^2 + \sigma_\epsilon^2 & if & i_1 = i_2, j_1 = j_2 \\ \sigma_u^2 & if & i_1 = i_2, j_1 \neq j_2 \\ 0 & otherwise. & \end{cases}$$

Therefore, the mean of y_ij is $\boldsymbol{x}_{ij}^T\boldsymbol{\beta}$ and the variance is $\sigma_u^2 + \sigma_\epsilon^2$. The covariance between two observations from different traces is zero, and the covariance between two observations from the same trace is σ_u^2. Observe that if the between-trace variability were not included, the models would be ordinary least squares regression (Bates et al. 2015, R Core Team, 2018).

The lme4 package in R was used to estimate the LME model. The r-squared values from each model and ANOVA test were used to evaluate the model's goodness of fit. The final model was produced using backward elimination, this is, a complex model was considered, and it was gradually simplified using full vs. reduced F-tests. First a model was fitted with all possible variables, gradually non-significant variables were taken out and the model was rerun, ANOVA test were used to check so that any important variable was not rejected.

4.4 Results and conclusions

The models for the upstream and downstream portions include the variables described in the Table 4-2. Furthermore, Table 4-2 shows the p-values for each one of the included variables; all the p-values are smaller than 0.1, except for static work zone signs and work zone speed limit sign, but it is included nevertheless since the interaction with location is present. Table 4-2 has some estimates which do not interact with other variables in the model. For these variables the estimates represent the change in speed in the presence of that object. For instance, in the area upstream of the lane or shoulder closure point, when a CMS sign is present, a speed decrease of 0.5 mph was noted. When a speed feedback sign was present, driver slowed 3.3 mph and a decrease of 0.3 mph was noted for other types of static work zone signs.

The before merge point model includes two interactions, one between work zone speed limit sign and location, another with static work zone sign and location. The after-merge point model includes three interactions, one between work zone speed limit signs and channelizing devices, another with work zone speed limit sign and location and the third with equipment and location. The interactions are presented in Table 4-4. The cells were computed with the appropriate linear combinations from coefficients in Table 4-3. For example, the effect of Work Zone Speed Limit when Cones are present as channelizing device is obtained by, (0.49-6.17= -5.67mph). Increase in non-forward glance after merge point model increases the speed by 0.71 miles per hour in average. The speed feedback sign, CMS, lane end sign and normal speed limit sign shows decrease in driver speed in the before merge point model.

Table 4-2 Anova for Before and After Merge Point Models.

Advanced warning area model					**Activity area model**				
	Chisq	Df	Pr(>Chisq)			Chisq	Df	Pr(>Chisq)	
CMS	0.82	1	0.36		Equipment	7.03	1	0.01	**
location	9.44	1	0.00	**	location	6.83	1	0.01	**
Lane End Sign	8.96	1	0.00	**	Non-forward	2.98	1	0.08	.
Normal Speed Limit	3.09	1	0.08	.	Channelizing Device	10.52	3	0.01	*
Speed Feedback	13.41	1	0.00	***	Equipment: location	2.88	1	0.09	.
Static WZ Signs	0.11	1	0.74		-	-	-	-	-
WZ Speed Limit	12.22	1	0.00	***	WZ Speed Limit	0.08	1	0.78	
location: WZ Speed Limit	5.38	1	0.02	*	location: WZ Speed Limit	3.43	1	0.06	.
location: Static WZ Signs	5.65	1	0.02	*	WZ Speed Limit: Channelizing Device	9.33	3	0.03	*

Table 4-3 Estimated Parameters

Advanced warning area model				**Activity area model**			
	Estimate	**Std. Error**	**t value**		**Estimate**	**Std. Error**	**t value**
(Intercept)	-0.24	0.49	-0.48	(Intercept)	-2.41	0.53	-4.53
CMS	-0.51	0.56	-0.91	Equipment	0.37	0.63	0.59
locationover_1.25_mile_upstream	-0.10	0.57	-0.17	location over half mile downstream	-0.03	0.59	-0.04
WZ Speed Limit	-2.23	0.55	-4.03	WZ Speed Limit	-0.17	0.70	-0.24
Normal Speed Limit	-1.07	0.61	-1.76	Channelizing Device Concrete	1.44	0.52	2.76
Speed Feedback	-3.33	0.91	-3.66	Channelizing Device Cones	0.49	1.14	0.43
Static WZ Signs	-0.29	0.51	-0.56	Channelizing Device Vertical Panels	-0.47	0.81	-0.59
Lane End Sign	-1.73	0.58	-2.99	**Non-forward**	0.71	0.41	1.73
location over_1.25_mile_upstream: Static WZ Signs	1.75	0.73	2.38	Equipment: location over half mile downstream	1.44	0.85	1.70
location over_1.25_mile_upstream: WZ Speed Limit	2.91	1.25	2.32	location over half mile downstream: WZ Speed Limit	1.64	0.89	1.85
				WZ Speed Limit: Channelizing Device Concrete	-0.96	0.91	-1.06
				WZ Speed Limit: Channelizing Device Cones	-6.17	2.14	-2.89
				WZ Speed Limit: Channelizing Device Vertical Panels	0.41	1.23	0.33

Table 4-4 Summary of the interaction

Before Merge Point			
Interaction between Static WZ Signs and location	**1.25 mile upstream**	**Over 1.25 mile upstream**	
Static WZ Signs	-0.29	1.46	
Interaction between WZ Speed Limit and location	**1.25 mile upstream**	**Over 1.25 mile upstream**	
WZ Speed Limit	-2.23	0.68	
After Merge Point			
Interaction between channelizing device and WZ Speed Limit	**Concrete**	**Cones**	**Vertical Panels**
Other Signs	1.44	0.49	-0.47
WZ Speed Limit	0.47	-5.67	-0.06
Interaction between WZ Speed Limit and location	**Half mile downstream**	**Over half mile downstream**	
WZ Speed Limit	-0.17	1.47	
Interaction between equipment and location	**Half mile downstream**	**Over half mile downstream**	
Equipment	0.37	1.81	

- In conclusion, the linear mixed effects model results indicate the following. The actual numbers of reduction or increase in speed is provided in Table 4-5.
- Speed feedback signs are more effective in reducing driver speed before the merge point.
- Lane end sign, normal speed limit sign, and CMS also reduced driver speed before the merge point.
- Non-forward related glance was seen to increase driver speed inside the work zone. Thus, driver's safety was compromised when drivers didn't look forward while driving for more than 2 secs.
- Static work zone signs and work zone speed limit sign was more effective about 1.25 mi before the start of work zone.
- Work zone speed limit signs were seen to be more effective within half mile inside a work zone than more than half mile inside the work zone.

- Presence of Work Zone Signs were more effective when the cones were placed as channelizing device inside the work zone.
- Vertical panels as channelizing device were used to decrease driver speed more effectively compared to concrete and cones.

Table 4-5 Results for each Variable

Temporary Traffic Control Devices	**Estimate**	**Results**
Upstream Model		
(Intercept)	-0.24	
CMS	-0.51	Presence of changeable message signs reduces driver speed by 0.51 miles per hour
Normal Speed Limit	-1.07	Presence of Normal Speed Limit reduces driver speed by 1.07 miles per hour
Speed Feedback	-3.33	Presence of Speed feedback sign reduces driver speed by 3.33 miles per hour
Lane End Sign	-1.73	Presence of Lane End Sign reduces driver speed by 1.73 miles per hour
Static WZ Signs within 1.25 mile upstream	-0.29	Presence of any static work zone sign reduces speed by 0.29 mph within 1.25 miles upstream of Start of Taper
Static WZ Signs Over 1.25 mile upstream	1.46	Presence of any static work zone sign does not help to reduce speed over 1.25 miles upstream of Start of Taper
WZ Speed Limit within 1.25 mile upstream	-2.23	Presence of any work zone speed limit sign reduces speed by 2.23 mph within 1.25 miles upstream of Start of Taper
WZ Speed Limit Over 1.25 mile upstream	0.68	Presence of any work zone speed limit sign does not help to reduce speed over 1.25 miles upstream of Start of Taper
Downstream Model		
(Intercept)	-2.41	
Non-forward Glance	0.71	Driver speed increases by 0.71 mph with non-forward glance
Concrete Channelizing Device during WZ Speed Limit	0.47	Work Zone Speed Limit is not that effective in reducing speed when concrete is present as channelizing device
Cone Channelizing Device during WZ Speed Limit	-5.67	Work Zone Speed Limit is reduced speed by 5.67 mph when cone is present as channelizing device
Concrete Channelizing Device during Other Signs	1.44	Other signs are not effective in reducing speed during concrete as channelizing device
Cone Channelizing Device during Other Signs	0.49	Other signs are not effective in reducing speed during Cones as channelizing device
WZ Speed Limit Sign Half Mile Downstream	-0.17	Work Zone Speed Limit Sign Reduce Speed within half mile downstream
WZ Speed Limit Sign Over Half Mile Downstream	1.47	Work Zone Speed Limit Sign is not effective in reducing speed over half mile downstream
Equipment present half mile downstream	0.37	Presence of Equipment did not reduce Speed within half mile downstream
Equipment present Over half mile downstream	1.81	Presence of Equipment did not reduce Speed over half mile downstream

CHAPTER 5. DRIVER'S BEHAVIOR IN SHOULDER CLOSURE AND LANE CLOSURE ON MULTILANE DIVIDED WORK ZONES

This chapter focusses on the analysis of speed change of drivers on multilane lane divided work zones. Data collection and analysis are like the work described in Chapter 4. Section 5.1 introduces to the objectives of the study. Section 5.2 discusses the final data used for the study. Section 5.3 discusses the results, conclusions and limitations of the study.

5.1 Objectives

The objective of the analysis described in this chapter was to evaluate how drivers' change their speed when encountering temporary traffic control (TTC) devices, workers and equipment when approaching a work zone on multilane divided exposure. MUTCD provides guidance on TTC devices and spacing between them for work zone. The TTC devices on shoulder closure and lane closure scenario on freeways are different to a considerable extent. This study attempts to investigate the effectiveness of each scenario on drivers' safe speed choice. This chapter also investigates the difference in driver behavior in work zones with lane closure and only-shoulder closure scenarios. Understanding the effectiveness of each of the TTC devices in different work zone scenarios will improve traffic management and safety and potentially aid on development and deployment of effective safety countermeasures.

5.2 Description of data

Data collection and reduction was described in Chapter 3. This section discusses additional information specific to the multi-lane analyses. Location of traffic control devices was manually extracted as described in Chapter 3. Due to the time and resources needed to manually code work zone characteristics or all the TTC devices from 2 miles upstream of the start of taper point (start of work zone) to a distance 1 mile inside the work zone (downstream), a sample of 357 traces were reduced which corresponded to multilane-lane work zones which represented 181 unique drivers.

A typical section of a multilane with lane closure configuration provided in MUTCD is shown in Figure 5-1. The layout of shoulder closure in the multilane is assumed to be like that of the four-lane divided work.

