Evaluations of Work Zone Safety Using the SHRP2 Naturalistic Driving Study Data

Phase 2 Final Report

SHRP2 Implementation Assistance Program

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1. EXECUTIVE SUMMARY

1.1 Background

Over 96,000 work zone crashes occurred in 2015, which equates to one work zone crash every 5.4 minutes. A fatal work zone crash occurs every 12 hours, and these crashes accounted for 1.7% of all roadway fatalities in the US (710 of 42,231) in 2017. Moreover, work zone fatalities on US roads increased by 3.2% from 2016 to 2017 (NWZSIC 2019).

Crash rates have also been found to increase from the period before a work zone is in place to the period during construction. In a study in Virginia comparing crash rates before and during work zone construction, Garber and Woo (1990) found a 57 percent increase in crashes on multi-lane highways and a 168 percent increase in crashes on two-lane urban highways when work zones were in place. Nemeth and Migletz (1978) also found that crash rates during construction increased significantly compared to crash rates in the period before construction. Hall and Lorenz (1989) found that crashes during construction increased by 26 percent compared to crashes in the same period in the previous year when no construction was occurring. Similarly, Rouphail et al. (1988) found that the crash rates during construction increased by 88 percent compared to crash rates before long-term work zones were in place. However, other results from the same study indicated that the crash rates for short-term work zones were not affected by the road work.

Various driver, environmental, and roadway factors are associated with work zone crashes. Several researchers have noted that work zone crashes are more likely to occur during the daytime (Akepati and Dissanayake 2011, Yang et al. 2013). However, Harb et al. (2008) found that nighttime conditions or conditions with low visibility increased the likelihood of a work zone crash. In their investigation of the characteristics of freeway work zone crashes using the Florida Crash Records Database from 2002 to 2004, Harb et al. (2008) used conditional logistic regression along with stratified sampling and multiple logistic regression models to model work zone freeway crash traits. According to the results, roadway geometry, weather conditions, age, gender, lighting conditions, and driving under the influence of alcohol and/or drugs were the most significant factors associated with work zone crashes.

Rear end crashes tend to be a result of the following driver not providing enough time and space to adequately slow for the vehicle ahead.

Work zone crashes are caused by a variety of factors, such as driver error, driver distraction, inadequate visibility, poor road surface conditions, roadway obstructions, inadequate traffic control, and improper management of material, equipment, and personnel in work zones. Many crashes result from unsafe behavior, such as failure to yield or traveling at unsafe speeds. A review of 2014 Fatal Accident Reporting System (FARS) data indicated that about 30 percent of all fatal crashes are speeding related, while 71.4 percent of fatal work zone crashes are speeding related.

Work zone crashes occur at different rates in different types of work zones. Akepati and Dissanayake (2011) determined that 37% of work zones crashes in two Midwestern states occurred during a lane closure; 18% occurred during work on the shoulder or median; 15% occurred when there was a lane shift, crossover, and/or head-to-head traffic; and 8.7% occurred at intermittent or moving work zones.

Work zone crashes are not only a problem for the traveling public, but are also a serious concern for highway workers. One hundred forty three work zone-associated fatalities occurred in 2016 among road workers, with 61% of these involving workers being struck by highway vehicles (NWZSIC 2019). Consequently, addressing work zone crashes is critical for both the traveling public and highway workers.

1.2 Project Scope

Several factors have been identified as contributing to work zone crashes. Driver factors have not been as well studied as other factors because driver factors have been difficult to extract from crash data. It is largely believed, however, that the main contributors to work zone crashes are inattentive driving, speeding, and other unsafe driver behaviors, such as following too closely. Information is also limited regarding which countermeasures, such as speed feedback signs or dynamic message signs (DMS), are effective in preventing work zone crashes.

The availability of naturalistic driving study data (NDS) collected by the second Strategic Highway Research Program (SHRP2) offers an opportunity for a first-hand view of work zone safety and, in particular, the observation of actual driver behavior in work zones. As a result, this study used the SHRP2 NDS data to evaluate the relationships between work zone crashes and work zone and driver characteristics. Only a small sample of work zone crashes were available for this study, though a related research project being conducted by University of Missouri is in the process of conducting a work zone crash analysis. As a result of the small sample size, this project utilized several crash surrogates, such as speed, to assess driver behavior in work zones that may have a negative impact on safety.

1.3 Data Utilized

Potential work zones were identified in five of the six NDS study states using the 511 data collected as part of the Roadway Information Database (RID) developed by the Center for Transportation Research and Education (CTRE) at Iowa State University (ISU) (511 data were not available for Indiana). Potential locations were further reduced to include only those work zones estimated to have lasted 3 or more days. A minimum of 3 days was used to ensure that multiple time series traces could be identified for a particular work zone. Next, a distance upstream and downstream of each work zone was established that was assumed to encapsulate the work zone's extent, and the Virginia Tech Transportation Institute (VTTI) provided several time series traces along the identified segments. These segments were reviewed, and only those where an active work zone was present were included as work zones of interest. Although more descriptive criteria were used to define "active" work zones, this was essentially considered to be a work zone with a lane or shoulder closure. Once a final set of active work zones was identified, the work zone extents were further defined, and time series traces through each work zone were requested.

Once the traces were received, data reductionists coded the characteristics of the work zones. Since a work zone can change even from day to day, work zone features had to be manually extracted for each time series trace, which required a significant amount of resources. Data were requested for two-lane, four-lane, and multi-lane facilities. However, few two-lane roadways with work zones were ultimately identified, and as a result work zones on this type of roadway were not included in the analyses. Work zone features were correlated to the time series traces. Consequently, the position of a driver/vehicle from a work zone feature at any point could be determined. The legibility distance for each sign was calculated using the *Manual on Uniform Traffic Control Devices* (MUTCD) and other research as a reference. Legibility distance was used to estimate the point at which a driver would be able to see a sign or other work zone feature, and it was assumed that some reaction would take place within that area.

Pre-work zone roadway conditions were also coded using the RID, the forward video view in the NDS data, or aerial views of the roadway. These conditions included characteristics such as number of lanes, type of median, etc. Weather conditions (dry, rain) were also coded. Finally, driver glance behavior and presence of a distraction were coded by either the research team or VTTI data reductionists. Due to the cost of reducing driver face video, only 1,099 traces were reduced. In a few cases, time series traces were utilized where the driver characteristics had not been reduced. In these cases, driver characteristics were not included in the corresponding model.

The work zone was divided into functional areas. The work zone was assumed to officially start at the taper point for the shoulder or lane closure. The work zone extent was defined as the distance from the taper point to the point where the lane/shoulder closure ended and normal traffic operations resumed. The area upstream of the taper point to the first work zone sign was termed as the work zone influence area. Further upstream, it was assumed that normal traffic operations were in effect.

1.4 Summary of Analyses

Several different analyses were conducted to assess the data from different perspectives. Each analysis is summarized below.

1.4.1 Work Zone Reaction Point

This analysis estimated whether drivers reacted within the influence area of various work zone features in the advance warning area. This study focused on four-lane work zones and used 299 speed traces in work zones with shoulder or lane closures. A change point model was used to detect the points along each time series trace where drivers reduced their speed by ≥ 3 mph with normal deceleration. These change points were surrogates for driver reaction and were mapped to the legibility area of each work zone feature. A mixed effects logistic regression model was developed, and the likelihood of a driver's response to each work zone feature was estimated.

The results showed that drivers were unlikely to respond to the first work zone sign when it was a static sign (OR = 1.07, p = 0.79) or enforcement sign (OR = 1.66, p = 0.39). When the first sign was a changeable message sign (CMS), drivers were 2.32 times more likely to react (p = 0.10). As a result, drivers are most likely to react when a CMS is the first sign encountered upon entering a work zone. It should be noted that there were occasions when the first work zone sign was a warning message significantly upstream (more than 2.5 miles) of the work zone, which was beyond the area coded. In such cases, the CMS was coded as the first sign but in actuality may not have been the first sign the driver encountered. In all cases, it can be interpreted that when the first sign a driver encountered when approaching within 2.5 miles upstream of the start of the work zone was a CMS, it was more likely to get a driver's attention than any type of static sign.

Once drivers were within the advance warning area, they were not likely to respond to enforcement signs (OR = 0.21, p = 0.129). In contrast, drivers were highly likely to react to a speed feedback or static work zone speed limit sign (OR = 2.02, p =0.23 and OR = 2.23, p = << 0 respectively). A separate t-test showed that the effects of speed feedback and static work zone speed limit signs were not statistically significantly different. This may suggest that after drivers are presented with a work zone speed limit sign, they are equally likely to react to a static or electronic sign.

Active changeable message signs in general were 2.32 times more likely to elicit a driver's response compared to static work zone signs (p = 0.01), and drivers were almost twice as likely to respond to a CMS even when it was not actively displaying a message (OR = 1.95, p = 0.06). This result refers to CMS other than those located at the beginning of the advance warning area.

1.4.2 Change in Speed

This analysis evaluated driver behavior from a different perspective than the change point analysis. In this case, the driver's change in speed was measured from a point upstream of the legibility distance of a sign or work zone feature to a point just past the feature. The intent was to determine whether drivers slowed down for particular features.

In some cases, a driver may slow within the legibility distance of a feature in response to that feature but then increase his/her speed again. For instance, a driver may slow when presented with a speed feedback sign but then speed up again after passing the sign. The change point model captures this behavior, while the change in speed analysis does not. Change in speed assumes a sustained response.

A linear mixed effects model was used to predict drivers' change in speed within the work zone. Change in speed was calculated within the influence area of each work zone feature for each time series trace. Any work zone-related object within 2.5 miles upstream of the taper point to a distance 1.0 mile inside the work zone (downstream) was included.

Separate models were developed for four-lane and multi-lane roadways. The final model for four-lane work zones indicated that an average increase of 0.97 mph occurred when a driver encountered a regular static work zone sign. When a driver encountered a concrete barrier, a decrease of 1.16 mph resulted. When cones were present, a decrease of 2.64 mph was noted, while the presence of barrels resulted in a decrease of 2.76 mph. The most significant decrease was the presence of concrete barriers with vertical panels, which resulted in a decrease of 3.64 mph. Interestingly, when construction equipment was present, drivers increased their speed by 1.77 mph. If a worker was present, this was noted as "worker" and was not found to result in a statistically significant change in speed.

Interactions were present for several features. When a speed limit sign was between 1 mile and 0.5 miles upstream of the taper point, drivers decreased their speed by about 1.1 mph, but a speed limit sign did not elicit a decrease in speed within the work zone. Rather, it was associated with a slight speed increase.

The results for the multi-lane model indicate that the presence of a lane end sign results in a decrease in speed of 2.21 mph on average. Presence of a left shoulder closure resulted in a 1.86 mph decrease in speed, while a left lane closure resulted in an increase in speed of 4.17 mph. (The closures referred to in these results reflect actual closures within the work zone rather than a type of sign.) The latter result may be due to drivers speeding up in an attempt to merge.

When a static work zone sign was present more than 0.5 miles upstream of the taper point, drivers increased their speed by 12.24 mph. This is an unexpected result. Between 0.5 miles upstream of the taper point and the taper point itself, when drivers encountered a static work zone sig, they decreased their speed marginally (0.28 mph), and within the work zone a static work zone sign resulted in a small increase in speed (1.10 mph).

An interaction was found between the presence of work zone speed limit signs and channelizing devices. Drivers increased their speed when both a work zone speed limit sign and barrels (1.85 mph increase) or cones (1.54 mph increase) were present. When concrete barriers were present and drivers encountered a work zone speed limit sign, they decreased their speed by 5.64 mph. There was no interaction between work zone speed limit signs and other types of barriers.

The effects of cell phone use on speed changes varied depending on the area of the work zone in which the cell phone was used. When drivers who were engaged in a cell phone-related task encountered a work zone object in the advance warning area, they tended to decrease their speed by 7.61 mph. When similarly occupied drivers encountered an object in the area just upstream of the merge area, they decreased their speed by 1.19 mph, and within the work zone they marginally increased their speed (0.21 mph). This phenomenon has been noted in other studies. In some cases, drivers who are engaged in a cell phone-related task are not attentive to the forward roadway and do not maintain their speed.

1.4.3 Back-of-Queue Behavior

The majority of rear end crashes occur at the back of a queue. A line of stopped or slowed traffic is common in work zones, and safety issues may arise when drivers are not paying attention or misjudge the forward vehicles' speed. As a result, driver behavior at the back of the queue was evaluated. A hard deceleration (≤ -0.40 g) as a driver encountered the back of a queue was used as a surrogate for unsafe behavior.

Back-of-queue and work zone-related crash/near-crash events were identified using the SHRP2 InSight website. Driver behavior and distraction were coded by VTTI for these events. A simple summary was developed of the main distracting behavior present during the 5 seconds before the point of the incident or the driver reached the back of the queue. About 33% of drivers experienced no distraction in the 5 seconds before reaching the back of the queue. Nineteen percent were engaged in reaching for or moving an object, while 17% were engaged in some cell phone-related task. A cell phone-related task (or any other distraction) was only coded when it involved a glance away from the forward roadway. A cell phone-related task involved reaching for a phone, texting, dialing, or any other activity that involved a cell phone. Talking on the phone was not coded as a distraction if the driver had eyes forward while he/she was talking, because phone conversations were not captured if they did not involve a glance away from the roadway. Some events where the driver was coded as "talking or singing" could have involved a driver talking on a cell phone. Additionally, some of the tasks coded as "reaching" could also have been cell phone related if the VTTI coders could not distinguish the object being moved. Overall, 67% of drivers who were involved in back-of-queue incidents were engaged in some type of distracting task.