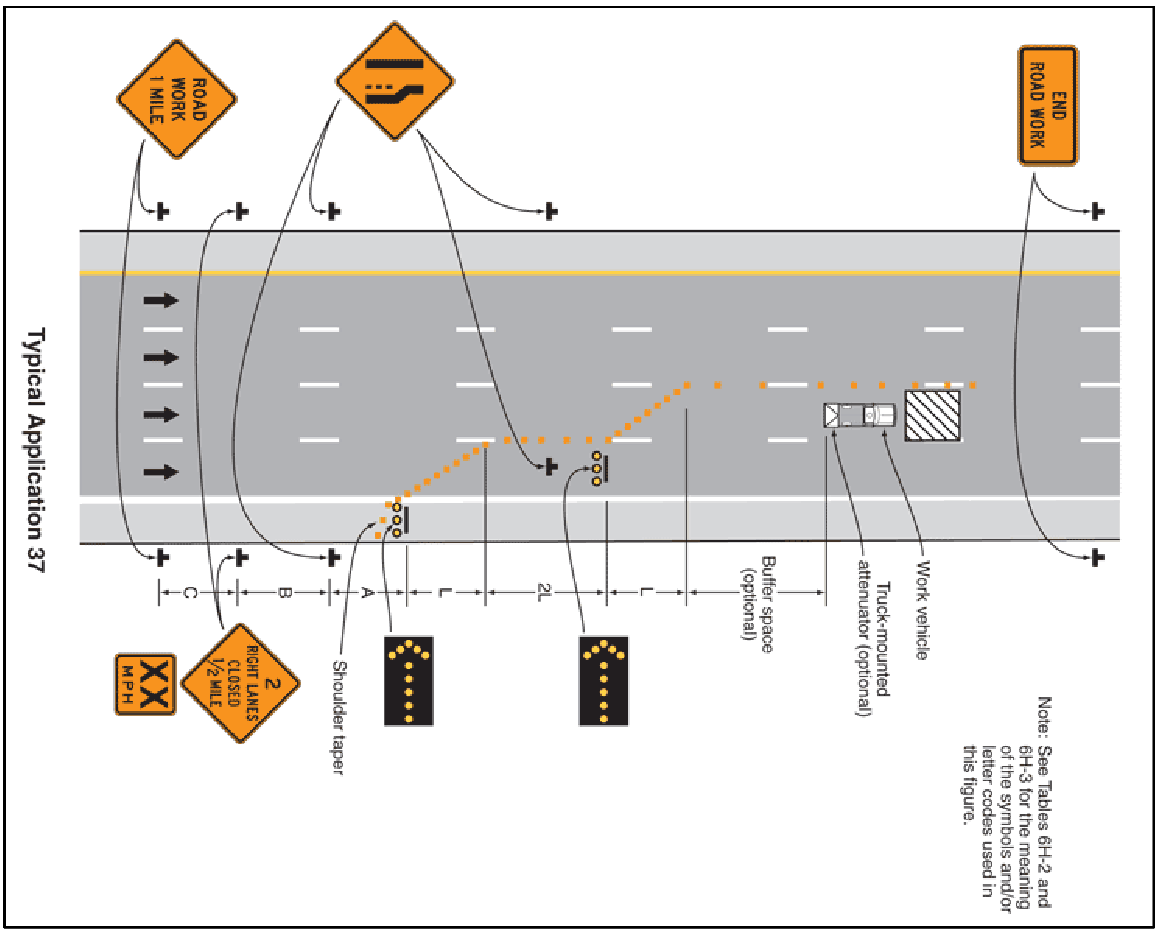


Figure 5-1 Double Lane Closure on a Freeway

Similar procedure to those described in Chapter 3 were adopted for calculation of change in speed for each work zone feature in the influence areas for each time series trace. Legibility of each work zone feature are represented in Chapter 3. Speed was measured just before the identified legibility distance for each sign and then measured again just past the sign. The buffered distance for each sign includes the calculated upstream legibility distance plus 100 meters upstream to ensure the first speed measurement is taken at a point where the driver would not have been influenced by the sign. The second speed measurement is taken at a point which is more than 50 meters downstream of the sign which accounts for a driver slowing after they have passed the sign. Finally, each row of the multilane dataset contained change in speed for each object (TTC signs, worker or equipment) in a work zone trace along with the associated work zone, roadway and driver characteristics. Since a driver may have encountered multiple TTC, multiple observations for the same trace were possible. Similarly, there can be multiple traces driven by a same driver in a work zone. There were a total of 2798 observations of objects (TTC Devices, presence of worker and presence of equipment) from 357 traces. The dataset was evaluated with an indicator variable representing two scenarios, first scenario was traces with only shoulder closure and second scenario included all traces that have one or more lanes closed. It should be remembered that for shoulder closure traces there can a portion of which that indicated shoulder taper, thus any work zone object located in that portion will be designated as shoulder closure configuration in the second scenario. There are 1788 observations of work zone objects, 256 unique traces (164 corresponding unique drivers) with only shoulder closure scenario. An exploratory analysis of the change in speed due to several variables in the dataset is provided below.

5.2.1.1 Work zone features

Figure 5-2 shows the change in speed for different multilane work zone TTC signs and features with respect to distance of the object from the work zone start point. Calculated change in speed for different work zone features or objects in the multilane traces were plotted against distance of their placement with respect to start of work zone. The start of work zone or taper was regarded as the zero position and objects placed upstream and downstream are represented in negative and positive sign respectively. Some of the extreme points more than 20mph are removed from this plot for better visualization. As seen from the plot that the green dots signify reduction in speed due to any signs/objects located upstream or downstream of the work zones and the red dots signifies that increase in speed, both in the order of zero to 10mph. It was seen that there were small number of increase or reduction in speed more than 10 mph. Majority of the greater reductions are due to equipment and worker beyond a mile in the downstream portion.

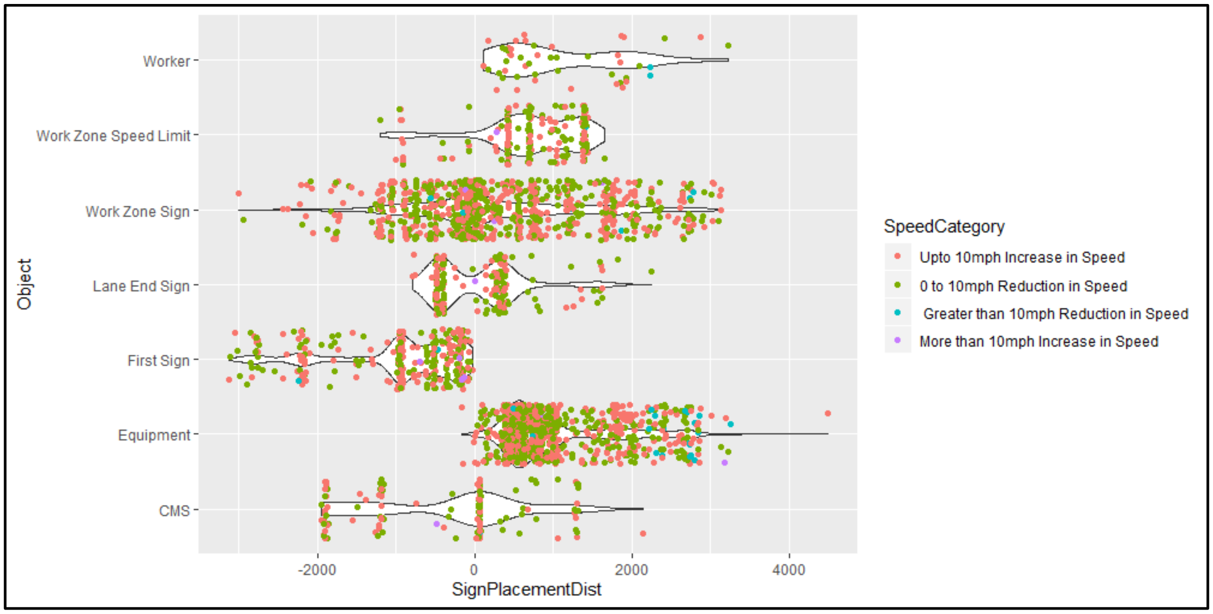


Figure 5-2 Change in Speed for Multilane Work Zone Features

5.2.1.2 Median

Change in speed in mph was plotted against the different median types in the upstream/advanced warning area of the traces. There were four types of median in the advanced warning area. Concrete, depressed median with and without barrier (guardrails mostly) and raised median. Figure 5 3 shows the change in speed for median types. From the figure majority of the traces had depressed median with barrier followed by raised medians, depressed grass median without barrier and concrete median. From the violin plots (which can be interpreted as boxplots) it was seen that there was not much difference among the median groups in variability of change in speeds. Greater reduction in speed of drivers were observed during presence of equipment and worker for raised median in a work zone.

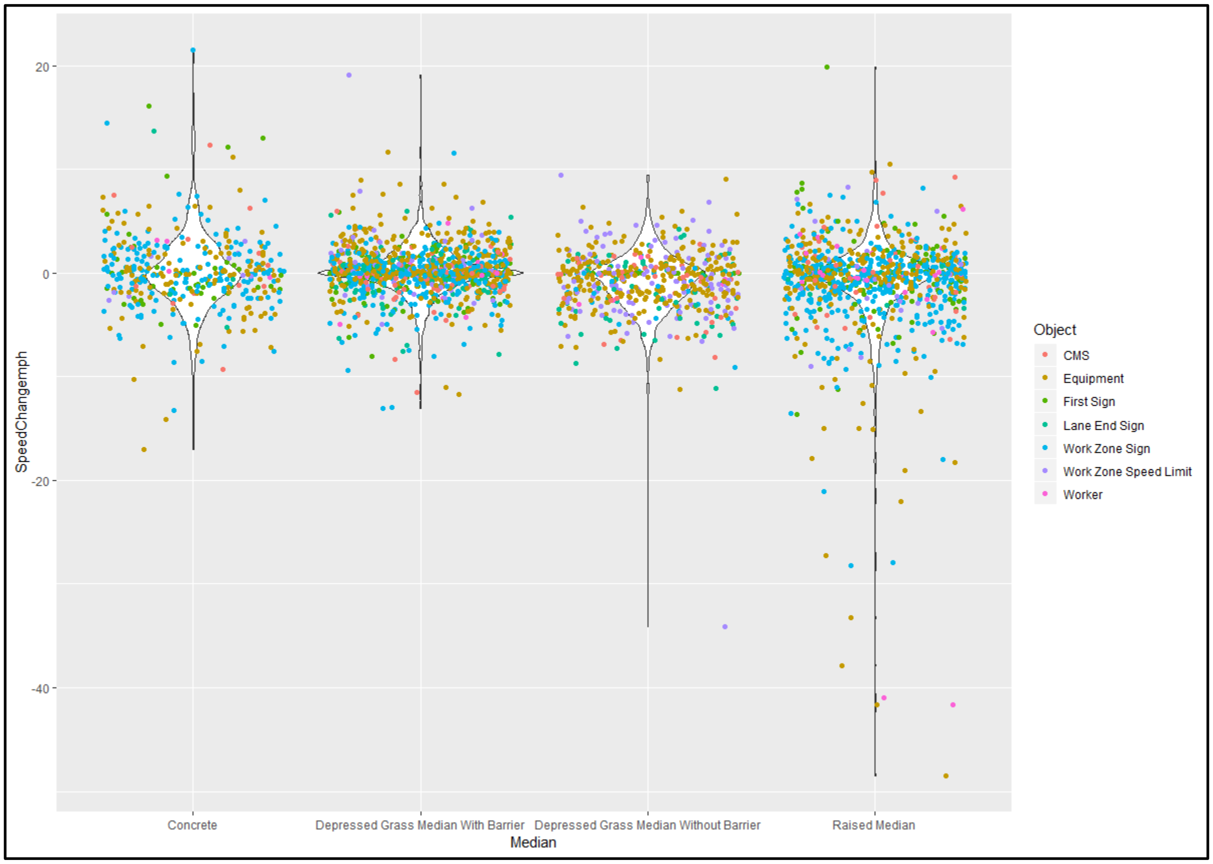


Figure 5-3 Change in Speed for Median Types

5.2.1.3 Channelizing device

Changes in speed were plotted against the presence of different channelizing devices in the work zone traces. It was seen that majority of the traces were provided with barrels and concrete in the work zone activity area followed by only barrels and only concrete respectively. There were few shoulder closure scenarios in the multilane roads with some minor construction work that used cones as channelizing device. The variation in change in speed is almost same for all the categories and some extreme values are observed in the presence of barrels but further investigation by overlaying the type of work zone feature or object that the drivers slowed down for showed that there were presence of equipment and worker.

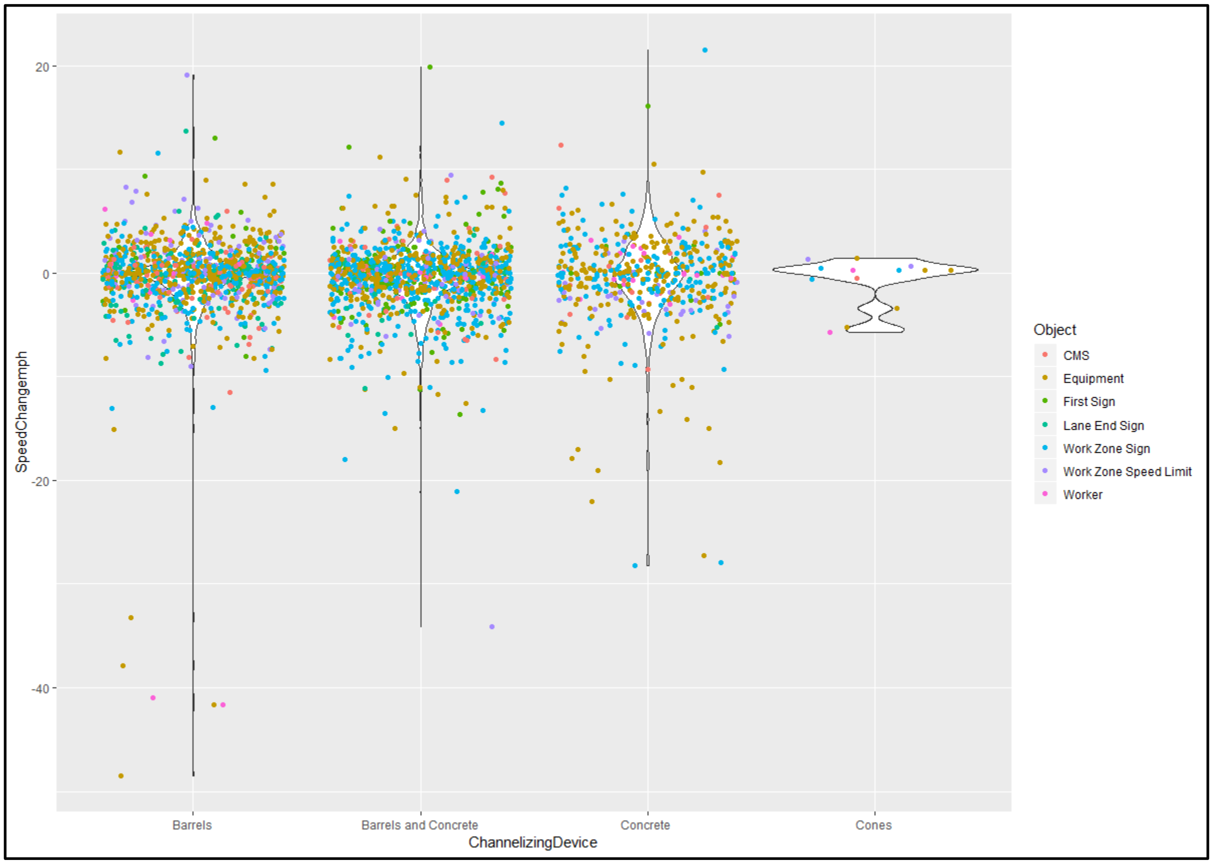


Figure 5-4 Change in Speed for Channelizing Devices

5.2.1.4 Driver demographics

As mentioned earlier, age was categorized into three groups, 24 and younger, 25 to 64 and older than 64. Change in speed was plotted for each of these groups against distance from the work zone. It was noticed that the younger than 24 group had more variation in change in speed when compared to the other two groups. It can be also seen that there was more observation for middle aged followed by older and younger drivers respectively. Also, it can be noticed that the younger and aged group have less variation for change in speed than middle age group (refer Figure 5-5). Change in speed was investigated between the genders. No considerable difference was observed among the two groups.

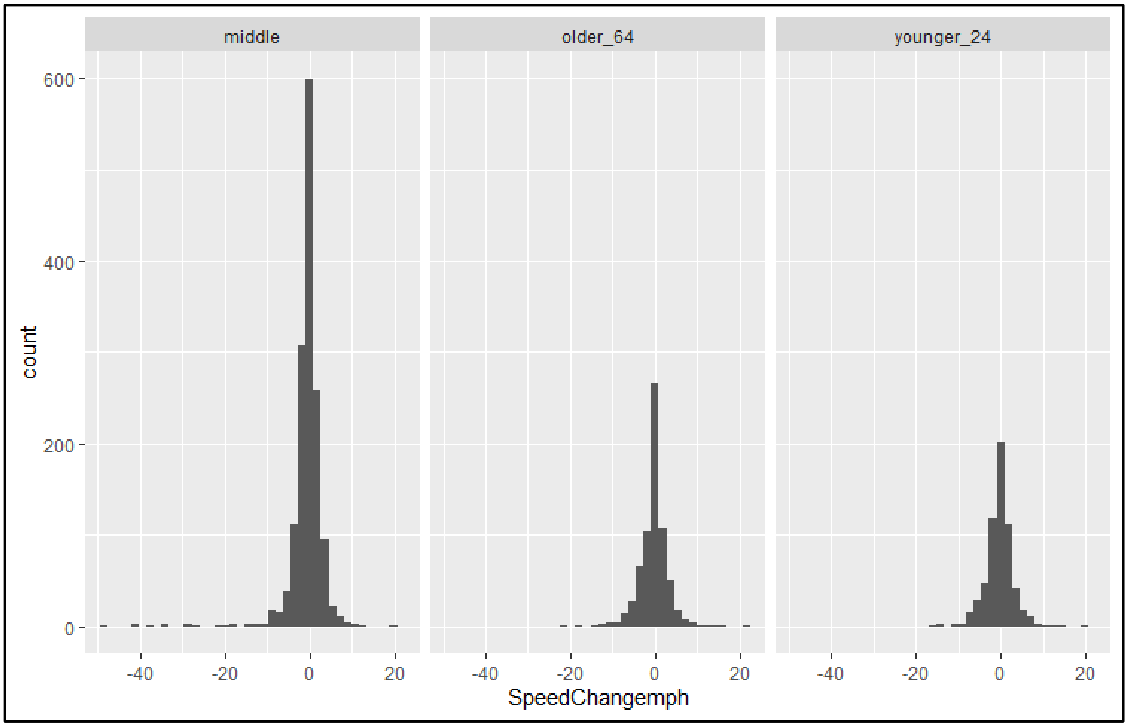


Figure 5-5 Change in Speed for Driver Age Groups

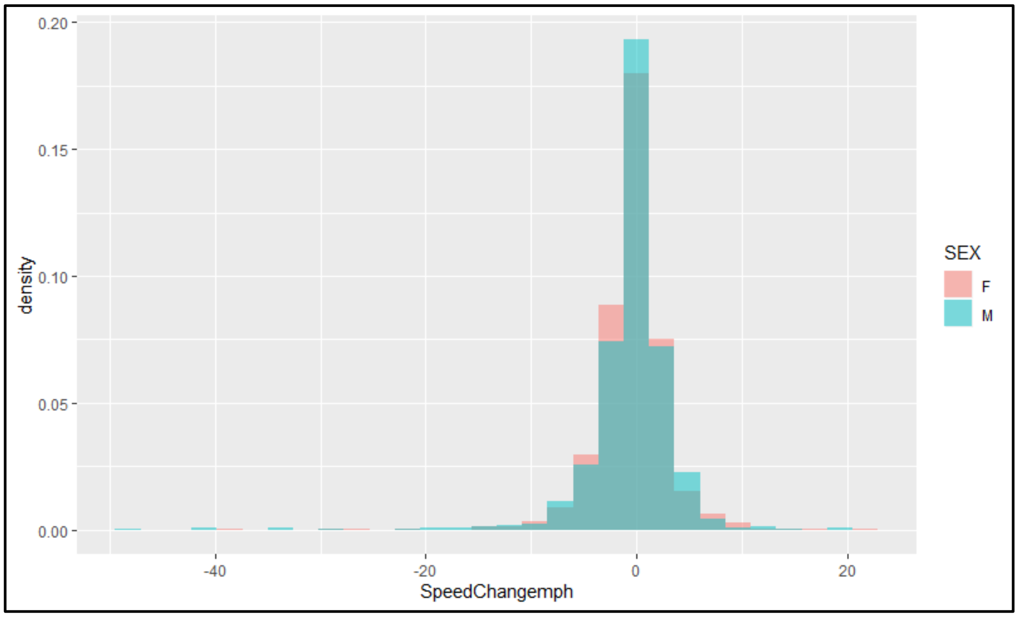


Figure 5-6 Change in Speed by Gender

5.2.1.5 Driver glance and distraction

A variable named as "Eyes off Road" indicated if drivers looked away from the road at any point of time during the legibility buffer (100m upstream and 50 m downstream of any object). Figure 5-7 shows the plot of change in speed for only those cases where the drivers had their eyes off the road or used cell phones or were engaged by any kind of distraction respectively from top to bottom. It was seen that drivers change in speed ranged for a reduction of 0 to 5 mph and an increase to 2.5 mph (for eyes off road) and 0 to 5 mph for cell phone use and any distraction scenarios.