An additional 110 back-of-queue events were identified among the time series traces used in the other models in this study. While back-of-queue events are most often associated with some congestion, time series traces where congestion was present were specifically not selected for the other analyses in this study. As a result, driver characteristics such as cell phone use or distraction were not coded for these vehicles in Phase 2. In Phase 3, these characteristics will be coded and used as a baseline for comparing the impact of cell phone use on how a driver encounters the back of a queue. In the present analysis, a logistic regression model was developed to assess other behaviors leading to hard decelerations at the back of a queue. The status of hard versus normal deceleration was used as a dependent variable, and variables such as speed at the reaction point and other environmental factors were used as independent variables.

The results showed that for every unit increase in the freeflow speed of a vehicle at the reaction point, the probability or odds of a driver engaging in a hard deceleration increased by 1.04. The odds of a driver engaging in a hard deceleration were 7.37 times greater on wet pavement compared to dry pavement. In addition, drivers were also more likely to engage in a hard deceleration during nighttime driving compared to daytime driving.

1.4.4 Lane Change Model

Lane closures in work zones require drivers in the closing lane to merge into an adjacent through lane before they enter the work zone area. A driver's merging behavior in the work zone merging area can be characterized by the distance from the point of the lane closure that the driver begins to merge.

A lane merge model was developed to determine which characteristics were associated with merge distance. A merge was defined as a driver moving from a lane that is closing ahead into an adjacent open lane. If a driver changed lanes several times, only the final move into the open lane was included.

The model showed that drivers who are traveling over the mean speed (based on the mean speed of all time series traces for the same work zone) merge later (i.e., closer to the work zone starting point). As the number of signs before a work zone lane closure increases, the distance of the lane merge from the start of the work zone also increases, meaning that drivers are more likely to merge earlier when more upstream signs leading to a work zone are present. This result is likely due to more complex work zones having more upstream distance and signing. The presence of a lane merge CMS in a work zone decreases the merge distance from the work zone starting point, meaning that drivers on average merge 425.6 meters later. This may be due to the fact that drivers are able to more clearly see the merge point and are not concerned about immediately moving into an open lane. Drivers merge 228.4 meters earlier when barrels are present than when concrete or vertical panels are present. When speed enforcement signs are present, drivers merge about 1,191.2 meters sooner. When rain is present, drivers tend to merge 379.2 meters later. No impact was found for cell phone use or distraction.

1.5 Limitations

Although every attempt was made to account for issues in the data and to ensure that the sample size was adequate, several limitations remained that may have influenced the results of the analyses. These limitations are summarized as follows:

(1) 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 and have a number of varying characteristics, it was difficult to gather enough samples to adequately represent all work zone 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 that adequate samples of these behaviors were present. Further reduction of data was not feasible due to time and resource constraints.

(2) Work zones lasting three or more days were selected for analysis. This was to ensure that several time series traces would be available 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 reacting to particular work zone features. Although it was possible to determine whether a driver had traversed the work zone before, this could not be accounted for in the models.

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

(4) NDS data have a certain amount of noise. For instance, speed data exhibit a number of fluctuations within short time periods that appear to represent acceleration/deceleration but in actuality are fluctuations in sensor measurements. As a result, predicting driver reactions based on speed changes can be challenging.

1.6 Summary

Several different analyses were conducted in order to evaluate the data from different perspectives. A summary of the findings is shown in Table 1-1.

Table 1-1. Summary of studies

Analysis	First sign static	First sign enforcement	First sign CMS	Enforcement sign	Speed limit sign	Lane end sign	Left lane closure sign	Left shoulder closure sign	DSFS	CMS	Barrels	Concrete barrier	Cone	Equipment	Cell	Distraction	Speed	Night
Reaction point – four-lane	none	none	+	none	+				+	+								
Speed change – four-lane					upstream +							+		-				
Speed change – multi-lane						+	+		-		with speed limit sign -	with speed limit sign +	with speed limit sign -		+			
Back of queue															-	-	-	-
Lane change				+						merge -	+						-	

Since the different models had different response variables (e.g., reaction point, change in speed), the summary simply indicates whether the predictor variable was determined to be significant. A positive sign indicates that a positive reaction was found, such as a reduction in speed, high likelihood of a reaction point, or an earlier merge. A negative sign indicates that a negative reaction was found, such as less likelihood of a reaction point, an increase in speed, or a later merge.

The selected response variables were used to demonstrate some kind of reaction. It is possible that they do not reflect driver behavior as interpreted. For instance, the change point and change in speed models assume that drivers decelerating or decreasing speed when they encounter a work zone feature are positive behaviors. However, these models do not capture drivers who may have slowed their speed upon entering the work zone and then maintained their slower speed throughout the rest of the work zone. These drivers would not have needed to slow further when encountering additional work zone features. In particular, the change in speed model showed a positive driver response related to cell phone use, in that drivers using a cell phone were found to decrease their speed. However, other studies have found that cell phone use results in decreased speed because drivers are not attending to the forward roadway. Since cell phone use is of particular interest, it will be further explored in Phase 3.

2. DESCRIPTION OF DATA

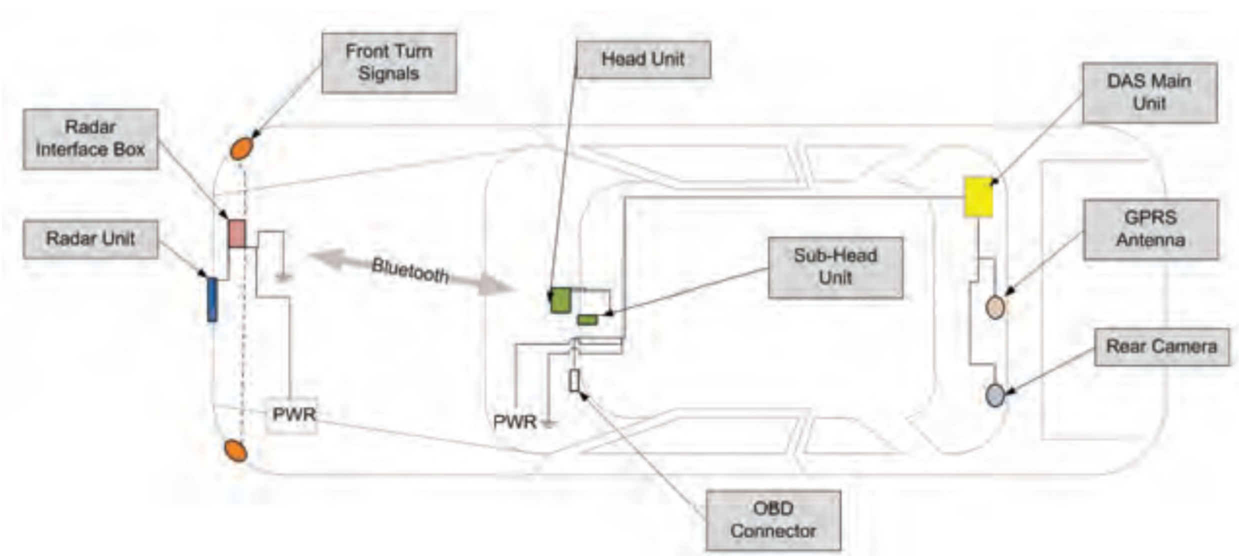
2.1 Source of Data

2.1.1 Naturalistic Driving Study Data

The naturalistic driving study performed under SHRP2 is the largest and most comprehensive NDS undertaken to date (in the US or elsewhere). Data were collected from over 3,000 male and female volunteer passenger vehicle drivers, ages 16 to 98, with most drivers participating between one and two years. Data were collected from sites in six US states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. The NDS data file contains about 50 million vehicle miles, 5 million trips, and more than 3,900 vehicle-years, for a total of about 2 petabytes of data.

The study was conducted from October 2010 to November 2013 (Dingus et al. 2014). In-vehicle data were collected via a data acquisition system (DAS). A large amount of vehicle information was captured, including speed, acceleration, and braking; forward radar; and multiple video views, including the forward roadway, the rear roadway, the driver's face, and over the driver's shoulder. Global positioning system (GPS) data were also collected and associated with the vehicle activity data so driving traces could be overlain with roadway or other spatial data. Vehicle data are provided in a time series database (.csv file). Most kinematic vehicle variables are reported at 0.1-second intervals.

The SHRP NDS data are stored at a secure data enclave at VTTI, which is located in Blacksburg, Virginia. Figure 2-1 shows the framework of the DAS for the SHRP2 NDS project, including the placement of various units.



Campbell 2012, *TR News*

Figure 2-1. Framework of SHRP2 NDS data acquisition system

For the present study, NDS data were provided as time series traces. Each of these represents the data in 0.1-second intervals for one trip for one driver through one work zone. A video clip of the forward roadway and a video clip of the rear roadway were also provided for each time series trace. The driver videos could only be reviewed at the VTTI secure data enclave.

2.1.2 Roadway Information Database

The RID was developed by the Center for Transportation Research and Education (CTRE) at the Institute for Transportation (InTrans) at Iowa State University (ISU). A mobile data collection van was used to collect about 12,500 centerline miles in the six SHRP2 NDS states. Roadway features collected included curve radius, number of lanes, roadway alignment, signing, presence and type of intersections, lane width, grade, shoulder types, and lighting. In the present study, RID data were linked to the NDS data.

The NDS data can be also linked to other roadway databases or aerial imagery to extract additional roadway features. In the present study, other data were collected and incorporated into the RID. These data came from several sources, including the NDS states' respective departments of transportation (DOT) and the Federal Highway Administration's (FHWA's) Highway Performance Monitoring System (HPMS); these sources cover most roadways for each study state. In addition, supplemental data such as 511 data, construction project data, crash data, and traffic volume data were also collected.

2.1.3 Safety Critical Events

VTTI reduced a set of crashes and near-crashes from the SHRP2 NDS data (4,246 total). Crashes/near-crashes can be viewed in an Event Detail Table available on the SHRP2 InSight website. Over 70 variables are provided, including crash type, severity, driver actions, etc. A brief video clip of the forward roadway is included, along with a graphical display of selected vehicle kinematics (e.g., speed, acceleration, distance into trip, and wiper status). High-level roadway and traffic characteristics are also included, such as intersection type, traffic control, alignment, and level of service.

A total of 552 work zone-related safety critical events (crash, near-crash, and crash relevant) were coded as "construction" in the Event Detail Table. A review using the forward roadway video indicated that many were coded as "construction" due to barrels or other work zone paraphernalia being present, but the work zone was not relevant to the event. Each event was reviewed to determine whether it was actually work zone related, that is, whether the event involved a lane closure, the presence of barrels or cones near the lane edge, the presence of construction equipment or workers, the presence of dynamic message signs, or other characteristics suggesting that the work zone may have contributed to the safety critical event. This review resulted in the identification of 148 events where an active work zone was present.

2.2 Identification of Work Zones

Data collection for this study entailed determining work zone locations within the SHRP2 NDS data. The steps taken to identify work zones and request data for project purposes are summarized below.

2.2.1 Step (1) Identify Potential Work Zones Using 511 Data

The RID contains 511 information for most states, and this information was queried for each of the three years the NDS was active (2011 through 2013). Because 511 data were not available for Indiana, this state was not included in the analyses. The 511 files primarily provide information about the locations and durations of traffic events. Over two million 511 records were available, since 511 information encompasses a wide range of different real-time updates of a variety of events occurring on roadways.

No specific field in the RID supplemental 511 data could identify work zones, but the fields representing event type and event description provided information about any construction or maintenance activities. Therefore, an attribute query was conducted using ArcGIS to identify potential work zones. Key words such as “construction,” “lane closure,” “road work,” or “maintenance” were used. This query was different for different states due to the disparity in 511 data among states. Table 2-1 shows the details of the 511 files and attribute queries.

Table 2-1. Available attribute fields for identifying work zones by state

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"

2.2.2 Step (2) Determine the Locations of Potential Work Zone Events and Obtain the Number of Likely Trips

The next step was to link the potential work zone events identified in the 511 data to the RID links. In some cases, the 511 data were in the form of a single point for each event, which did not indicate work zone extent, or in the form of a line. Figure 2-2 (left) shows 511 line data for Washington State, and Figure 2-2 (right) shows 511 point data for New York State.