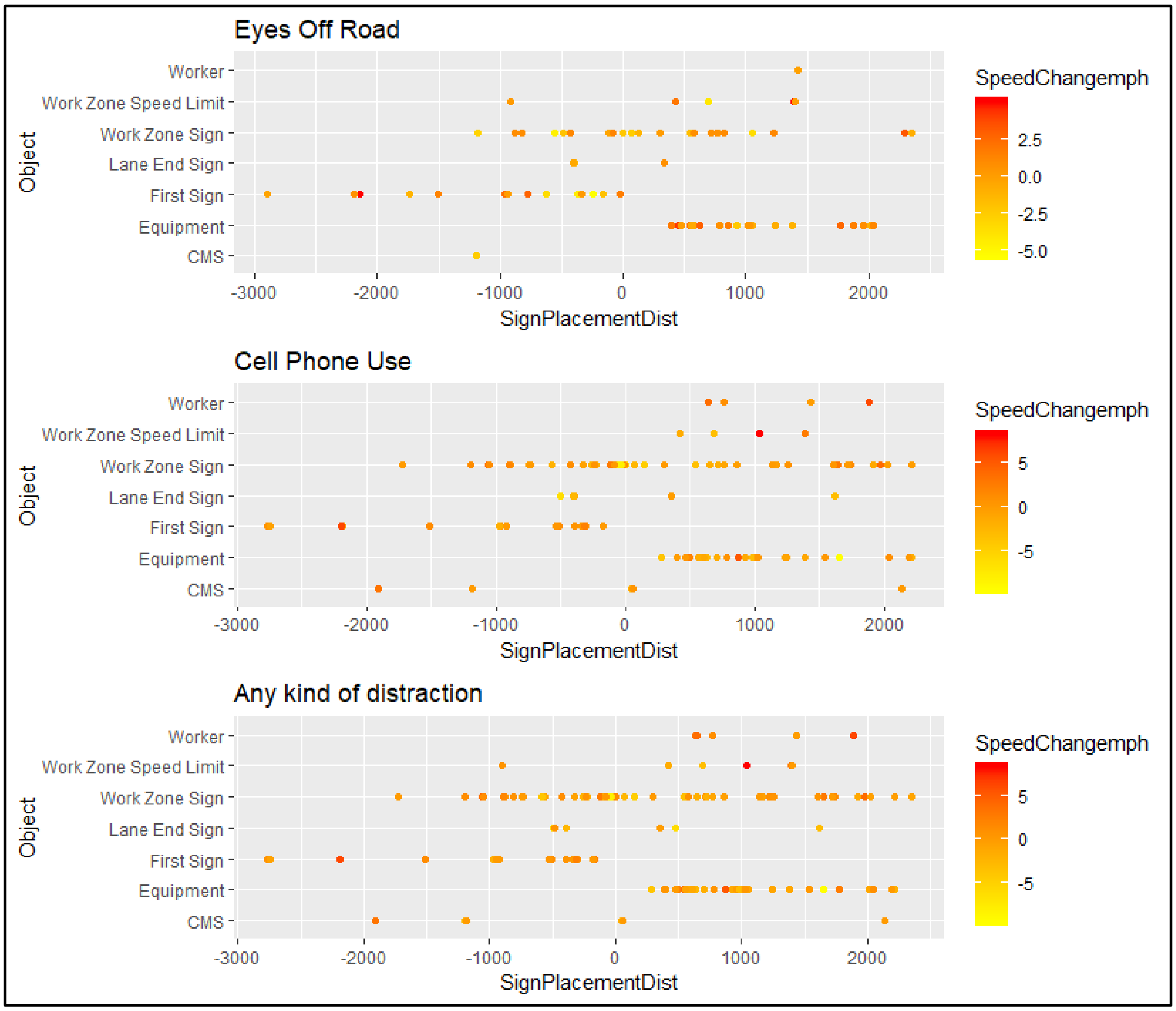


Figure 5-7 Change in Speed for only Eyes off Road Cases

Table 5-1 Descriptive statistics for Multilane Work zones

	Advanced warning area				Activity area			
Variables	**Mean**	**Std. Dev**	**Min**	**Max**	**Mean**	**Std. Dev**	**Min**	**Max**
Female	0.49	0.50	0.00	1.00	0.47	0.50	0.00	1.00
Twenty-Four Younger	0.26	0.44	0.00	1.00	0.19	0.39	0.00	1.00
Twenty-Five to Sixty Four	0.50	0.50	0.00	1.00	0.56	0.50	0.00	1.00
Sixty-Four Older	0.24	0.42	0.00	1.00	0.24	0.43	0.00	1.00
First Sign	0.34	0.47	0.00	1.00	0.00	0.00	0.00	0.00
CMS	0.06	0.23	0.00	1.00	0.05	0.23	0.00	1.00
Equipment	0.00	0.05	0.00	1.00	0.51	0.50	0.00	1.00
Lane End Sign	0.10	0.30	0.00	1.00	0.06	0.24	0.00	1.00
Work Zone Sign	0.47	0.50	0.00	1.00	0.25	0.43	0.00	1.00
Work Zone Speed Limit	0.02	0.15	0.00	1.00	0.10	0.30	0.00	1.00
Worker	0.00	0.00	0.00	0.00	0.03	0.16	0.00	1.00
Only Shoulder Closure	0.73	0.45	0.00	1.00	0.59	0.49	0.00	1.00
Both Shoulder closure	0.34	0.47	0.00	1.00	0.32	0.47	0.00	1.00
Left Lane and Right Shoulder Closure	0.01	0.09	0.00	1.00	0.02	0.14	0.00	1.00
Left Lane Closure	0.25	0.44	0.00	1.00	0.36	0.48	0.00	1.00
Left shoulder closure	0.32	0.47	0.00	1.00	0.21	0.41	0.00	1.00
Right lane closure	0.01	0.09	0.00	1.00	0.03	0.18	0.00	1.00
Right shoulder closure	0.07	0.25	0.00	1.00	0.06	0.24	0.00	1.00
Object Placement Distance	-701.44	675.44	-3126.9	-2.50	977.2	727.91	0.00	4483.5
Eyes Off Road	0.03	0.17	0.00	1.00	0.02	0.15	0.00	1.00
Distracted	0.06	0.23	0.00	1.00	0.04	0.20	0.00	1.00
Cell Phone Use	0.05	0.22	0.00	1.00	0.03	0.18	0.00	1.00
Congestion Level	1.27	0.45	1.00	2.00	1.32	0.47	1.00	2.00
Speed Change mph	-0.37	3.01	-21.09	21.50	-0.48	4.24	-48.47	19.11
Speed Limit	0.72	6.32	0.00	60.00	6.31	18.78	0.00	70.00
Concrete Median	0.11	0.31	0.00	1.00	0.15	0.36	0.00	1.00
Depressed Grass Median with Barrier	0.46	0.50	0.00	1.00	0.32	0.47	0.00	1.00
Depressed Grass Median Without Barrier	0.07	0.26	0.00	1.00	0.26	0.44	0.00	1.00
Raised Median	0.36	0.48	0.00	1.00	0.27	0.45	0.00	1.00
Concrete Barrier Type	0.45	0.50	0.00	1.00	0.37	0.48	0.00	1.00
Guardrail Barrier Type	0.48	0.50	0.00	1.00	0.37	0.48	0.00	1.00
No Barrier	0.07	0.26	0.00	1.00	0.26	0.44	0.00	1.00
Glare Screen on Barrier	0.04	0.20	0.00	1.00	0.00	0.00	0.00	0.00
Barrel channelizing Device	0.29	0.45	0.00	1.00	0.49	0.50	0.00	1.00
Barrels and Concrete channelizing device	0.62	0.49	0.00	1.00	0.28	0.45	0.00	1.00
Concrete Channelizing device	0.09	0.28	0.00	1.00	0.23	0.42	0.00	1.00

Table 5-2 continued

	Advanced warning area				Activity area			
Variables	**Mean**	**Std. Dev**	**Min**	**Max**	**Mean**	**Std. Dev**	**Min**	**Max**
Cones Channelizing Device	0.00	0.00	0.00	0.00	0.01	0.08	0.00	1.00
Location of Channelization: Edge	0.09	0.29	0.00	1.00	0.31	0.46	0.00	1.00
Location of Channelization: Median	0.56	0.50	0.00	1.00	0.35	0.48	0.00	1.00
Location of Channelization: Median and Edge	0.35	0.48	0.00	1.00	0.34	0.47	0.00	1.00
Clear Cloudy	0.90	0.30	0.00	1.00	0.90	0.30	0.00	1.00
Rainy Foggy	0.08	0.27	0.00	1.00	0.00	0.06	0.00	1.00
Night	0.20	0.40	0.00	1.00	0.21	0.41	0.00	1.00
Day	0.80	0.40	0.00	1.00	0.79	0.41	0.00	1.00

5.2.1.6 Descriptive statistics of multilane data

Table 5-1 Descriptive statistics for Multilane Work zones for the upstream and downstream portions of the work zone. As mentioned in the previous chapter 4 the portion before the start of work zone was modeled separately from the portion after the start of work zone as the study wanted to capture the driver behavior when they approach and exit a work zone separately.

Variable like worker were present inside the work zone thus there were no observations of this variable in the upstream portion model. Additionally, an indicator variable designating shoulder closure only work zones shows that about 73% of the traces used in the study were shoulder closure only and the rest has any type of lane closure.

Median type showed that about 46% of the traces had depressed median with barrier followed by raised median. The barrier type of the medians with barrier were also recorded. Guardrails and concrete median both were equally distributed among the traces.

Type of channelization and its location was also recoded. It was seen that majority of the traces had both barrels and concrete as channelizing device. Weather and day/night conditions were also recoded, majority of the traces had clear weather. About 9% of traces has adverse weather conditions in the form of rainfall or fog. 20% of the traces recoded nighttime active work zones.

5.3 Results, conclusions and limitations

Two separate models for Multilane divided roads were developed using a linear mixed effects (LME) models, which account for some dependency in the observations. One models was developed for the advanced warning area and another model as developed for the activity area. In these two models, a random effect for trace was introduced to deal with the dependency of the observations from the same trace. The placement position or location of every object were calculated with respect to start of work zone as the zeroth point. Thus the positions in the upstream portion represented negative sign and the positions in the downstream portion represented positive sign. Moreover, the upstream and downstream portions were divided in to three portions to study the different between driver behavior way ahead/behind and in the vicinity of the start of work zone. The upstream portion was divided into: within half a mile upstream representing the objects located within half mile before the start of work zone; between half an mile and one mile upstream representing the objects located beyond half mile but within one mile distance before from the start of work zone; and the third portion represented any object which was located over one mile upstream. Similarly, the downstream portion was divided into three portions: within half a mile downstream representing the objects located within half mile after the start of work zone; between half an mile and one mile downstream representing the objects located beyond half mile but within one mile distance after from the start of work zone; and the third portion represented any object which was located over one mile downstream.

The models for the upstream and downstream portions include the variables described in Table 5-2. Furthermore, Table 5-2 shows the p-values for each one of the included variables in the two models; all the p-values are smaller than 0.1. Table 5-2 has some estimates which do not interact with other variables in the model. For these variables the estimates represent the change in speed in the presence of that object. Table 5-3 provides the parameter estimates of each of the statistically significant variables.

In the upstream model, rainy or foggy weather influences drivers to decrease their speed by 0.82 mph. With the increase in congestion level from 1 to 2 driver reduced their speed by 0.48mph. Presence of any kind of median reduced speed in the range of 0.26 mph to 1.12mph. Some estimates showed drivers not reducing their speed. For example, presence of glare screen on medians did influence drivers to reduce their speed in the upstream model. Finally, for the upstream model the estimate of the between traces standard deviation (σ_u) is 1.132 and the estimate of the within traces standard deviation (σ_ϵ) is 2.671. For the downstream model, the estimate of the between traces standard deviation (σ_u) is 1.813 and the estimate of the within traces standard deviation (σ_ϵ) is 3.710.

Table 5-3 Anova Table for Multilane Models

Upstream					**Downstream**				
	Chisq	**Df**	**Pr(>Chisq)**			Chisq	Df	Pr(>Chisq)	
Object	15.27	5	0.01	**	**Object**	15.62	5	0.01	**
location	17.46	2	0.00	***	**location**	19.19	2	0.00	***
Weather	4.96	1	0.03	*					
Median	12.48	3	0.01	**					
Glare Screen	3.20	1	0.07	.					
Congestion Level	3.80	1	0.05	.					
Object: location	27.53	5	0.00	***	**Object: location**	26.82	5	0.00	***

Table 5-4 Parameter estimates of the multilane models

Advanced Warning Area Model			
Variables	**Estimates**	**Std. Errors**	**t-values**
(Intercept)	0.984	0.771	1.275
Equipment	-0.078	2.005	-0.039
First Sign	-0.249	0.637	-0.391
Lane End Sign	-0.055	1.199	-0.046
Work Zone Sign	1.127	0.665	1.695
Work Zone Speed Limit	0.275	0.933	0.295
Within half mile upstream	0.010	1.298	0.008
Over one mile upstream	1.690	0.827	2.043
Rainy / Foggy	-0.823	0.369	-2.228
Depressed Grass Median with Barrier	-0.256	0.423	-0.606
Depressed Grass Median without Barrier	-0.441	0.566	-0.779
Raised Median	-1.118	0.428	-2.610
Glare Screen	1.238	0.692	1.790
Congestion Level	-0.478	0.245	-1.949
First Sign * Within half mile upstream	0.530	1.349	0.393
First Sign * over one mile upstream	-0.663	0.936	-0.709
Work Zone Sign * Within half mile upstream	-2.144	1.339	-1.601
Work Zone Sign * over one mile upstream	-2.613	1.094	-2.387
Work Zone Speed Limit * Within half mile upstream	-0.577	1.707	-0.338
Activity Area Model			
Variables	**Estimates**	**Std. Errors**	**t-values**
(Intercept)	-0.7174	0.5766	-1.244
Equipment	0.5419	0.4708	1.151
Work Zone Sign	0.3475	0.5415	0.642
Work Zone Speed Limit	0.5454	0.5784	0.943
Worker	0.853	0.8734	0.977
Between half and one mile downstream	0.6414	1.1588	0.554
Over one mile downstream	1.2521	3.944	0.317
Work Zone Sign * Between half and one mile downstream	-1.3253	1.2615	-1.051
Work Zone Sign * over one mile downstream	-0.3881	3.9657	-0.098
Work Zone Speed Limit * Between half and one mile downstream	0.217	1.2779	0.17
Work Zone Speed Limit * over one mile downstream	-0.5524	5.5575	-0.099
Equipment * Between half and one mile downstream	0.1839	1.204	0.153
Equipment * over one mile downstream	-1.7899	3.9543	-0.453
Worker * Between half and one mile downstream	-0.5678	2.0999	-0.27
Worker * over one mile downstream	-3.8036	4.1284	-0.921

The interaction between work zone speed limit sign and channelizing device is presented in Table 5-4. The upstream model includes three interactions, between first sign, work zone signs and work zone speed limit sign and the variable location. The Between half and one-mile upstream category was taken as base in the model. The downstream model includes five interactions, between first sign, work zone signs and work zone speed limit sign, lane end sign, worker and equipment and location. The Within half mile downstream category in the location variable was taken as base. The cells were computed with the appropriate linear combinations from coefficients in Table 5-3. For example, the effect of first sign within half mile upstream was obtained by, (-0.25+0.53= 0.28 mph).

Table 5-5 Interactions for Multilane Models

Upstream			
Interaction between Objects and location	**Within half mile upstream**	**Between half and one mile upstream**	**Over one mile upstream**
Object: First Sign	0.28	-0.25	-0.91
Object: Work Zone Sign	-1.02	1.13	-1.49
Object: Work Zone Speed Limit	-0.30	0.28	0.28
Interaction between Objects and location	**Within half mile downstream**	**Between half and one mile downstream**	**Over one mile downstream**
Downstream			
Object: Work Zone Sign	0.35	-0.98	-0.04
Object: Work Zone Speed Limit	0.55	0.76	-0.01
Object: Lane end sign	-0.56	-1.34	-1.63
Object: Worker	0.85	0.29	-2.95
Object: Equipment	0.54	0.73	-1.25

In conclusion, the interaction in linear mixed effects model results for the multilane work zones indicate the following:

- Work Zone Signs are effective in two sections of the upstream portions as well as beyond half a mile downstream of start of work zone.
- Work Zone Speed Limit Signs are effective when placed within half mile upstream.
- Lane end sign are effective in all the sections of locations in the downstream model. Some lane end signs are inside the work zone as the first part of the work

zone may be a shoulder closure to some distance and then there can be a lane closure, so the lane end sign was placed somewhere inside the work zone. The lane end signs reduced speed in the range from 0.56 mph to 1.63 mph.

- Drivers reduced speed due to presence of any worker or equipment inside the work zone, mostly after a mile inside the work zone. This may be since the equipment and workers were positioned more than a mile inside the work zone for many of the traces. Drivers reduced speed in the range of 1.25 mph to 2.95 mph.

CHAPTER 6. DRIVERS' LANE MERGE BEHAVIOR IN WORK ZONES WITH LANE CLOSURE

This chapter focusses on driver's lane change behavior in work zones with lane closure on four lane divided work zones. Section 6.1 introduces to the objectives of the study. Section 6.2 discusses background and previous work on this subject. Section 6.3 highlights the data collection, reduction and final data descriptive. Section 6.4 provided the statistical methodology used for the study. Section 6.5 discusses the results, conclusions and limitations of the study.

6.1 Objectives

Closing a lane or even a shoulder of a road segment in a work zone may cause disruptions in traffic flow, which can result in travel delays and increased travel times due to reduced capacity. Work zones can become points of congestion that can lead to driver frustration and aggressive driver behavior. In work-zone configurations where lane drops are present, merging of traffic at the taper presents an operational concern. In addition, as flow through the work zone is reduced, the relative traffic safety of the work zone is also reduced as there is higher risk of rear end crashes. Improving work-zone flow-through merge points depends on the behavior of individual drivers. By better understanding driver behavior, in terms of when and why they merge with respect to the merge point (start of work zone), traffic control plans, work-zone policies, and countermeasures can be better targeted to improve safety and work-zone capacity. A better understanding of the merging behavior of drivers will lead to the development of better lane-drop traffic-control plans and strategies, which will provide better guidance to drivers for safer merging (Hallmark et al., 2015).

To accomplish this goal, the objectives of this effort were as follows: Identify work-zone traces with drivers merging to open lane from closed lane. Relevant work zone warning signs and countermeasures were recorded. Develop models for distance of merging from start of work zone.

6.2 Background

The vehicles upstream of the closed lane must merge with traffic on the unclosed lane when they approach the work zone. Compared with common merging circumstances they are familiar with, such as highway ramps and interchanges, drivers' responses to lane drop at work zones can be uncertain. Some drivers may conduct discretionary lane changes upstream of the lane drop site, while others might travel a longer distance to find preferred merging locations, or even wait until the last minute to do so. Lane closures in work zones require drivers in the closing lane to merge into to the adjacent through lane before they enter the work zone area. The drivers' merging behavior in the work zone merging area can be characterized by the distance of driver from the start of the work zone where drivers cross the center line to consider merging.

With increased seasonal traffic volume, work zones become points of congestion that can lead to driver frustration and aggressive driver behavior (Hallmark et al., 2015). Aggressive driving is often a safety and efficiency concerns at work zones. Aggressive driving may occur at work zone lane closures. Some drivers may vacate the closed lane as soon as possible and some may stay in the closed lane as long as possible to avoid waiting in the queue. Having both kinds of drivers in the same facility, may result in confusion, sometimes resulting in aggressive driving.

Several studies have focused on methods to improve merging operations at work zones. The early merge and late merge concepts are the two methods in literature to alleviate safety and capacity concerns at work zones. Each strategy is designed to improve merging operations at lane closures associated with work zones.

Hallmark et al. (2015) studied merging behavior at lane drops. They concluded that early-merge scenario was characterized by more consistent speeds and reduced both queue lengths and queue stop. It made merging smoother and decreased speeds upstream more and pushed the queue farther away from the merge point. Overall, both the early-merge and late-merge strategies were found to improve operations and to smooth flow at the merge points in the work zone. Queue lengths were decreased in both situations. The early merge was found to be a better option for moderate congestion. If vehicles increased, however, this option could result in longer queues.

Hallmark et al. (2011) investigated driver behavior of merge practices for drivers at work zone closures. They collected data at freeway work zones for six days to identify behaviors that affected work zone safety and operations, which included forced and late merges, lane straddling, and queue jumping. This study identified behaviors that can compromise safety in work zones. Forced merges were associated with safety problems, because a driver behind a forced merge must slow or, in some cases, take some evasive action to avoid colliding with the merging vehicle. Queue jumping also compromises safety, because it creates forced merges and often resulted, in this study, in aggressive actions by other drivers.

Weng et al. (2010) characterized merging behavior at work zone merging areas using two models. First, the desired merging location of drivers starting to consider merging and second, the probability of a driver successfully merging into the current adjacent gap. A logit model was developed in order to determine the merging probability. Work zone traffic data from Singapore were used to calibrate the proposed models. The results showed that the speed-flow relationship in the through lane is affected by the merge lane traffic under uncongested conditions. The satisfactory results showed that the proposed merging behavioral models predict drivers' real-life merging behavior well and that the merging distance model could provide accurate information for traffic engineers.

Weng et al (2017) investigated the drivers' merging behavior in work zone merging areas during the entire merging implementation period from the time of starting a merging maneuver to that of completing the maneuver. They proposed a time-dependent logistic regression model considering the possible time-varying effects of influencing factors, and a standard logistic regression model for model comparison. Model comparison results showed that the time-dependent model performs better than the standard model because the former can provide higher prediction accuracy. The time- dependent model results showed merging vehicle speed, through lane lead vehicle speed and through lane lag vehicle speed, longitudinal gap between the merging and lead vehicles, longitudinal gap between the merging and through lane lead vehicles, types of through lane lead and through lane lag vehicles exhibit time-varying effects. Interestingly, both the through lane lead vehicle speed and the through lane lag vehicle speed are found to exhibit heterogeneous effects at different times of the merging

Implementation period. Also merging vehicle has a decreasing willingness to take the choice of "complete a merging maneuver" if the through lane lead vehicle is a heavy vehicle.

Li and Zhang studied merging vehicles and lane speed flow relationships in a work zone. The study mainly investigated the spatial distribution of drivers' merging behaviors along work zones from a macroscopic perspective. It was found that drivers' merging choices vary with cross-sectional flow, average lane speed, and drivers' distances to the work zone. Lane speed-flow relationships at different locations of the work zone were analyzed. The researchers found that merge-lane traffic presents different speed-flow relationships with that of other lanes. The results showed median- and inside-lane traffic suffers capacity drop due to influence of vehicle insertions. It was also found that more merging behaviors occurring at some locations could make it more difficult for lane traffic to recover from congestion.