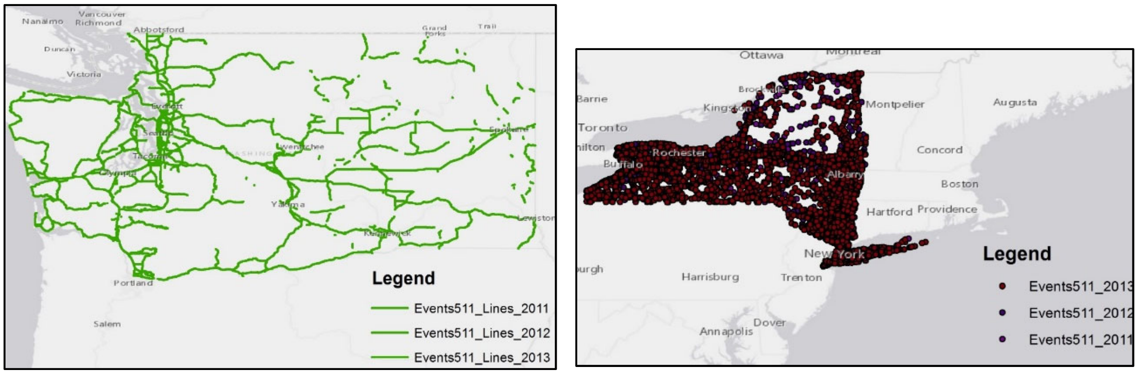


Figure 2-2. 511 point (left) versus line (right) events

When 511 events were provided as lines, the lines were associated with links in the RID. In order to locate the links that directly intersected the 511 events, a dynamic segmentation method was utilized. An estimate of the work zone extents was assumed using the corresponding RID links. When 511 events were provided as points, each point was mapped to the RID, and the nearest corresponding link ID was extracted. Dynamic segmentation was used to extract links two miles upstream and downstream of the point.

Next, start and end dates were used to select work zones that lasted more than three days. A minimum of three days was used to ensure that multiple time series traces could be identified for a particular work zone. This narrowed the sample of potential work zones by a significant amount. A total of 9,290 work zones lasting three or more days were identified for the five NDS states included in the study, as shown in Figure 2-3. Indiana was not included because 511 data were not available for that state.

Image source: ESRI; Data source: VTTI

Figure 2-3. Locations of potential work zones

The estimated extents of the work zones were sent to VTTI, and the number of time series traces and unique drivers and the drivers' age/gender information for the links of interest were requested. Potential work zone trips were determined by identifying the trips falling within the dates indicated in the 511 data. VTTI provided a list of potential trips and unique drivers and the age/gender of each driver.

Table 2-2 shows the number of trips and unique drivers available in each state.

Table 2-2. Descriptive statistics of trips and participants for potential work zones in each state

State	Total No. of Work Zones	Trip Counts			Participants		
		Mean	Min	Max	Mean	Min	Max
North Carolina	90	500.9	32	7,715	91.37	11	410
Florida	39	1,026.13	34	9,056	124.5	17	579
New York	1,748	2,033.86	31	23,187	127.4	11	665
Washington	6,984	2,267.99	31	13,097	193.1	11	665
Pennsylvania	429	307.25	31	11,836	58.14	11	224

As the table shows, 90 of the 9,290 potential work zones were in North Carolina, with an average of 501 trips per work zone. An average of 91 unique drivers per work zone was also available in North Carolina.

2.2.3 Step (3) Refine the Extents of Potential Work Zones

The data set resulting from Step 2 was reviewed, and work zones with at least 15 NDS time series traces were selected, resulting in 1,680 potential work zones. About 7,220 work zones in the initial data set had fewer than 10 trips and were not utilized.

In order to request time series traces, it was necessary to make some estimate of the actual physical extent of each potential work zone. When 511 data were presented as a link, the link was mapped to the RID and the corresponding link IDs extracted. Dynamic segmentation was then used to add links approximately 0.5 miles upstream and downstream of each identified work zone to increase the likelihood that the actual work zone was included. When 511 data were presented as points, dynamic segmentation was used to extract links 2 miles upstream and downstream of each point.

2.2.4 Step (4) Confirm Work Zone Presence and Duration

A list of link IDs and work zone dates was submitted to VTTI. Several time series traces and forward videos were requested for each of the 1,680 work zones identified in Step 3. Multiple traces were requested because information about start and end times in the 511 data were not always accurate, work zones did not always start or end on time, and 511 records were not always updated.

About 3,000 traces were received, and the forward videos were reviewed to determine whether a work zone was actually present and whether the work zone was active. In some cases, no work zone was present. Work zones that contained signals or other non-work zone-related interruptions in traffic flow were excluded because predicting speed or reaction point would have been difficult when external stimuli were present.

The next step was to determine whether the remaining work zones were active in terms of affecting traffic; a set of barrels or cones along the side of a roadway did not represent the type of work zones that were of interest to the project team and technical advisory committee (TAC). An active work zone was defined as having one of the following characteristics: lane closure, shoulder closure, workers present, or equipment present. Ultimately, all work zones included in the analyses had a shoulder or lane closure.

2.2.5 Step (5) Identify Work Zones Using Near-Crashes

Another method to identify potential work zones was through construction-related near-crashes. A list of safety critical events including crashes and near-crashes was available through the SHRP2 InSight website. Crashes were not included in the analyses since location could not be provided due to privacy constraints. Each of the available near-crashes was reviewed using the tools on the InSight webpage, including the forward video clip and other characteristics available for each near-crash event. Near-crashes in work zone locations that met the criteria used in Step 4 were flagged. A time series trace and forward video through each identified location was requested for each near-crash to confirm whether the location met the criteria specified in previous steps.

2.2.6 Step (6) Request Final Data Sets

Using the process described in Steps 4 and 5, about 240 viable work zones were identified that included four-lane, multi-lane, or two-lane roadways with shoulder or lane closures. The beginning and end points of each work zone that had initially been identified were adjusted based on a review of the forward video and corresponding spatial locations from the time series data. Once the beginning and end points were established, a distance 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.

2.3 Data Reduction

The following summarizes the general data reduction activities for this study. If additional data reduction was necessary for a particular analysis, it is detailed within the corresponding summary.

Raw NDS data were provided by VTTI in terms of events. Each event included one trip by one driver through a particular 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's face and hand positions was accessible at the VTTI secure data enclave and was utilized to reduce driver characteristics as noted in Section 2.3.4. About 10,000 time series traces were received.

Since the time series data can have missing observations, only time series traces that had more than 90% of speed data available were utilized in the study. Time series data are reported at 10 Hz (0.1-second intervals). When speed was missing for an interval, speed was interpolated using the nearest neighbor approach. This reduced the number of traces that were available to about 50%. 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 should have specified a threshold percentage of "good" speed data.

Each of the remaining time series traces was geocoded and matched to the corresponding roadway link in the RID, and roadway characteristics were extracted as noted in Section 2.3.1. Time of day (daytime, nighttime with no street lighting, nighttime with street lighting), ambient conditions (e.g., foggy), and pavement surface condition (e.g., wet, dry) were also coded. Work zone characteristics were also coded as noted in Section 2.3.2.

The number of available events was further reduced since some events either did not occur when the work zone was present or the configuration changed so that the work zone was no longer considered active. Additionally, traces for which the approximated traffic conditions were lower than Level of Service (LOS) C were also not used for most of the analyses since it was felt that 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.

Since work zone configuration can change from day to day, even for the same work zone, reduction of work zone characteristics could not be automated in any fashion and required manual data reduction. Additionally, reduction of driver face video was significantly time consuming for the team and was ultimately outsourced to VTTI. As a result, due to the actual cost or resources of data reduction, only a subset of the data could be reduced within project resources.

As a result, the events remaining after those meeting the previously described criteria had been selected were further sampled, e.g., traces with less than 90% of speed data. Sampling was done to represent both day and night. The next step was to filter based on age and gender.

Ultimately 489 time series traces were reduced for multi-lane work zones, and 518 were reduced for four-lane work zones.

2.3.1 Roadway Characteristics

Non-work zone roadway characteristics of interest were extracted for each time series trace. When roadway characteristics could not be obtained from the RID data, they were extracted from Google Earth, the forward view video, or aerial images. Roadway characteristics included the following:

- Number of lanes
- Type of median
- Surface type (asphalt versus concrete)
- Shoulder type
- Speed limit
- Presence of lighting
- Number of uncontrolled intersecting roadways
- Presence and type of traffic control

2.3.2 Work Zone Characteristics

Work zone configuration and characteristics were coded using the forward view video and included the following:

- Type and location of barriers
- Number of closed lanes
- Presence and type of DMS or other intelligent transportation system (ITS) countermeasures
- Presence of workers
- Presence of equipment
- Lane shifts
- Temporary pavement markings

Figure 2-4 illustrates the components of a work zone.

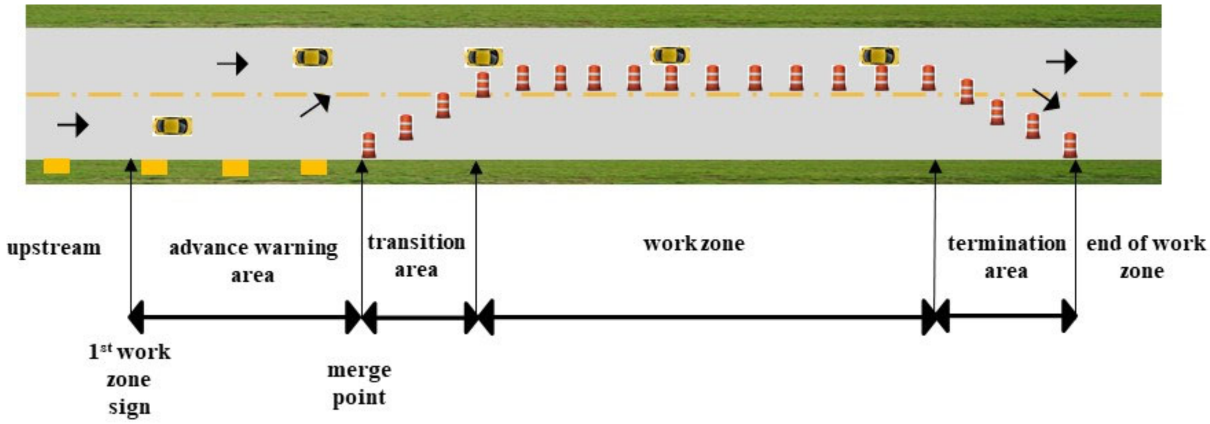


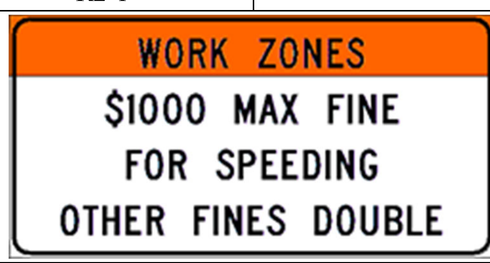
Figure 2-4. Schematic showing the components of a work zone

The start of the work zone influence area was indicated by the first work zone sign. This included any type of sign that alerts drivers to the presence of an upcoming work zone. In a few cases, signs were placed several miles upstream of a work zone and may not have been captured because the requested video trace was typically 2 miles upstream of the merge point.

The point between the first work zone sign and the merge point was referred to as the advance warning area and was characterized by various types of traffic control depending on the individual work zone, such as a reduced speed limit, changeable message signs, static signing, etc. The work zone proper was considered to start at the beginning of the merge point until the transition away from the shoulder or lane closure at the termination area.

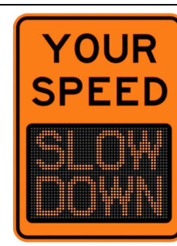
A number of different types of signs were coded, as shown in Tables 2-4 and 2-5.

Table 2-4. Examples of static signs coded

Type of Sign	Examples		
Standard work zone	 W21-5	 W20-1	 W20-5R-A
Work zone speed limit	 W3-5	 G20-5aP over R2-1	
Regular speed limit	 R2-1		
Work zone enforcement			
Work zone closure	 W4-2		

Sources: FHWA 2019 MUTCD, Iowa DOT, and Tampa Hillsborough Expressway Authority

Table 2-5. Examples of dynamic signs coded

Type of Sign	Examples	
Work zone enforcement	 Michigan State University	
Dynamic arrow board	 https://www.streetsmartrental.com/smart-work-zones.html	
Trailer-mounted changeable message sign	 https://mister-sign.info/portable-changeable-message-signs/portable-changeable-message-signs-portable-changeable/	 www.addco.com
Speed feedback sign	 https://www.streetsmartrental.com/products/radar-speed-trailers-rental.html/?portfolioID=10822	 https://trafficalm.com/applications-work-zones/
Overhead changeable message sign	 Iowa DOT	

2.3.3 Locating Features within Time Series Traces

Time series data were extracted for the distance from the start of the work zone to a point 200 meters upstream of the first work zone sign, as shown in Figure 2-5.