Idewu and Wolshon et al. (2010) discussed the development of the joint merge or alternating merge patterns to examine its effects on traffic flow. The joint merge involves a two-sided taper in which both approach lanes are reduced simultaneously into a single lane, thereby eliminating an assigned lane priority. Results showed that merging speeds were found to be similar at volumes ranging from 600 to 1,200 vehicles per hour and did not affect the discharge rate at the merge outflow point. Also, they concluded that drivers were more cautious in their merging maneuvers as joint merge produced a more evenly balanced lane volume at the transition zone entrance.

Several other studies have conducted micro-simulations to assess work-zone merge strategies. McCoy et al. (1999) used FRESSIM for the operational effects of the Indian Lane Merge (early merge) compared to no merge control strategy, as well as a constant half-mile no-passing zone in advance of the work zone. Beacher et al. (2004) used VISSIM to compare MUTCD treatments to the late-merge strategy using throughput volume as a measure of effectiveness. Zaidi et al. (2013) used VISSIM to evaluate dynamic merge systems. A two-to-one work-zone lane closure was modeled. Conventional work-zone planes were modeled along with dynamic early- and late-merging systems. Variable speed limits were also modeled.

6.3 Description of data

A merge was defined as a driver moving from an adjacent lane which is closing ahead into the open lane. If a driver moved lanes several times, only the final move into the open lane was included. The study focused on lane change behavior on four lane divided work zones. Among the 343 traces coded in chapter 4 for four lane divided work zones, about 115 traces had drivers merging to the adjacent lane due to lane closure ahead. Other drivers were already travelling in the open lane, so they were not included in this study.

6.3.1 The study design

A lane merge was defined as a driver crossing the center line from the closing lane into the open lane. The dependent variable is the vehicle distance from the start of work zone/taper point when the merge occurs. Most of the drivers merged before the static lane merge sign. They may either merge due to observing other temporary traffic control signs or the static lane merge sign. All the static lane merge signs were placed within 500 m from the start of work zone. A typical lane merge sign would be the W4-2 sign.

Figure 6-1 Lane Merge Sign W4-2

As pointed out by Li and Zhang (2018) that traffic oscillations arising at lane-drop sites derive from merging vehicles and the oscillatory patterns could be affected by travel demand, roadway geometry, merging frequency, and driver characteristics. The uncertainty of drivers' choices on merging locations upstream of lane-dropped sites, could aggravate the influence of traffic oscillations on segment capacity. A reasonable interpretation proposed by

Zhang and Shen (2009) could connect merging behaviors and traffic oscillations at the lane drop site.

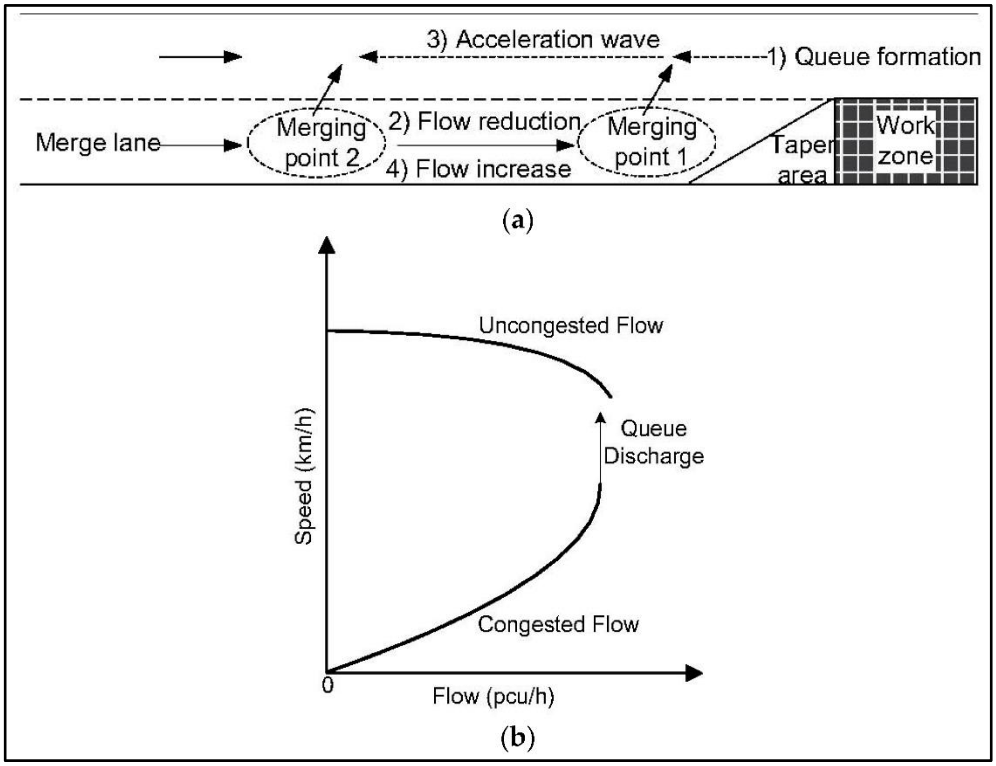


Figure 6-2 Traffic oscillations at work zone merge areas

As noted in Figure 6-2, at first, since the lane drop site is a physical bottleneck of the segment, the vehicles on the merging lane inserting at merging point 1 close to the taper generate a queue on the through lane. Next, when such a queue spills back to the upstream location parallel to merging point 2, merging into the remaining through lanes becomes harder because of the increased density on the through lanes. Drivers attempting to merge at this location must slow down to find acceptable inserting gaps nearby, thus blocking the vehicles that intend to merge at merging point 1. Thus, the merge-lane flow downstream of merging point 2 declines. Third, since fewer vehicles merge at point 1, more vehicles on the through lane can be discharged, which lowers the density of through-lane traffic and generates an acceleration wave traveling upstream along the through lane. Finally, when the acceleration wave reaches point 2, the density reduction of through-lane traffic there allows for more vehicles on the merge lane to insert. Hence, more vehicles intending to merge at point 1 can enter the downstream segment to accomplish implementing their intentions, which will launch a new round of oscillation. Due to these reasons, this study considered late merge or merging after the start of taper of a work zone to be unsafe.

The taper length is calculated by Table 6H-4 in MUTCD (refer which suggests an equation that involves width of the offset and posted speed limit. This study calculated distance of lane merge from the start of taper. The distance between that start of taper and end of taper is (L+A/2). For this study the length L was determined to be approximately 500 feet using 9 feet as average offset width and 55mph as the average posted speed limit for this study. As the study was conducted on mainly freeways, the value of Spacing "A" was chosen to be 1000 feet. Thus, the length of taper (L+A/2) = 500 +1000/2 = 500 feet which is approximately 300m. Thus, 300m was added to all the distance of lane merge in the study, thus the study analyzed distance of lane merge from the end of taper.

6.3.2 Description of variables

A total of 115 traces from the analysis were available where the driver was in the closing lane and were utilized in this analysis. Many of the existing variables (Chapter 3) were also utilized. Several other variables relevant to lane merge behavior were also coded or reduced or obtained as part of this study. Variables like presence of lead vehicle in the same lane, presence of lead and rear accommodating vehicles in the other lane that the driver wish to merge were coded manually. All of the 47 variables were double checked as part of quality assurance and quality control of the data used for the study using forward videos, driver key and time series files provided by VTTI. Times series traces from congestion levels

1 and 2 were only considered. Congestion level 1 suggested no congestion in the traces, congestion level 2 designated moderately congested traces but the driver did not stop at any point due to the congestion in the traces. Congestion level 3 had congestion in the traces and thus were not considered in the analysis.

As described above the dependent variable was a discrete variable with three levels of safety assigned to lane merge behavior based on merging distance from the start of work zone. There were 75 cases of safe merge (early merge before the static lane merge sign) in the dataset of 115 observations. There were 24 cases of moderately safe merging behavior (merged after the static work zone sign but after the start of work zone) and finally 16 cases of unsafe merge behavior (merges after start of taper). The descriptive statistics of the variables that were included in the models are provided in Table 6-1.

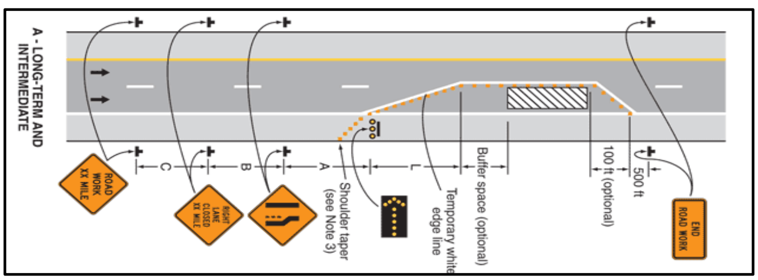


Table 6H-3. Meaning of Letter Codes on Typical Application Diagrams

Road Type	Distance Between Signs**		
	A	B	C
Urban (low speed)*	100 feet	100 feet	100 feet
Urban (high speed)*	350 feet	350 feet	350 feet
Rural	500 feet	500 feet	500 feet
Expressway / Freeway	1,000 feet	1,500 feet	2,640 feet

Table 6H-4. Formulas for Determining Taper Length

Speed (S)	Taper Length (L) in feet
40 mph or less	$L = WS^2 / 60$
45 mph or more	$L = WS$

Where:

- L = taper length in feet
- W = width of offset in feet
- S = posted speed limit, or off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph

Figure 6-3 Calculation of length of Taper

Table 6-1 Descriptive Statistics for Lane Merge Data

Variables	Description	Mean	Std. dev	Min	Max
Female	1 if the participant was female, 0 otherwise	0.59	0.49	0.00	1.00
Twenty-four younger	1 if the participant was younger than 24, 0 otherwise	0.12	0.32	0.00	1.00
Twenty-five to sixty-four	1 if the participant was between 25 to 64, 0 otherwise	0.69	0.46	0.00	1.00
Above sixty-four	1 if the participant was older than 64 years	0.18	0.39	0.00	1.00
Car	1 if the participant vehicle is a car, 0 otherwise	0.67	0.47	0.00	1.00
Pickup truck/ van/ minivan	1 if the participant vehicle is a pickup truck or minivan, 0 otherwise	0.09	0.29	0.00	1.00
SUV / crossover	1 if the participant vehicle is a SUV, 0 otherwise	0.24	0.43	0.00	1.00
Distance of lane merge (in meters)	Dependent variable, distance of lane merge in m	-789.96	1018.65	-9735.89	208.76
Speed in mps	Speed of vehicle at the lane merge point	27.58	2.59	21.77	35.64
Presence of lead vehicle	1 if lead vehicle is present in the same lane of the driver when crossing centerline, 0 otherwise.	0.39	0.49	0.00	1.00
Presence of lead accommodating vehicle	1 if lead vehicle is present in the lane to which driver wants to merge when crossing centerline, 0 otherwise.	0.55	0.50	0.00	1.00
Presence of rear accommodating vehicle	1 if rear vehicle is present in the lane to which driver wants to merge when crossing centerline, 0 otherwise.	0.39	0.49	0.00	1.00
Right to left	1 if driver merges from right to left, zero other wise	0.48	0.50	0.00	1.00
Left to right	1 if driver merges from left to right, zero other wise	0.52	0.50	0.00	1.00
Distance of first sign	Distance of first sign in meters from the start of work zone	-1916.20	1230.67	-10143.56	-294.93
Day	1 if daytime, 0 otherwise	0.85	0.36	0.00	1.00
Night	1 if Nighttime, 0 otherwise	0.12	0.33	0.00	1.00
Dusk dawn	1 if Dusk/dawn, 0 otherwise	0.03	0.17	0.00	1.00
Clear/cloudy	1 if weather is clear/cloudy, 0 otherwise	0.90	0.30	0.00	1.00
Rainy	1 if weather is Rainy, 0 otherwise	0.10	0.30	0.00	1.00
Depressed grass median without barrier	1 if the median type is depressed median without barrier, 0 otherwise.	0.57	0.50	0.00	1.00
Depressed grass median with barrier	1 if the median type is depressed median with barrier, 0 otherwise.	0.34	0.47	0.00	1.00
Concrete Median	1 if the median type is concrete, 0 otherwise.	0.10	0.30	0.00	1.00
New York	1 if State is New York, 0 otherwise	0.35	0.48	0.00	1.00
Pennsylvania	1 if State is Pennsylvania, 0 otherwise	0.64	0.48	0.00	1.00
Not congested	1 if roadway is not congested at all, 0 otherwise	0.84	0.37	0.00	1.00
Moderately congested	1 if moderately congested roadway, 0 otherwise	0.16	0.37	0.00	1.00