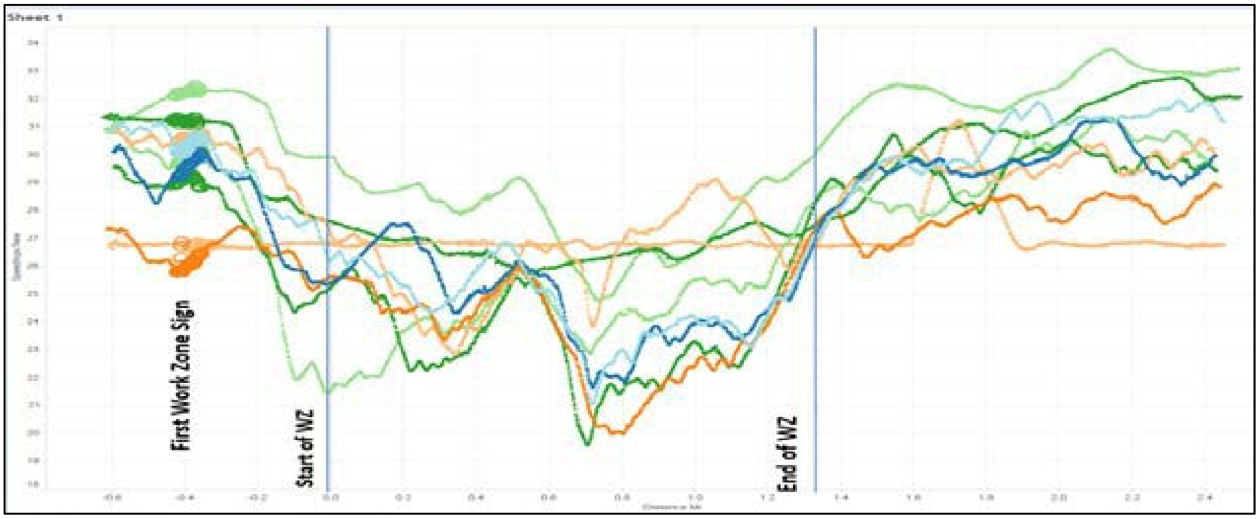


Figure 2-5. Time series traces in relation to work zone features

Because work zone configurations differed, the analysis distance differed accordingly. As noted previously, in a few cases the first work zone sign was placed several miles upstream of the work zone and was not captured in the time series traces for that work zone.

The location of relevant roadway and work zone characteristics, such as signs or merge points, were coded in relation to vehicle position in the time series traces. Features such as work zone signage or the start of the work zone were identified in the forward video and then spatially located by noting the nearest video time stamp. The time stamps were physically located using the most proximate GPS records (latitude/longitude) and interpolation. As a result, the vehicle's position relative to each work zone feature (e.g., 200 meters upstream of the work zone merge point) was calculated and added as a variable in each row of the corresponding time series trace for each work zone trip (at 0.1-meter intervals). Using this information, a vehicle's position relative to any roadway feature could be determined. Figure 2-5 illustrates several time series traces plotted in relation to a variable message sign (VMS), the start of the work zone, and the end of the work zone.

2.3.4 Driver Characteristics

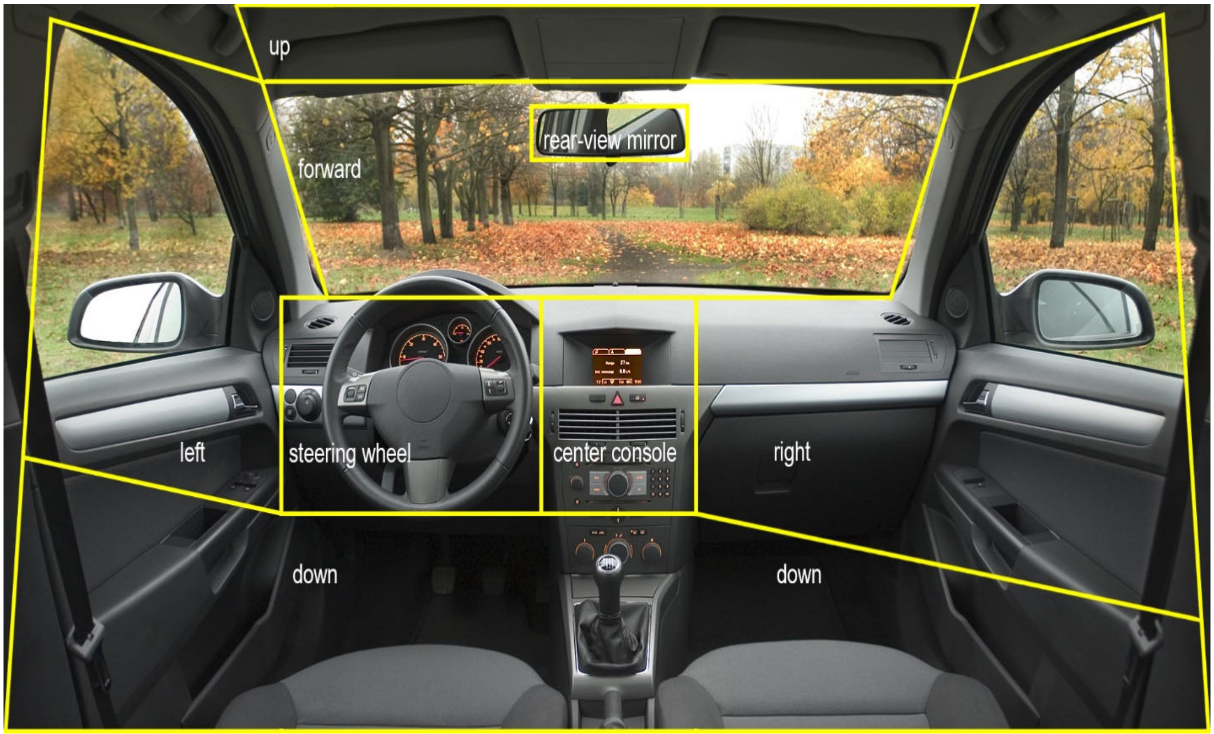
Driver characteristics, including age, gender, and other socioeconomic characteristics, were provided by VTTI along with the time series traces. Driver distraction and kinematic driver characteristics were initially reduced for 134 time series traces. It was later decided that having VTTI reduce the 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 whether the driver's hands were on the steering wheel, impairments (e.g., drowsiness, intoxication), seat belt use, driving action (e.g., failure to yield), and speeding (exceeding the speed limit or driving too fast for conditions). Driver distraction was also coded in terms of secondary tasks, including non-driving-related glances away from the driving task.

Driver glance locations and any visual distractions (i.e., distractions that drew the driver's glance away from the forward roadway) were manually coded at the secure enclave at VTTI. These behaviors were 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 University, while the remaining 984 traces were coded using the same protocol by the team at VTTI.

For each trace, the driver's glance locations and visual distractions were coded at 15 Hz. Possible glance locations are shown in in Figure 2-6 and included the following:

- Forward
- Left
- Right
- Up
- Down
- Over the shoulder (not shown in the figure, but involved a glance beyond the B pillar)
- Center console
- Steering wheel
- Rear view mirror
- Other (used when blinks, squints, or closed eyes lasted more than 10 frames)
- Missing (used when the eyes were obscured or obstructed for more than 10 frames or when video was missing)



Original vehicle interior (before markup and annotations) from Shutterstock

Figure 2-6. 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 the driver looked to the right at the passenger while talking to him/her, that was coded as a distraction. Distractions were coded as follows:

- Passenger
- Route planning (locating, viewing, or operating a device)
- Moving or dropped object in vehicle
- Animal/insect in vehicle
- Cell phone (locating, viewing, or operating the device)
- IPod/MP3 player (locating, viewing, or operating the device)
- In-vehicle controls
- Drinking/eating
- Smoking
- Personal hygiene
- Other task

In addition, because the use of cell phones in work zones was a research question of particular interest to the research team and TAC, the use of a cell phone was coded in its own category in addition to being coded as a visual distraction. VTTI coded the respective timestamps for the beginning and end of a cell phone conversation. If the beginning or end occurred outside of the time frame requested for the time series trace, the beginning or end timestamp of the coding period was used to indicate the respective beginning or end of the cell phone conversation. Distractions caused by a cell phone that were not associated with a glance away from the forward roadway were also included. These included tasks such as reaching for the phone, adjusting the charger, texting, etc. Hands-free usage was not able to be determined because cell phone records were not available for all traces.

2.3.5 Quality Control/Quality Assurance of the Reduced Data

Because the data were reduced by multiple researchers over a period of time, there were inconsistencies and irregularities in the coding. Efforts were made to minimize these human errors in the traces that were ultimately used in the analyses. Three hundred forty-three coded time series traces (0.1 seconds apart) from work zones on four-lane divided roadways were stacked together, and the data set represented a combined file comprised of multiple time series files that included other variables associated with the time stamps. Similarly, 511 traces from work zones on multi-lane roadways were stacked together. Driver characteristics (e.g., age and gender) provided for each driver by the VTTI team were linked to these data sets. Mismatches between the variables of different traces were identified, and efforts were made to minimize errors. For example, the roadway's median type was coded in some traces upstream of the work zone, in some for the entire trace, and in some for a certain portion of the trace. For other variables, such as work zone configuration, channelizing device, and weather/lighting conditions, different coders used different subcategory names.

Some traces from each of the two data sets were spot-checked against the available forward videos. Missing information for certain variables in the data sets were imputed using available information from traces from the same work zones.

2.4 Defining Legibility Distance

Sign and object legibility distance was used to determine the point upstream from a sign at which the sign impacts driver behavior. It was assumed that drivers would begin reacting to the presence of a sign or object as soon as it could be detected and interpreted. As a result, sign legibility distance was used to determine the influence area for each sign.

The minimum distance for sign legibility depends on the time it takes for a driver to read the sign and then react and maneuver to comply with the sign. As the vehicle's speed increases, the viewing distance decreases, which means that drivers need more distance to view the entire message. In addition, legibility depends on the sign's placement (perpendicular or parallel). Overall, legibility distance is a complex phenomenon that describes the amount of time drivers need to detect a sign, read it, and then react to the displayed message based on the surrounding traffic scenario (Bertucci, 2006). Legibility distance differs by the type of work zone sign and the speed of the surrounding traffic. Other factors affecting legibility distance are the driver's perception time, the driver's reaction time, time of a day, the driver's acuity of vision, and the driver's age.

The legibility distance for each type of work zone sign was calculated to determine how far upstream a sign would have be visible to the average driver for it to influence driver behavior. This was referred to as the distance of influence for each sign. The legibility distances for various types of signs or objects were determined based on the MUTCD, findings from various studies, and engineering judgement.

A minimum legibility index ratio of 30 feet of legibility distance per inch of letter height was used in accordance with the MUTCD. For example, a letter height of 6 inches would yield a minimum legibility distance of 180 ft for static work zone signs.

The rationale for selecting the legibility distance for each sign type is described below. Table 2-5 summaries the legibility distances used for the different types of work zone signs in this study.

Table 2-5. Legibility distance for different types of work zone signs

Type of Work Zone Sign	Legibility Distance, ft (m)
Static Work Zone Sign with 6 in. Letter Height	180 (54.86)
CMS	600 (182.88)
Arrowhead VMS or CMS	600 (182.88)
Speed Limit Signs (Normal, Work Zone, Feedback)	450 (137.16)
Lane Ends Sign	450 (137.16)

2.4.1 Static Work Zone Signs

Using MUTCD guidance, a legibility index of 30 feet of legibility distance per inch of letter height was used, with an assumed letter height of 6 inches, which yields a legibility distance of 180 feet for this sign type.

2.4.2 CMS

CMS is used to refer to both changeable message signs and dynamic message signs. General guidance on displaying messages on a DMS or CMS indicates that on roadways with speed limits of 55 mph or higher, signs should be visible from half a mile under both daytime and nighttime conditions. The message should be designed to be legible from a minimum distance of 600 feet for nighttime conditions and 800 feet for normal daylight conditions. The MUTCD similarly recommends that changeable message signs should be legible from at least 600 feet for nighttime conditions and 800 feet for normal daylight conditions.

Since the guidance consulted for this study agrees that the message displayed on a CMS should be legible from at least 600 feet, that was the distance utilized in the analyses.

2.4.3 Arrow Boards

The legibility distance for arrow board signs was selected to be the same as that for a CMS (600 feet). In reality, an arrow board can be detected at a much greater distance, but in the absence of additional information, it was decided to use the conservative estimate for a CMS.

2.4.4 Speed Limit and Dynamic Speed Feedback Signs

A study by Perez et al. (2016) showed that, depending on the type and placement of the sign, the mean legibility distance for speed limit signs is close to 1,250 feet due to the large size of speed limit numbers and universal driver recognition of this type of sign. Jacobs et al. (1975) found that the legibility distance for signs displaying symbols was double that of alphanumeric signs. Other studies have also found that increasing the character height does not linearly or proportionally increase the sign's legibility distance. For instance, doubling the character height does not double a sign's legibility distance (Allen et al. 1967). Garvey and Mace (1996) found that increases in character height greater than about 8 inches resulted in non-proportional increases in legibility distance.

Given that work zone speed limit signs vary considerably, an average character height of 15 inches was assumed for the speed limit characters, and the legibility distance was calculated as 450 feet.

2.4.5 Lane Ends Signs

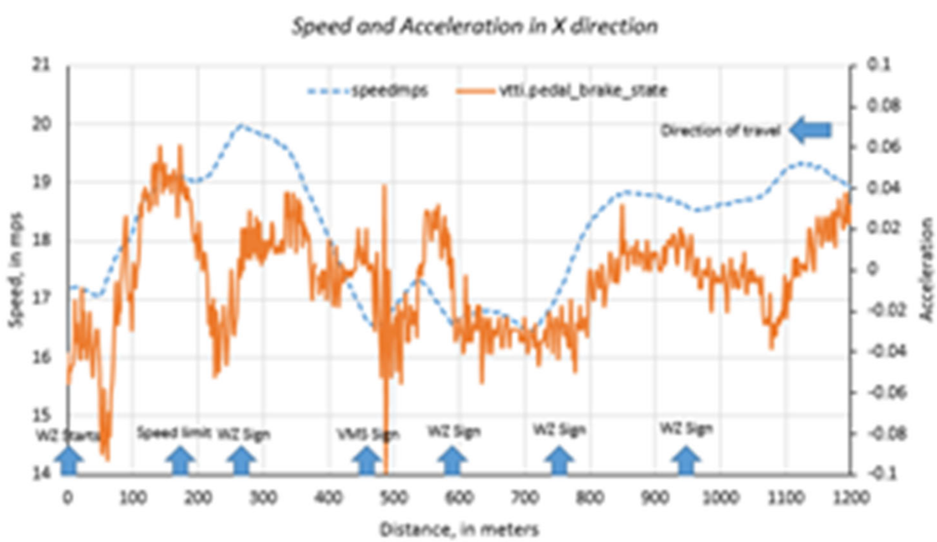
The lane ends sign uses a symbol larger than the characters used on other sign types. A study by Paniati (1988) used an FHWA sign simulator to show a legibility distance equivalent to 295 feet (90 meters) for the lane merging sign (W4-1). Another study by Zwahlen et al. 1991 involving actual field tests found the legibility distance for the W4-1 sign to be close to 900 feet, which is significantly larger than the distance found by Paniati (1988). Since the two studies showed a wide range, it was assumed that the effect of the size of the symbol on a lane ends sign was comparable to that of the text size on a speed limit sign. As a result, a legibility distance of 450 feet was utilized in the present study.

3. EVALUATION OF REACTION POINT

The main objective of this analysis was to assess where drivers begin reacting or responding to different work zone signs in the advance warning area. Different surrogates such as change in acceleration, speed, lane position, or pedal position have been used to detect changes in driving behavior (Chen et al. 2015, Sayer et al. 2007, Af Wåhlberg 2008, Miyajima et al. 2006). It is assumed that when drivers are presented with traffic control or changes in roadway characteristics, they are likely to engage in some measurable response, such as adjusting their speed or attending to their lane position.

Several surrogate measures were considered based on those utilized by other researchers. Steering wheel position has been used as a measure of driver attentiveness (Kircher and Ajlstrom 2017 Bach et al. 2008). However, steering wheel position could only be extracted from the time series traces for a subset of vehicles due to differences in vehicle systems. As a result, this measure could not be utilized. Lane position is not an accurate reflection of driver behavior in work zones since its measurement relies on lane lines, which are often obscured, missing, or overlapping in work zones. Pedal position was not available for a large number of traces, and as a result using this measure would have resulted in a much smaller sample size. Pedal position is also correlated to speed.

Forward acceleration was also considered as a surrogate measure, but the manner in which the acceleration data were gathered resulted in a significant amount of noise, as shown in Figure 3-1.



Data source: VTTI

Figure 3-1. Vehicle kinematics showing noise in the acceleration data

Additionally, acceleration and speed are highly correlated. Since the speed data had less noise, was more likely to be reported at regular intervals in the data, and was a common measure used in the literature, speed was selected as the variable of interest to detect changes in driving behavior.

A change in speed was used as a surrogate for driver reaction. It was assumed that when drivers encounter a work zone feature, such as traffic control or equipment, they will decrease their speed. However, in some cases drivers do not decrease their speed when they encounter a work zone feature. They may have already slowed to a safe speed at the start of the work zone and as a result do not need to take further action. Additionally, a driver may see a work zone feature and become more alert and prepared to take action when needed but does not slow down. In many cases, drivers may simply not change their speed even when conditions indicate that they should. However, a driver's mental state cannot be detected, and as a result only reactions that manifested in a physical change could be identified.

3.1 Description of Data for Evaluation of Reaction Point

This study focused on work zones on four-lane divided roadways. Only traces with good speed data (less than 10% missing data) within the advance warning area were used. Additionally, only traces that could be considered to be traveling at freeflow speeds were utilized. The advance warning area distance was different for each work zone, since traffic control configurations vary. As noted above, the advance warning area extended 200 meters upstream of the first work zone sign to the beginning of the first taper for the work zone. This filtering resulted in 299 time series traces corresponding to 142 unique drivers and 25 unique work zones on four-lane divided roadways with either lane or shoulder closures, as shown in Table 3-2.

Table 3-2. Summary of traces used in reaction point models

Type of Work Zone	Total number of traces	Unique Drivers	Unique Work Zones	States
All	299	142	25	(PA = 140 and NY = 159)
Shoulder Closed	82	56	8	
Lane Closed	217	107	19	

All signs within the work zone influence area were included in the analyses. Sign locations were identified in relation to each time series trace. As a result, a vehicle's position in relation to each work zone feature was available at 0.1-second intervals. Figure 3-2 shows the average locations of work zone signs in relation to the beginning of the taper for the shoulder closure or lane closure. As the figure shows, CMS, when present, were typically placed near the first work zone sign.

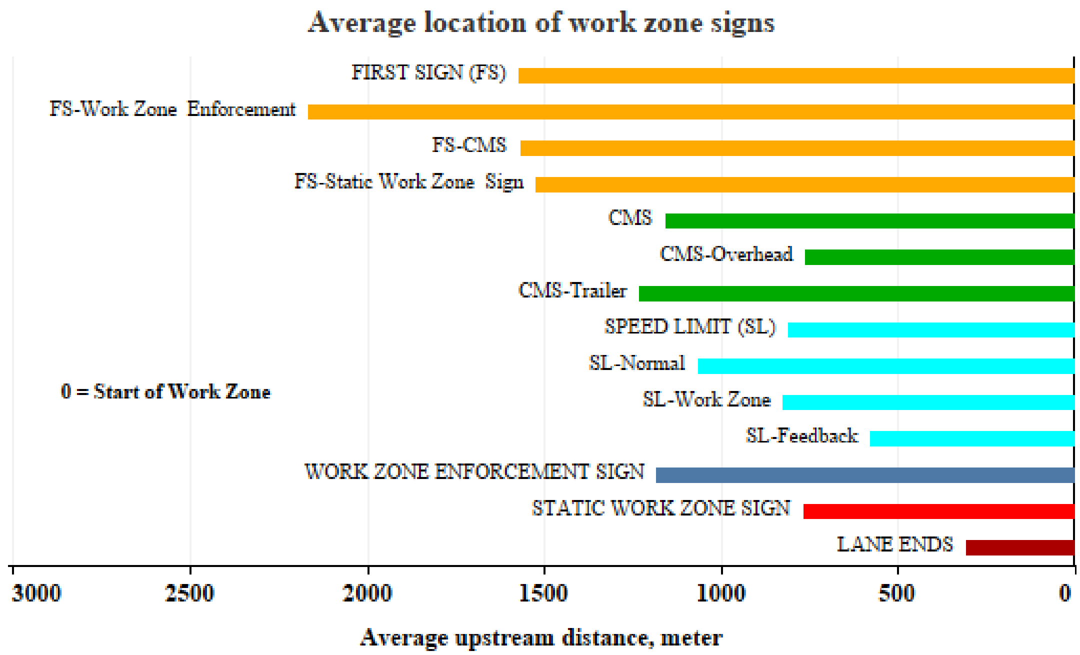


Figure 3-2. Average distance of work zone signs in relation to start of work zone

A change point model was developed for each of the 299 time series traces that included the advance warning area. Statistically significant change points were detected for each trace using the speed and acceleration threshold described in the previous section. As shown in Figure 3-3, about 15% of the speed traces (45) had no discernable reaction points for any work zone feature.

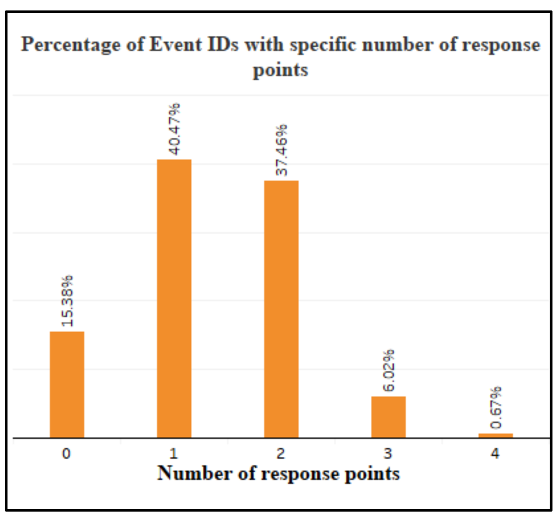


Figure 3-3. Percentage of speed traces (Event IDs) with associated number of reaction points

As the figure shows, the majority of drivers had one or two reaction points in the advance warning area, and 6% had three reaction points. This suggests that most drivers reacted only a couple of times as they approached the work zone.

3.2 Model Description for Evaluation of Reaction Point

Several methods are available to detect change point locations based on changes in mean or variance or changes in the parameters of the fitted linear segments (Haccou et al. 1998, Chen and Gupta 1997, Fryzlewicz 2014, Gerard-Merchant et al. 2008, Matteson and James 2014, Muggeo 2008). Based on the nature of the data set, a piecewise linear regression approach was used to detect change points. Models were developed using R's "Segmented" package. A linear model was developed for each time series trace using speed as a dependent variable, as shown in Equation 3-1.

$$y = \beta_0 + \beta_1 D + \beta_2 (D - D^*) \qquad (3\text{-}1)$$

where y is the dependent variable for each model, D is the distance upstream from the beginning of the work zone (negative value), and D^* is the change point (the distance at which the driver reacts to the work zone feature).

Data were modeled for a distance of 200 feet upstream of the first work zone sign to the start of the work zone (see Figure 3-1). Depending on the placement of the first sign, the length of the upstream section differed by work zone.

The model detected a change point if a significant difference was found in the slope of the fitted model (Muggeo 2008). A Davies test was used to check whether the detected change points were significant. Thresholds can be set so that only changes of a certain magnitude are found. This is important since there is a certain amount of noise in the data and not all significant changes in speed necessarily indicate that a driver is reacting to an external stimulus.

Since numerous minor changes in speed were present in the time series traces, a threshold for what was indicative of a change in driver behavior was established. Various studies were consulted, and it was found that many researchers used a speed reduction of 3 to 7 mph as a threshold to detect reaction to work zone signs (Sorel et al. 2007, Edara et al. 2013, Finley et al. 2008, Meyer 2003, Benekohal et al. 2010, Finley et al. 2014). However, the scientific rationale for this range of thresholds was not explained in the available research. As a result, the team also considered the number of reaction points identified at different thresholds in a set of sample speed traces using a range of 3 to 10 mph. This was done to assess whether there was a clear point at which the number of reaction points dropped off rapidly, which would thus indicate a threshold between regular driving fluctuations and actual responses to external stimuli. For instance, using a threshold of 1 mph would lead to a significant number of reaction points, since this speed change is within the threshold of normal driving.

After careful evaluation of the sample speed traces, it was decided to use a threshold of $\geq$ 3 mph. The speed change threshold was also coupled with a deceleration rate of a certain magnitude. Otherwise, changes in speed over a long distance would have been identified as single reaction points. It was determined that about 90% of reaction points were in the range of 0.1 to 1.5 m/s^2. Deligianni et al. (2017) estimated a maximum deceleration rate of about 2.45 m/s^2 during normal driving conditions. The Institute of Transportation Engineers (ITE) (1999) and the American Association of State Highway Transportation Officials (AASHTO) (2004) consider 3.0 and 3.4 m/s^2 as the limit of comfortable deceleration for stopping behavior. While these values represent the upper range of normal driving and could be used to filter out abnormal events, no information was available to select a lower bound. A final threshold of ≥ 3 mph with a deceleration rate in the range of 0.1 to 2.0 m/s^2 (0.2 g) was considered as a threshold for further analysis. Based on the threshold, a reaction point was defined as a point with a change in speed of ≥ 3 mph and a deceleration rate of 0.1 to 2.0 m/s^2. Only detected reaction points satisfying the criteria were used for the analysis.

Additionally, reaction points were reviewed in conjunction with the forward video, and reaction points due to scenarios such as a lane merge, traffic entering from a ramp, and sudden braking due to traffic ahead were removed. The effects of roadway geometry (horizontal curve or grade) were was not considered since the grade was reasonably flat in most cases and no sharp horizontal curves were present.

As mentioned previously, the locations of work zone signs and features were identified for each time series trace. The detected reaction points were then linked to each feature. The legibility distance of each sign was determined as described in Defining Legibility Distance above and represented the likely distance within which a driver was able to see and therefore react to the sign.

Using sign location and legibility distance, an influence area for each sign was specified for each time series trace. It was assumed that a driver may react at any point after a sign becomes legible, including some distance downstream from the sign. For instance, a driver may see a work zone speed limit sign but not slow down until he/she has passed the sign. As a result, a distance of 50 meters downstream of each sign was also included in the influence area. This distance was determined using average speed limit and a response time of 2.5 seconds.