Table 6-1 continued

Variables	Description	Mean	Std. dev	Min	Max
Head to head	1 if work zone configuration was head to head, 0 otherwise	0.49	0.50	0.00	1.00
Lane closure	1 if work zone configuration was lane closure type, 0 otherwise	0.51	0.50	0.00	1.00
Barrels	1 if barrels are present as channelizing device, 0 otherwise	0.58	0.49	0.00	1.00
Concrete	1 if Concrete is present as channelizing device, 0 otherwise	0.05	0.22	0.00	1.00
Cones	1 if Cone is present as channelizing device, 0 otherwise	0.05	0.21	0.00	1.00
Vertical panels	1 if channelizing device was Vertical Panels, 0 otherwise	0.32	0.47	0.00	1.00
Not forward related	1 if driver glance was not forward related, 0 otherwise	0.17	0.37	0.00	1.00
Cell phone	1 if driver glance was on cell phone at any time before lane change, 0 otherwise	0.14	0.36	0.00	1.00
Distracted	1 if the participant was distracted at any time before lane change, 0 otherwise	0.35	0.48	0.00	1.00
Arrow CMS	1 if driver saw Arrow CMS before merging, 0 otherwise	0.55	0.50	0.00	1.00
LMS	1 if driver saw LMS before merging, 0 otherwise	0.59	0.49	0.00	1.00
Other CMS	1 if driver saw other CMS before merging, 0 otherwise	0.50	0.50	0.00	1.00
Police patrol	1 if driver saw Police Patrol before merging, 0 otherwise	0.01	0.09	0.00	1.00
Overhead CMS	1 if driver saw Overhead CMS before merging, 0 otherwise	0.14	0.35	0.00	1.00
Speed Feedback	1 if driver saw Speed feedback before merging, 0 otherwise	0.29	0.45	0.00	1.00
Number of Enforcement Sign	Number of Enforcement sign before merging	0.67	0.59	0.00	2.00
Enforcement Sign	1 if driver saw Enforcement sign before merging, 0 otherwise	0.61	0.49	0.00	1.00
Number of Normal Speed Limit Sign	Number of Normal Speed Limit Sign before merging	0.37	0.54	0.00	3.00
Normal Speed Limit Sign	1 if driver saw Normal Speed Limit Sign before merging, 0 otherwise	0.36	0.48	0.00	1.00
Number of Work Zone Speed Limit	Number of Work Zone Speed Limit Sign before merging	1.09	0.79	0.00	4.00
Work Zone Speed Limit	1 if driver saw Work Zone Speed Limit Sign before merging, 0 otherwise	0.83	0.38	0.00	1.00
Number of Static Work Zone Sign	Number of Static Work Zone Sign before merging	1.50	1.25	0.00	6.00
Static Work Zone Sign	1 if driver saw Static Work Zone Sign before merging, 0 otherwise	0.83	0.38	0.00	1.00

6.4 Results

Each row represents one driver through one work zone. A lane merge model was developed to determine which characteristics were associated with lane merge distance. A linear mixed effect model as described in chapter 4 was developed to assess the effect of work zone signs and characteristics on driver lane merge distance. The results from the model are presented in Table 6-2. Presence of rear accommodating vehicle tends to increase distance of lane merge from the end of taper. Thus, the drivers tend to merge early in a lane closure scenario in a four-lane divided (farther from work zone activity area). Similarly, presence of enforcement sign before merging, tends to increase distance of lane merge from the end of taper showing that the drivers merge early in a lane closure scenario in a four-lane divided. Non-forward related glance was associated with drivers merging early in a lane closure scenario in a four-lane divided. The study also showed that driver moving over to left from right lane closure were choosing to merge early than when they were moving from right lane closure to left lane. This phenomenon cannot be fully justified as the sample size of this study was small. Head to head configuration was associated with drivers merging late.

Influence of distraction and cell phone use was seen on drivers' lane change behavior. Though distraction and cell phone use didn't come out to be significant on its own in the models. When drivers were distracted, the arrowhead CMS sign was not seen to be effective, meaning that the drivers did not choose to merge early in work zones lane closure scenario. The drivers merged later closer to the taper that is activity area. Similarly, when they were distracted by cell phone, the normal speed limit signs were not effective to influence the drivers to merge early for a lane closure ahead scenario. The interaction terms are also provided at the end of Table 6-2. However, it should be noted that the drivers were not seen to choose an earlier merge distance when not distracted or when they were not using cell phones during the presence of arrow CMS and normal speed limit signs.

Table 6-2 Results of Lane Merge Model

Variables	Estimate	Std. Err	t values	Pr(>|t|)		Direction	Result
(Intercept)	2131.13	390.46	5.458	1.62E-06	***		
Presence of Rear Accommodating Vehicle	310.7	145.01	2.143	0.03589	*	increases distance	Drivers tend to merge early (farther from start of taper)
Head to Head Configuration	-349.27	188.8	-1.85	0.07153	.	decreases distance	Drivers tend to merge later (closer to start of taper)
Enforcement Sign	167.95	309.41	0.543	0.58857		increases distance	Drivers tend to merge early (farther from start of taper)
Merging from right to left	524.23	230.31	2.276	0.02535	*	increases distance	Drivers tend to merge early (farther from start of taper)
Not Forward Related	348.13	194.24	1.792	0.08066	.	increases distance	Drivers tend to merge early (farther from start of taper)
Distracted	-577.63	289.08	-1.998	0.04937	*		
Cell Phone	598.09	253.49	2.359	0.02096	*		
Arrow CMS * Not Distracted	-708.4	218.91	-3.236	0.00188	**	decreases distance	Drivers tend to merge later (closer to start of taper)
Arrow CMS * Distracted	525.22	311.54	1.686	0.09585	.	decreases distance	Drivers tend to merge later (closer to start of taper)
Normal Speed Limit Sign *No Cell phone	-543.49	270.35	-2.01	0.04737	*		
Normal Speed Limit Sign * Cell Phone	-1278.19	412.63	-3.098	0.00288	**	decreases distance	Drivers tend to merge later (closer to start of taper)

Interactions			
Arrow CMS * Not Distracted	-708.4	decreases distance	Drivers tend to merge later (closer to start of taper)
Arrow CMS * Distracted	-183.18	decreases distance	Drivers tend to merge later (closer to start of taper)
Normal Speed Limit Sign *No Cell phone	-543.49	decreases distance	Drivers tend to merge later (closer to start of taper)
Normal Speed Limit Sign * Cell Phone	-1821.68	decreases distance	Drivers tend to merge later (closer to start of taper)

CHAPTER 7. SUMMARY

This chapter reviewed the main findings from this dissertation in Section 7.1 and further discussed the implications for future research in Section 7.2.

7.1 Summary of major findings

The goal of this research is to investigate work zone safety using the unique SHRP 2 data. The main purpose of the project is to identify safe driving behavior and reduce work zone crashes. Thus, it was necessary to observe how drivers change speed in relationship to various work zone characteristics. It is assumed that reduction in speed has a positive safety benefit especially in work zones. Further the study was extended to investigate driver's merge behavior for work zones that involved lane closure. Chapter 4 addresses research objective of development of a conceptual model which answered what work zone characteristics cause drivers to change speed (more importantly reduced speed) in work zones on four-lane divided highways. Chapter 5 is an extension of chapter 4 addressing the same objective of evaluation of driver's change in speed due to work zone characteristics on multilane divided highways. Chapter 6 addresses the research objective to answer how upstream signing/countermeasures impact lane change behavior of drivers in lane closure scenario in work zones.

The research team manually coded the locations of work zone features starting from first work-zone sign to the end of work-zone. The change in speed from a point upstream of the legibility distance of each work zone feature was compared to the speed just past the feature. Driver distraction and eye glance were also included. Linear mixed effects model was used to predict drivers' change in speed in the work zone in advanced warning area and activity area separately.

For work zones on four-lane divided highways, speed feedback signs, lane end sign, and changeable message signs were found to be effective in reducing driver speed before the merge point. Non-forward related glance was seen to increase driver speed inside the work zone. Work zone speed limit signs were seen to be more effective within half mile inside a work zone. Presence of static work zone signs were more effective when the cones were placed as channelizing device inside the work zone. Vertical panels as channelizing device were used to decrease driver speed more effectively compared to concrete and cones. The change in speed model for multilane work zones showed static work zone signs to be effective in the upstream portion of start of taper of a work zone. Work zone speed limit signs are effective when placed within half mile upstream. Lane end signs are effective in all the sections of locations in the downstream model. Drivers reduced speed due to presence of any worker or equipment inside the work zone.

Driver's lane change behavior in work zones with lane closure on four-lane divided work zones were analyzed. It was seen that with presence of rear accommodating vehicle in the open lane, the drivers tend to merge early in a lane closure scenario in a four-lane divided (farther from work zone activity area). Similarly, presence of enforcement sign before merging, tends to increase distance of lane merge from the end of taper showing that the drivers merge early in a lane closure scenario in a four-lane divided. Non-forward related glance was associated with drivers merging early in a lane closure scenario in a four-lane divided. The study also showed that driver moving over to left from right lane closure were choosing to merge early than when they were moving from right lane closure to left lane.

This phenomenon cannot be fully justified as the sample size of this study was small. Head to head configuration was associated with drivers merging late. Influence of distraction and cell phone use was seen on drivers' lane change behavior. When drivers were distracted, the arrowhead CMS sign was not seen to be effective, meaning that the drivers did not choose to merge early in work zones lane closure scenario. Similarly, when they were distracted by cell phone, the normal speed limit signs were not effective to influence the drivers to merge early for a lane closure ahead scenario.

7.1.1 Change in speed models

In conclusion, the linear mixed effects model for work zones on 4-lane divided highways results indicate the following. Speed feedback signs are more effective in reducing driver speed before the merge point.