Each reaction point was linked to the nearest corresponding work zone sign using the influence area for each sign. In some cases, the influence areas of two signs overlapped. In these cases, a node was created within the overlapping area, and when a reaction point fell within the overlapping area, it was assigned to the overlapping area rather than to an individual sign.

The methodology for linking work zone signs to reaction points is illustrated in Figure 3-4.

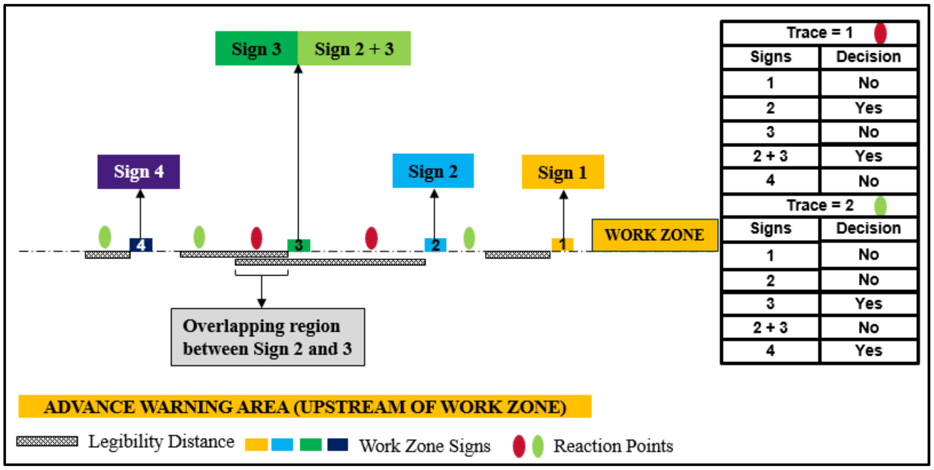


Figure 3-4. Methodology to combine work zone signs and reaction points

Based on the binary variable, a mixed effects logistic regression model was developed to find the different factors affecting driver behavior within advance warning areas, such as the presence of work zone signs, sign locations and types, vehicle speed, environmental factors, and driver information. The "glmer" function available in the "lme4" package was used in R 3.5.1 to develop the model using driver ID and work zone ID as the repeated effect. The fit of the model was checked based on the Akaike information criterion (AIC), log likelihood, and residual plots.

Reaction points were identified for 299 time series traces corresponding to 142 unique drivers and 25 unique work zones on four-lane divided roadways with either lane or shoulder closures. As noted above, 46 time series traces, or 15% of the traces, had no discernable reaction points and were not included in the models. Table 3-3 summarizes information about the variables.

Table 3-3. Summary of data used in change point analysis

Variable	Count				
Total number of nodes (Y variable)	1529 (1 = 272, 0 = 1257)				
Total reaction points captured	272 (67% of 407)				
Work Zone (WZ) Type	**Count (Unique Traces)**	**Unique Driver ID**	**Unique WZ ID**		
Total	299	142	25		
Shoulder closed	82	56	8		
Right side closed	13	10	1		
Left side closed	69	50	10		
Lane closed	217	107	19		
Right side closed	131	81	11		
Left side closed	86	53	9		
Different Sign Types	**Count (# of nodes)**	**Average distance to the signs or nodes, meters**			
Total number of nodes	**1560**	**Min.**	**Max.**	**Std. Error**	**Average (Fig 3)**
Static Work Zone Sign	413	57.96	2201.56	495.64	764.99
First Sign	270	9.45	4106.16	807.07	1569.42
Enforcement	18	1687.74	2626.56	445.79	2164.51
CMS	22	1287.74	1753.43	134.17	1567.10
Static Work Zone Sign	230	9.45	4106.16	847.78	1523.06
Speed Limit	310	7.11	4558.64	707.02	810.67
Normal	47	148.98	4558.64	689.73	1064.77
Work Zone	197	7.11	2697.36	799.11	827.86
Feedback	66	110.65	670.22	108.67	578.44
CMS	120	164.42	1922.27	585.93	1155.12
Active	65	164.42	1915.31	513.93	795.09
Not Active	55	410.26	1922.27	321.09	1580.62
Trailer	123	291.88	1922.27	546.38	1228.76
Overhead	19	164.42	1915.32	647.28	763.69
Emergency Sign	28	357.14	2510.60	347.32	1179.86
Overlapping Signs	208	74.73	4394.82	546.66	749.18
Lane Ends	180	136.03	593.55	103.04	307.29
Total number of signs (count) at each work zone		1	10	2.17	5.71
Travelling speed					
Speed difference only at First Sign (Travelling – Posted Speed limit)	299	-10.84	33.63	8.36	11.71
Speed difference at all the Signs (Travelling – Posted Speed limit), mph	299	-16.91	33.27	7.61	7.65
	Count	**Min.**	**Max.**	**Std. Error**	**Average**
Driver Age (Time of trip collection)	142	17	88	19.35	48.29
Driving experience	142	0	70	19.41	31.02
Sex (Male = 1, Female = 0)	70				
Count	**0**	**1**	**2 or more**		
Number of violations	226	43	30		
Number of crashes	218	72	9		
Count	**Car**	**Pickup Truck**	**SUV**	**Van**	
Types of Vehicle (Car = 1)	206	20	64	9	
Day vs Night (Day = 1)	242				
Pavement Condition (Dry = 1)	273				
Location of vehicle (Right = 1)	993				

A total of 276 reaction points were within the work zone influence area and were included in the model. The First Sign, Speed Limit, and CMS categories under Different Sign Types in Table 3-3 are further divided based on the sign types within the respective categories, and the average distances of the signs from the start of the work zone are provided. Table 3-3 also shows the average distance of each type of sign from the beginning of the taper point.

Table 3-3 also includes information about the drivers, vehicles, and pavement conditions. The driver's speed at each reaction point was compared to the posted speed limit, which was either a normal or work zone speed limit, and the difference was calculated. Driver characteristics such age, gender, driving experience, and crash experience are also summarized in the table. Pavement conditions at the reaction point were coded as dry if the weather conditions were described as sunny, cloudy, or dry. The location of the vehicle indicates the lane movement of the subject vehicle at the sign location.

3.3. Results for Evaluation of Reaction Point

A logistic regression model was used to assess the likelihood that a driver would respond to a particular work zone feature. Change points were identified for each time series trace as described in the previous section. The logistic regression model included one observation for each work zone feature (node) for each time series trace. For example, if a driver passed 10 work zone features in one time series trace, 10 observations were noted. If a change point was detected within the legibility distance defined for that feature, the observation was assigned a value of 1. If no change point was detected, the observation was assigned a value of 0.

A mixed effects logistic regression model was developed to address random effects due to repeated measures. Driver ID and work zone ID were used as random effects in this model to account for multiple samples from the same driver or work zone. The "glmer" function available in the "lme4" package was used in R 3.5.1 to fit the model. The best fit model was selected based on the minimized AIC. In addition, the fit of the model was also checked by visualizing residuals in R.

The results of this model are shown in Table 3-4.

Table 3-4. Model results for change point analysis

Description	Variables	Baseline	Estimate	Std. Error	Z- value	P-value	Odds Ratio
	Intercept		-1.793	0.151	-11.870	0.000	0.167
Work Zone Signs (Baseline: Static Work Zone Sign)	Enforcement	Static Work Zone Sign	-1.567	1.032	-1.519	0.129	0.209
	Overlapping		-0.172	0.265	-0.649	0.516	0.842
	Lane Ends		0.429	0.240	1.785	0.074	1.536
	SL_Normal		-0.397	0.508	-0.781	0.435	0.672
	SL_Feedback		0.703	0.318	2.213	0.027	2.019
	SL_WorkZone		0.803	0.228	3.529	0.000	2.232
	CMS_Active		0.842	0.319	2.636	0.008	2.320
	CMS_NotActive		0.666	0.359	1.856	0.063	1.947
	FS_Enforcement		0.506	0.594	0.852	0.394	1.658
	FS_CMS		0.842	0.510	1.650	0.099	2.321
	FS_WZ		0.063	0.233	0.269	0.788	1.065
Log likelihood: -709.6, AIC: 1447.2							

The odds ratio in Table 3-4 is the likelihood of a change point occurring for a particular type of sign using static work zone signs as the baseline. We use the terminology "driver response" or "reaction" to indicate the likelihood of a change point occurring, which signifies that a driver reduced his/her speed when encountering the sign or work zone feature.

As Table 3-4 shows, when a driver first enters the work zone, there is no statistically significant change in the likelihood that the driver will respond when the first sign he/she is presented with is a static work zone sign (OR = 1.07, p = 0.79) or enforcement sign (OR = 1.66, p = 0.39). When the first sign is a CMS, drivers are 2.32 times more likely to react (p = 0.10). As a result, drivers are most likely to react when a CMS is the first sign encountered upon entering a work zone. It should be noted that there were occasions when the first work zone sign was a warning message significantly upstream (more than 2 miles) of the work zone. In such cases, a CMS was coded as the first sign but in actuality may not have been the first sign a driver encountered. In all cases, it can be interpreted that when the first sign a driver encountered when approaching within 2.5 miles of the start of the work zone was a CMS, it was more likely to get a driver's attention than static signs.

Once drivers were within the advance warning area, they were not likely to respond to enforcement signs (OR = 0.21), p = 0.129). In contrast, drivers were highly likely to react to a speed feedback or static work zone speed limit sign (OR = 2.02, p =0.23 and OR = 2.23, p = << 0 respectively). A separate t-test showed that the effects of speed feedback and static work zone speed limit signs were not statistically significantly different. This may suggest that after drivers are presented with a work zone speed limit sign, they are equally likely to react to a static or electronic sign.

Active changeable message signs in general were 2.32 times more likely to elicit a driver's response compared to static work zone signs (p = 0.01), and drivers were almost twice as likely to respond to a CMS even when it was not actively displaying a message (OR = 1.95, p = 0.06). This result refers to CMS other than those located at the beginning of the advance warning area.

3.3 Limitations

The brake activation variable was available in the time series files, but due to some missing values in some traces, it was not always possible to use it as a variable of interest to detect reaction point. When speed was used as a variable of interest, a few traces were removed because many values in the speed column were missing. Only traces with high accuracy in terms of speed were used for the analysis. Traces where the speed of the subject vehicle was influenced by the forward vehicle were also removed. The effect of the presence of a police car, though initially planned to be included in the study, was not considered separately in the analysis due to the limited sample size. In addition, the effect of different types of text displayed on CMS was not considered. Due to the quality of the video, it was not always possible to reduce the text displayed on the CMS.

4. EVALUATION OF CHANGE IN SPEED

The main objective of this analysis was to predict how drivers change their speed in relation to work zone characteristics. It was assumed that reduction in speed has a positive safety benefit. However, note that in many cases, by the time drivers reach certain work zone features they 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 initially attempted, but speed is highly correlated to distance from the taper point. Additionally, the location of many work zone features is also correlated to distance from the taper point. As a result, it was difficult to fit a model that could account for these correlations but still provide a meaningful relationship between speed and work zone features. As a result, change in speed was used because it could isolate the impact of individual work zone features.

4.1 Description of Data for Change in Speed Model

Change in speed was calculated for each work zone feature within the influence area for each time series trace. Any work zone-related object within 2.5 miles upstream of the taper point to a distance 1.0 mile inside the work zone (downstream) was included. The vehicle’s upstream speed for each object was captured 100 meters upstream of the start of the legibility distance, and the vehicle’s downstream speed was captured 50 meters downstream of the object. It was assumed that drivers upstream of that initial upstream point had not yet seen the object and were not influenced by the object. The downstream distance accounts for drivers slowing after they have passed the object. Change in speed was calculated as 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.

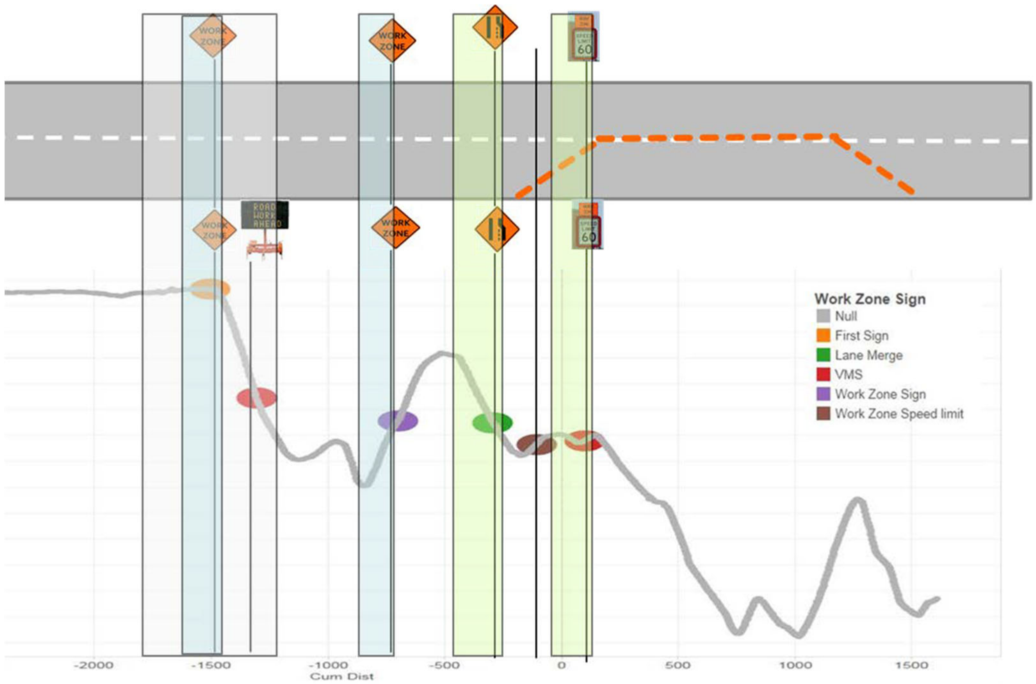


Figure 4-1. Change in speed between buffered legibility distances

As mentioned earlier, a forward-related glance was coded when the driver was looking forward, left, right, or at the rear view mirror. The percentage of forward glances was coded as the number of timestamps in which the driver was looking forward divided by the total number of timestamps inside the upstream buffered legibility distance only. 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.

Similarly, a cell phone-related distraction was coded when a driver was using a cell phone in some capacity; all other distraction categories were grouped as non-cell phone-related distractions. The percentage of cell phone use was coded as the number of timestamps the driver was distracted by a cell phone divided by the total number of timestamps inside the upstream buffered legibility distance only.

Age was categorized into three groups: drivers younger than 25 years old, drivers between 25 and 64 years old, and drivers 65 years old or older.

Other characteristics specific to each object were also summarized. Each row in each trace file represented change in speed (in mph) and the other summarized characteristics of that trace for different bands along the length of the work zone.

4.2 Model Description for Change in Speed Model

A linear mixed effects model was used to predict drivers' change in speed in relation to work zone characteristics. A linear mixed effects model provides a linear relationship between a dependent variable (change in speed) and fixed effects. Mixed effects models incorporate both fixed effects parameters and random effects. The fixed effects are the variables of interest, and the random effects are the variables that account for dependency. A random effects variable was included for each driver to account for repeated measurements.

In these two models, only one random effect is being considered. The model for a single observation is as follows:

$$y = x^T \beta + u + \epsilon \tag{4-1}$$

where y is the response, x is the vector of explanatory variables, β is the vector of coefficients, u is the random effect for trace, and ϵ is the error. The random effect u is normally distributed with mean zero and variance σ_u^2, while ϵ is normally distributed with mean zero and variance σ_ϵ^2.

Moreover, the mean of y is $x^T\beta$ 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.

The lme4 package in R was used to estimate the model. The r-squared values from each observation-level model and an ANOVA test were used to evaluate the model's goodness of fit. Residual plots were also constructed to check the assumptions of the model. The final model was produced using backward elimination. That is, a complex model was initially considered, and it was gradually simplified using F-tests.

The variables evaluated in the models for each observation are included in Table 4-1.

Table 4-1. Descriptive statistics for work zones on four-lane divided roads

Variable	Description	Mean	Std Dev	Min	Max
Female	1 if the participant was female, 0 otherwise	0.57	0.50	0.00	1.00
TwentyFourYounger	1 if the participant was younger than 24, 0 otherwise	0.15	0.36	0.00	1.00
TwentyFiveToSixtyFour	1 if the participant was between 25 to 64, 0 otherwise	0.60	0.49	0.00	1.00
SpeedChangemph	Change in speed in miles per hour	-1.37	4.24	-33.17	35.80
SignPlacementDist	Distance of objects from the start of work zone	-296.66	1060.39	-3937.62	1607.76
CMS	1 if changeable message sign was present, 0 otherwise	0.15	0.35	0.00	1.00
CMSFirstSign	1 if changeable message sign was present as the first sign, 0 otherwise	0.00	0.07	0.00	1.00
CMSStatus	1 if changeable message sign was active, 0 otherwise	0.08	0.27	0.00	1.00

Variable	Description	Mean	Std Dev	Min	Max
EnforcementSign	1 if enforcement sign was present, 0 otherwise	0.03	0.17	0.00	1.00
Equipment	1 if equipment was present, 0 otherwise	0.12	0.33	0.00	1.00
LaneEndSign	1 if Lane end sign was present, 0 otherwise	0.07	0.26	0.00	1.00
NormalSpeedLimit	1 if Normal Speed Limit sign was present, 0 otherwise	0.04	0.21	0.00	1.00
SpeedFeedback	1 if speed feedback sign was present, 0 otherwise	0.02	0.14	0.00	1.00
StaticWZSigns	1 if static work zone sign was present, 0 otherwise	0.35	0.48	0.00	1.00
WZSpeedLimit	1 work zone speed limit sign was present, 0 otherwise	0.20	0.40	0.00	1.00
Worker	1 if worker was present, 0 otherwise	0.01	0.12	0.00	1.00
PercentGlance	Percentage of time the driver was looking forward	73.31	41.57	0.00	100.00
LessThanHalfTheTimeFR	1 if driver glance was less then half of the time, 0 otherwise	0.01	0.12	0.00	1.00
PercentCellPhone	Percentage of time the driver was on cell phone	2.17	14.50	0.00	100.00
CellPhoneUse	1 if driver glance was on cell phone, 0 otherwise	0.02	0.15	0.00	1.00
TwoSecGlanceAway	1 if driver had a long glance of more than 2 secs away from road, 0 otherwise	0.01	0.07	0.00	1.00
LaneClosure	1 if work zone configuration was lane closure type, 0 otherwise	0.22	0.41	0.00	1.00
HeadToHead	2 if work zone configuration was head to head, 0 otherwise	0.04	0.18	0.00	1.00
ShoulderClosure	3 if work zone configuration was shoulder closure type, 0 otherwise	0.15	0.36	0.00	1.00
Barrels	1 if channelizing device was Barrels, 0 otherwise	0.20	0.40	0.00	1.00
Cones	1 if channelizing device was Cones, 0 otherwise	0.01	0.12	0.00	1.00
Concrete	1 if channelizing device was Concrete, 0 otherwise	0.12	0.33	0.00	1.00
VerticalPanels	1 if channelizing device was Vertical Panels, 0 otherwise	0.06	0.23	0.00	1.00
ChannelizationOnBothSides	1 if channelization was present on both sides of road, 0 otherwise	0.04	0.20	0.00	1.00
EquipmentInsideBarrier	1 if worker present inside barrier, 0 otherwise	0.12	0.33	0.00	1.00
WorkerInsideBarrier	2 if equipment present inside barrier, 0 otherwise	0.99	0.11	0.00	1.00

Variable	Description	Mean	Std Dev	Min	Max
FollowingCar	1 if driver followed a vehicle, 0 otherwise	0.13	0.34	0.00	1.00
LaneChange	1 if driver was at the verge of changing lanes, 0 otherwise	0.02	0.13	0.00	1.00
Rainy	1 if it was raining or snowing, 0 otherwise	0.07	0.26	0.00	1.00
Night	1 if it was nighttime, 0 otherwise	0.20	0.40	0.00	1.00

4.3 Results of Evaluation of Change in Speed in Work Zones on Four-Lane Divided Roads

The final model for work zones on four-lane divided roads included the variables presented in Table 4-2, which includes two interactions, one between static work zone signs and channelizing devices and another between CMS and channelizing devices.

Table 4-2. ANOVA results for the model for work zones on four-lane divided roads

	Chisq	Df	Pr(>Chisq)
Equipment	26.79571	1	2.26E-07
StaticWZSigns	17.57096	1	2.77E-05
WZSpeedLimit	0.010431	1	0.91865
Location	25.30843	2	3.19E-06
ChannelizingDevice.1	37.21588	4	1.63E-07
WZSpeedLimit:Location	20.34083	2	3.83E-05

Table 4-2 also shows the p-values for each of the included variables; all of the p-values are smaller than 0.005 except for the p-value for work zone speed limit signs (WZSpeedLimit), but this variable is included nevertheless since the interaction with location is very small.

Table 4-3 presents a breakdown of the estimates for these variables.

Table 4-3. Estimates of parameters for work zones on four-lane divided roads

	Estimate	Std. Error	t value
(Intercept)	-1.76919	0.243201	-7.27459
Equipment	1.892666	0.36563	5.176457
StaticWZSigns	0.968503	0.231049	4.191772
WZSpeedLimit	-0.99144	0.429937	-2.30602
Location:Downstream	1.378596	0.616797	2.235089
Location:Half_mile_upstream	1.092333	0.277096	3.942066
ChannelizingDevice.Barrels	-2.76266	0.626523	-4.40952
ChannelizingDevice.Concrete	-1.5844	0.649704	-2.43865
ChannelizingDevice.Cones	-2.64147	1.039598	-2.54086
ChannelizingDevice.VerticalPanels	-3.64491	0.704319	-5.17508
WZSpeedLimit:Downstream	2.186838	0.547176	3.996591
WZSpeedLimit:Half_mile_upstream	-0.10141	0.705557	-0.14374

An increase of 0.97 mph was noted when a driver encountered a regular work zone sign. When a driver encountered concrete barriers, a decrease of 1.158 mph resulted. When cones were present, a decrease of 2.64 mph was noted, while the presence of barrels resulted in a decrease of 2.76 mph. The most significant decrease was noted for the presence of concrete barrels with vertical panels, which resulted in a decrease of 3.64 mph. Interestingly, when equipment was present, drivers increased their speed by 1.77 mph. If a worker was present, this was noted as "worker" and was not found to result in a statistically significant change in speed.

The interaction between work zone speed limit signs and sign locations is presented in Table 4-4.

Table 4-4. Interaction between work zone speed limit signs and sign locations

Sign	0.5 to 1 mile upstream	0.5 miles upstream	Downstream
WZSpeedLimit	-0.991444	-1.092858	1.195394

Each cell in the table represents the change in speed (in mph) in the presence of a work zone speed limit sign in a given location relative to the taper point. The values in the cells were computed using the appropriate linear combinations from the coefficients listed in Table 4-3. For example, the incremental change in speed in the presence of a work zone speed limit sign located more than half a mile upstream of the taper point (-1.092858) was obtained by adding the estimates for "WZSpeedLimit" (-0.99144) and "WZSpeedLimit:Half_mile_upstream" (-0.10141) in Table 4-3. As the table shows, when the speed limit sign was between 1 mile and 0.5 miles upstream of the taper point, drivers decreased their speed by about 1.1 mph, and within the work zone (downstream of the taper point), the presence of a speed limit sign was associated with a slight speed increase.

Finally, the estimate of the standard deviation between the traces (σ_u) is 1.4287, and the estimate of the standard deviation within the traces (σ_ϵ) is 3.8542.

4.4 Results of Evaluation of Change in Speed in Work Zones on Multi-Lane Roads

The final model for work zones on multi-lane roads includes the variables presented in Table 4-5, which includes two interactions, one between static work zone signs and channelizing devices and another between CMS and channelizing devices.

Table 4-5. ANOVA results for the model for work zones on multi-lane roads

	Chisq	Df	Pr(>Chisq)
LaneEndSign	5.514366	1	0.018861
StaticWZSigns	26.0149	1	3.39E-07
Location	442.3592	2	8.77E-97
LeftShoulderClosure	7.235542	1	0.007147
leftLaneClosure	57.30764	1	3.73E-14
ChannelizingDevice	1.561773	4	0.815646
WZSpeedLimit	2.47499	1	0.11567
CellPhoneUse	1.934805	1	0.164234
StaticWZSigns:location	64.81206	2	8.44E-15
ChannelizingDevice:WZSpeedLimit	11.79382	3	0.008124
location:CellPhoneUse	8.586999	2	0.013657

Table 4-5 also shows the p-values for each of the included variables. Note that unlike the other p-values, the p-values for channelizing device, work zone speed limit, and cell phone use are greater than 0.02. Although these variables are not statistically significant, they are included for the sake of interpretability of the model, since they have interactions with other variables that are significant.

Table 4-6 presents a breakdown of the estimates for these variables.

Table 4-6. Estimates of the parameters in the model for work zones on multi-lane roads

	Estimate	Std. Error	t value
(Intercept)	3.478861	1.641178	2.119735
LaneEndSign	-2.21041	0.941294	-2.34827
StaticWZSigns	12.24086	1.323277	9.250415
locationhalf_mile_upstream	-3.04132	1.677475	-1.81303
locationdownstream	-3.98593	1.452951	-2.74333
LeftShoulderClosure	-1.85619	0.690058	-2.6899
leftLaneClosure	4.166882	0.550434	7.570181
ChannelizingDeviceConcrete	0.975652	0.522819	1.866137
ChannelizingDeviceCones	-0.89981	2.700554	-0.3332
ChannelizingDeviceNoChannelization	0.583732	0.937622	0.622566
ChannelizingDeviceVerticalPanels	-1.32009	4.009665	-0.32923
WZSpeedLimit	1.854468	1.189121	1.559528
CellPhoneUse	-7.60889	2.392944	-3.17972
StaticWZSigns:locationhalf_mile_upstream	-12.5208	1.800916	-6.95247
StaticWZSigns:locationdownstream	-11.1387	1.432244	-7.77707
ChannelizingDeviceConcrete:WZSpeedLimit	-5.64006	1.773455	-3.18027
ChannelizingDeviceCones:WZSpeedLimit	1.544447	7.460541	0.207015
ChannelizingDeviceNoChannelization:WZSpeed Limit	-4.29406	1.733177	-2.47757
locationhalf_mile_upstream:CellPhoneUse	6.420885	2.860108	2.24498
locationdownstream:CellPhoneUse	7.814445	2.669163	2.927676

When no interactions are present, the estimates represent the change in speed (in mph) in the presence of a given object. For example, the table shows that the presence of a lane end sign results in a decrease in speed of 2.21 mph on average. The table also shows that the presence of a left shoulder closure results in a 1.86 mph decrease in speed, while a left lane closure results in an increase in speed of 4.17 mph. This latter result may be due to drivers speeding up in an attempt to merge.