- Lane end sign, normal speed limit sign, and CMS also reduced driver speed before the merge point.
- Non-forward related glance was seen to increase driver speed inside the work zone. Thus, driver's safety was compromised when drivers didn't look forward while driving for more than 2 secs at a stretch.
- Static work zone signs and work zone speed limit sign was more effective about 1.25 mi before the start of work zone.
- Work zone speed limit signs were seen to be more effective within half mile inside a work zone than more than half mile inside the work zone.
- Presence of Work Zone Signs were more effective when the cones were placed as channelizing device inside the work zone.

- Vertical panels as channelizing device were used to decrease driver speed more effectively compared to concrete and cones.

The results of the models from work zones on multilane highways indicated the following:

- Work Zone Signs are effective in two sections of the upstream portions as well as beyond half a mile downstream of start of work zone.
- Work Zone Speed Limit Signs are effective when placed within half mile upstream.
- Lane end sign are effective in all the sections of locations in the downstream model. Some lane end signs are inside the work zone as the first part of the work zone may be a shoulder closure to some distance and then there can be a lane closure, so the lane end sign was placed somewhere inside the work zone. The lane end signs reduced speed in the range from 0.56 mph to 1.63 mph.
- Drivers reduced speed due to presence of any worker or equipment inside the work zone, mostly after a mile inside the work zone. This may be since the equipment and workers where positioned more than a mile inside the work zone for many of the traces. Drivers reduced speed in the range of 1.25 mph to 2.95 mph.

7.1.2 Lane change model

This chapter focusses on driver's lane change behavior in work zones with lane closure on four lane divided work zones. A lane merge model was developed to determine which characteristics were associated with lane merge distance. A linear mixed effect model as was developed to assess the effect of work zone signs and characteristics on driver lane merge distance. It was seen that presence of rear accommodating vehicle, tends to increase distance of lane merge from the end of taper. Thus, the drivers tend to merge early in a lane closure scenario in a four-lane divided (farther from work zone activity area). Similarly, presence of enforcement sign before merging, tends to increase distance of lane merge from the end of taper showing that the drivers merge early in a lane closure scenario in a four-lane divided. Non-forward related glance was associated with drivers merging early in a lane closure scenario in a four-lane divided. The study also showed that driver moving over to left from right lane closure were choosing to merge early than when they were moving from right lane closure to left lane. This phenomenon cannot be fully justified as the sample size of this study was small. Head to head configuration was associated with drivers merging late.

Influence of distraction and cell phone use was seen on drivers' lane change behavior. Though distraction and cell phone use didn't come out to be significant on its own in the models. When drivers were distracted, the arrowhead CMS sign was not seen to be effective, meaning that the drivers did not choose to merge early in work zones lane closure scenario. The drivers merged later closer to the taper that is activity area. Similarly, when they were distracted by cell phone, the normal speed limit signs were not effective to influence the drivers to merge early for a lane closure ahead scenario. However, it should be noted that the interaction terms showed that drivers were not seen to choose an earlier merge distance when not distracted or when they were not using cell phones during the presence of arrow CMS and normal speed limit signs.

7.1.3 Comparison of study results with literature

The results of previous studies were compared to the findings from this study. Table 7-1 provides the detailed results and the comparison of Change in speed study results with previous studies. Table 7-2 provides information about the general speed change at different scenario in work zones for temporary traffic control. A negative sign indicates reduction in speed and positive sign did not specify positive driver behavior in terms of speed reduction in work zones.

Table 7-1 Comparison of Change in speed study results with previous studies

Work Zone Speed Limit Signs	
Richards et al. (1985)	reduced the mean speed in the range of 0 to 5 mph
McCoy et al. (1995)	mean speed of vehicles were reduced by 4 to 5 mph
Carlson et al. (2000)	reduce speed significantly higher between 2 to 7.5 mph upstream and 3 to 6 miles with in the work zone
Maze (2000)	decreased in the mean and 85th percentile speed but not statistically significant
Meyer (2003)	both mean and 85th percentile speed was significantly decreased by about 5 miles per hour
Brewer et al. (2006)	device that display the speed of vehicles has the most significant effect
Finley (2008)	85th percentile speed downstream of a work zone speed limit sign decreased on average by 3 mph.
Finley et al. (2014)	85th percentile speed limit due to digital speed limit sign from 1.0 to 12.1 mph at different sites
This study (4-lane Model)	**Presence of Speed feedback Limit reduces driver speed by 3.33 miles per hour, Work zone speed limit sign reduces speed by 0.29 mph within 1 miles upstream of Start of Taper, Work zone speed limit sign does not help to reduce speed over 1 miles upstream of Start of Taper.**
This study (Multilane Model)	**work zone speed limit sign reduced speed by 0.3 to1.49 mph in advanced warning area (upstream of Start of Taper)**
CMS Signs	
Thompson (2002)	Mean speed reduced from 55 mph to 48 mph = 7 mph
Dixon and Wang (2002)	significant reduction in speed adjacent to the sign by 6-7 mph in upstream but not inside Work Zone
Wang et al. (2003)	CMS with radar with radar reduced the vehicles speed on the vicinity of sign by 8 mph
Brewer et al. (2006)	2 mph reduction in 85th percentile speed downstream of the location of the sign
Sorel et al. (2006)	reduction in mean speed of 3 to 10 mph
This study (4-lane Model)	**Presence of changeable message signs reduces driver speed by 0.51 miles per hour.**
This study (Multilane Model)	**No significant Effect**
Enforcement Signs	
Richards et al. (1985)	stationary patrol car was able to reduce mean speed by 4-12 mph and circulating patrol car was able to reduce mean speed by 2-3 mph
Benekohal et al. (1992)	an average speed was reduced by about 4 to 5 mph
Benekohal et al. (2010)	average speed of free-flowing cars reduced by 6.3-7.9 mph traveling on median lane and 4.1-7.7 mph traveling on shoulder lane
Finley et al. (2014)	85th percentile speed limit decreased by 14 mph
This study (4-lane Model)	**No significant effect**
This study (Multilane Model)	**No significant Effect**

Table 7-2 Additional takeaways from this study

Additional Takeaways from work zone on 4-lane divided Models	
Advanced Warning Area	**Speed changed by**
Normal Speed Limit	-1.07
Lane End Sign	-1.73
Static WZ Signs within 1 mile upstream	-0.29
Static WZ Signs Over 1 mile upstream	1.46
Activity Area	**Speed changed by**
Non-forward Glance	0.71
WZ Speed Limit Sign when concrete Channelizing Device present	0.47
WZ Speed Limit Sign when Cone Channelizing Device present	-5.67
Other Signs when Concrete Channelizing Device present	1.44
Other Signs when Cone Channelizing Device present	0.49
Equipment present half mile downstream	0.37
Equipment present Over half mile downstream	1.81
Additional Takeaways from work zone on multi-lane divided Models	
Advanced Warning Area	**Speed changed by**
Equipment	-0.08
Lane End Sign	-0.05
Work Zone Speed Limit	0.28
Rainy Foggy	-0.83
Depressed Grass Median: With Barrier	-0.26
Depressed Grass Median: Without Barrier	-0.44
Raised Median:	-1.12
Glare Screen	1.24
Congestion Level	-0.48
First Sign within half mile upstream	0.28
First Sign between half and one mile upstream	-0.25
First Sign over half and one mile upstream	-0.91
WZ Sign within half mile upstream	-1.02
WZ Sign between half and one mile upstream	1.13
WZ Sign over half and one mile upstream	-1.49
Activity Area	
WZ Sign within half a mile downstream	0.35
WZ Sign half and one mile downstream	-0.98
WZ Sign over a mile downstream	-0.04
Worker within half a mile downstream	0.85
Worker half and one mile downstream	0.29
Worker over a mile downstream	-2.95
Equipment within half a mile downstream	0.54
Equipment half and one mile downstream	0.73
Equipment over a mile downstream	-1.25

7.2 Limitations

Although every attempt was made to account for issues in the data and to ensure sample size was adequate, several limitations were still present which may have influenced results. They are summarized below.

Sample size may have been an issue. Although over 1,000 traces were ultimately available, they represented several different work zone configurations. Since work zones are complicated with a number of varying characteristics, it was difficult to have enough samples to adequately represent all features. Additionally, driver distraction was of significant interest. Since there was no method to detect driver distraction or cell phone use in the raw time series data, it was difficult to ensure adequate samples of these behaviors were present. Further reduction of data was not feasible within time or resource constraints.

Although the SHRP2 NDS data provided opportunity to study drivers' naturalistic driving behaviors in work zones, there were also many challenges to work with the data. The quality of coded or collected data should be carefully examined before conducting any Statistical research. The common issues included large noises in the recorded variables of interest, data acquisition sensor malfunction, missing data, outliers and omitted variables. Second, the large size of the collected data is an advantage of the SHRP2 NDS data. Due to the size of the data, it also brought many issues for data storage, data management, and data analysis. Third, the data collected in the SHRP2 NDS included both structured data in data sheet format for example event table data) and unstructured data for example video data. It was a big challenge to assemble useful data from the diverse datasets and find correlations between different variables. Lastly, most of the video data were manually reduced that brought human errors with it. A thorough quality control was conducted on the data sheets before analysis.

Work zones of 3 or more days were selected. This was to ensure there would several time series traces through the work zone. However, the the longer a work zone was in place, the more likely drivers were aware of the work zone conditions and reacted accordingly. For instance, drivers may have slowed before particular work zone features because they were anticipating changing conditions in the work zone rather than they were reacting to work zone features. Although it was possible to tell whether a driver had traversed the work zone before, this could not be accounted for in the models.

Work zones are complicated entities. Even with a sample of several hundred observations, the myriad of complex features makes it difficult to isolate the impact of a specific feature or set of features.

NDS data have a certain amount of noise. For instance, speed data have a number of fluctuations within short time periods that appear to exhibit acceleration/deceleration but in actuality are fluctuations in sensor measurements. As a result, trying to predict driver reaction can be challenging.

7.3 Implications for future research

As mentioned above, the research in this dissertation was developed using a limited sample of the SHRP 2 NDS work zone data set. The models in Chapters 4 & 5 and 6 could be improved by including additional data. As traces were manually reduced to extract several variables, it was not possible to collect a very large dataset before the deadline of the project. Thus, if more traces would be reduced, a better sampling of trips through work zones with countermeasures of interest could be made.

A potential future research can be conducted to verify the spacing of the work zone temporary traffic control devices of the work zone traces obtained from this study with the MUTCD typical applications.

The future entails implementation of connected vehicles in the roadway network. The lessons learned from these kind of naturalistic driving studies could be directly transferred to studying the calibration connected vehicle. Connectivity between vehicles and roadway conditions is important. Uniformity of work zones should be maintained din future for the sake of safety. The autonomous driving research could also benefit from the SHRP2 NDS work zone data analysis results. Autonomous vehicles should be programmed or taught to make decisions in complex traffic environment, and how to create a comfortable experience for the passengers. The SHRP2 Naturalistic Driving Study dataset is an ideal dataset providing information about divers' decision-making complex conditions like work zones. The drivers' behaviors and decisions could be learned from the naturalistic driving study and implemented in autonomous driving scenarios.

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