The interaction between static work zone signs and sign locations is presented in Table 4-7.

Table 4-7. Interaction between static work zone signs and sign locations

	0.5 to 1 mile upstream	0.5 miles upstream	Downstream
static work zone sign	12.2408593	-0.2799532	1.1021906

Each cell in the table represents the change in speed (in mph) in the presence of a static work zone sign in a given location relative to the taper point. As the table shows, when a static work zone sign was present more than 0.5 miles upstream of the taper point, drivers increased their speed by 12.24 mph. This is an unexpected result. Between 0.5 miles upstream of the taper point and the taper point itself, drivers encountering a static work zone sign decreased their speed marginally (0.28 mph), and within the work zone, the presence of a static work zone sign resulted in a small increase in speed (1.10 mph).

The interaction between work zone speed limit signs and channelizing devices is presented in Table 4-8.

Table 4-8. Interaction between work zone speed limit signs and channelizing devices

	Barrels	Concrete	Cones
work zone speed limit sign	1.854468	-5.640063	1.544447

Each cell in the table represents the change in speed (in mph) in the presence of a work zone speed limit sign and a given channelizing device. (There were no observations of the simultaneous presence of vertical panels and work zone speed limits signs.) As the table shows, drivers increased their speed when they encountered a work zone speed limit sign and barrels (1.85 mph increase) or cones (1.54 mph increase). When drivers encountered a work zone speed limit sign and concrete barriers were also present, drivers decreased their speed by 5.64 mph. There was no interaction between work zone speed limit signs and other types of barriers.

The effects of cell phone use differed depending on the area of the work zone in which cell phone use was observed, as shown in Table 4-9.

Table 4-9. Interaction between cell phone use and location

	0.5 to 1 mile upstream	0.5 miles upstream	Downstream
cell phone	-7.6088938	-1.1880088	0.2055508

When drivers who were engaged in a cell phone-related task encountered a work zone object in the advance warning area (0.5 to 1 mile upstream of the taper point), they tended to decrease their speed by 7.61 mph. When drivers encountered an object in the area just upstream of the taper point (0.5 miles upstream), they decreased their speed by 1.19 mph, and within the work zone drivers marginally increased their speed (0.21 mph). This phenomenon has been noted in other studies. In some cases, driver who are engaged in a cell phone-related task are not attending to the forward roadway and do not maintain their speed.

Finally, the estimate of the standard deviation between the traces (σ_u) is 2.474, and the estimate of the standard deviation within the traces (σ_ϵ) is 9.581.

5. BACK-OF-QUEUE MODELS

A model was developed that assessed driver behavior at the back of a queue. About one-third of work zone crashes are rear end and often occur when a driver unexpectantly encounters the back of a queue. A hard deceleration as a driver encountered the back of a queue was used as a surrogate for unsafe behavior.

5.1 Description of Data

Data were reduced using the front view video and time series data. For each event ID, the front view video, speed, and acceleration (in x direction) profiles were checked, and the information described in this section was reduced.

Time series traces were first identified for crash and near-crash events, which are available on the SHRP2 InSight webpage. These events were initially sorted by those coded as being construction related and rear end related. The crash and near-crash events were further reviewed to extract the information described below.

Additionally, another set of back-of-queue events was identified in the time series traces that were utilized for the other analyses.

5.1.1 Queue

Only queues that appeared to be related to work zones were considered for this study. These queues were associated with merging vehicles at lane closures, slow moving vehicles, and reduced capacity at work zones. Other scenarios where queues formed were not considered for this study. These involved vehicles entering from the merge ramp, slow moving vehicles outside of the presence of an active work zone, the presence of only a single vehicle in the queue ahead, or queues moving at normal speed.

5.1.2 Incident or Back of Queue

The point where the subject vehicle reached the back of the queue and started moving at the speed of the queue, that is, where the vehicle adjusted its speed or reacted, was reduced. These events were tagged as incidents of interest.

5.1.3 Reaction Point

The point after which the subject vehicle started reducing its speed for the queue ahead was termed as the reaction point. The reaction point is associated with the vehicle's maximum speed before the back-of-queue incident.

5.1.4 Point of Impact

The period of maximum deceleration between the reaction point and the point of the incident or back of the queue is termed as the point of impact. The acceleration of each trace was plotted to obtain the location of the point of impact. The forward view video was also checked at the time stamp associated with the maximum acceleration to ensure that the point of impact was due to a queue. Based on the reduced data set, the point of impact generally lies within the 5-second interval from the reaction point to the time of the incident or back of the queue. Figure 5-1 shows the general locations of the abovementioned terms.

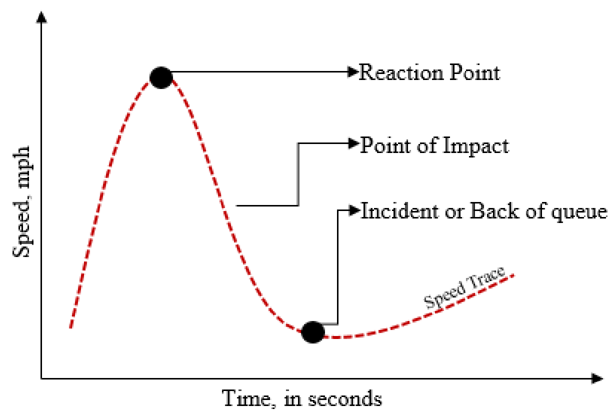


Figure 5-1. Location of reduced information along a speed trace

5.1.5 Level of Service (LOS)

The LOS for the section of road between the reaction point and the time the subject vehicle reached the back of a queue (incident) was coded as A, B, C, D, E, or F according to the definitions used in the *Highway Capacity Manual*.

5.1.6 Distraction

Distraction data have not yet been reduced as of Phase 2. The time series traces for the crash/near-crash events do not overlap with those used in the other analyses, and sufficient resources and time were not available to reduce regular driving data from the crash/near-crash traces. The distraction variable will be considered in the back-of-queue model after the data become available. Including this variable will allow the effect of distraction on drivers' deceleration behavior to be examined. However, some distraction data were available for the crash and near-crash back-of-queue events, and a summary of that information is provided.

5.1.7 Other Information

Other information that was reduced included the following:

- Location of the incident (inside the work zone or in the advance warning area)
- Weather conditions
- Time of day
- Road surface conditions
- Speed at the point where drivers started reducing their speed for the back of the queue ahead
- Maximum deceleration at the point of impact

5.2 Data Available

A total of 225 traces were reduced for the back-of-queue model. Traces from all types of work zones were used, with most of the traces collected from work zones on four-lane divided and multi-lane roadways. Out of the 225 traces, 125 traces were associated with crash or near-crash events, and the remaining traces were associated with the normal back-of-queue scenario. "Crash" and "near-crash" are simply termed as "near-crash" in the following sections.

5.3 Defining Hard Deceleration

Many studies have analyzed driver behavior and differentiated events based on deceleration behavior. Simons-Morton et al. (2009) used naturalistic driving data from 42 teenage drivers to evaluate hard braking events among novice drivers during the first 6 months of licensure. The study used a longitudinal deceleration of ≤ -0.45 g as a threshold to define a hard deceleration event.

Dingus et al. (2006) used 100-car naturalistic driving study data to analyze the differences in driving behavior between safe and unsafe drivers during both crash/near-crash events and normal driving. Unsafe drivers included drivers who were involved in a higher number of crashes, while safe drivers were those involved in fewer crashes. Unlike previous studies, which prioritized driving behavior during crash/near-crash events, this study also analyzed unsafe driving behavior for normal or baseline driving scenarios. The results showed that even during normal driving conditions, unsafe drivers exhibited a deceleration rate greater than 0.30 g.

Using a data set from National Automotive Sampling System Crashworthiness Data System, Kusano and Gabler (2011) presented a method to estimate time to collision. A total of 47 rear end crashes were examined where the drivers of the striking vehicles applied their brakes prior to the collision. Using the speed information from the striking vehicles, the study found an average deceleration of 0.52 g.

Gartner et al. (2001) used a mean deceleration rate of -0.55 g to define unexpected deceleration. ITE and AASHTO also proposed thresholds of 3.0 m/s^2 and 3.4 m/s^2 to define comfortable deceleration.

Based on the results of other studies, the present study defined a hard deceleration as any deceleration ≤ -0.40 g. Since deceleration in this case is negative, this definition includes values such as -0.50 g, -0.60 g, etc. A hard deceleration was used as a surrogate measure of safety.

5.4 Characteristics of Back-of-Queue Events

As noted above, 125 traces were coded as crash or near-crash events and were obtained via the SHRP2 InSight website. Driver behavior and distraction were coded by VTTI for these events, and a summary of the characteristics of these back-of-queue events was included in the data set. Driver distraction and behavior will be coded in Phase 3 for the baseline events and can be used to assess the extent to which distraction or cell phone use contribute to back-of-queue incidents.

Figure 5-2 shows crash/near-crash back-of-queue events by the main distracting behavior present during the 5 seconds before the point of the incident or before the driver reached the back of a queue (as illustrated in Figure 5-1). More than one distraction could have been present in that 5-second window, but only the distraction that occupied the most time in that interval or that indicated the most serious behavior is shown in Figure 5-2.

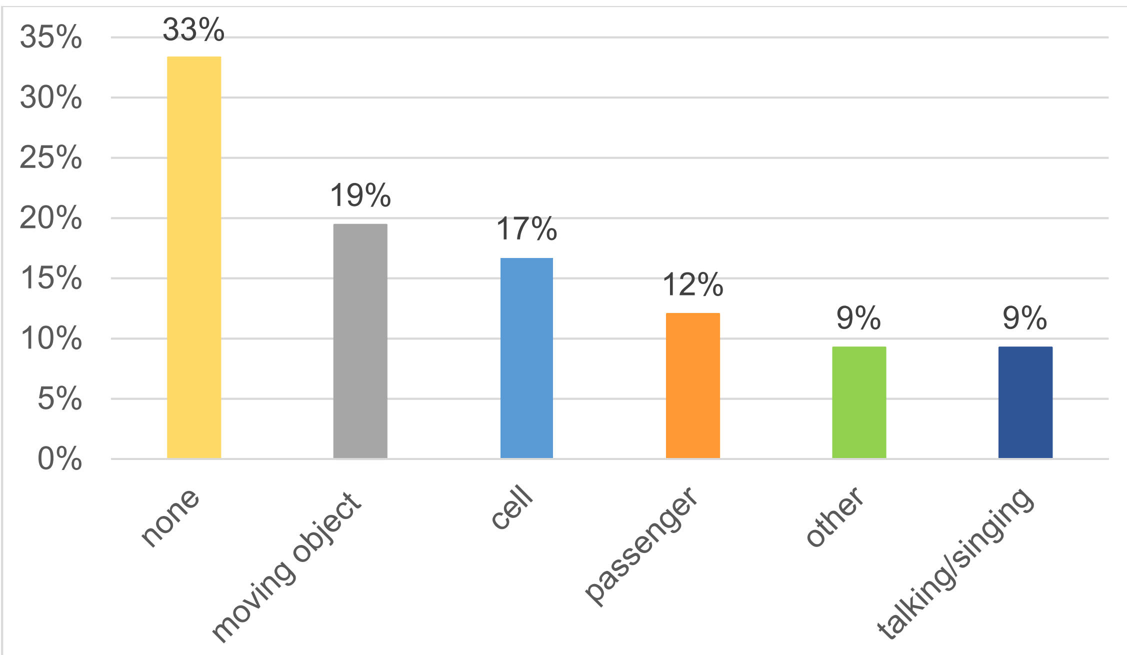


Figure 5-2. Types of driver distraction associated with back-of-queue crash/near-crash events

As the figure shows, 33% of drivers experienced no distraction in the 5 seconds before arriving at the back of the queue. Nineteen percent were engaged in reaching for or moving an object, while 17% were engaged in some cell phone-related task. A cell phone-related task (or any other distraction) was only coded when it involved a glance away from the forward roadway. A cell phone-related task involved reaching for a phone, texting, dialing, or any other activity that involved a cell phone. Talking on the phone was not coded as a distraction if the driver had eyes forward while talking. In such cases, a driver could have been talking on the phone but not engaged in some physical task that took his/her eyes away from the roadway. Some events where the driver was coded as "talking or singing" could have involved a driver talking on a cell phone. Additionally, some of the tasks coded as "reaching" could also have been cell phone related if the VTTI coders could not distinguish the object being moved. Since the sample size for crash/near-crash events is only 125, it will be possible to code the point at which a driver began using a cell phone in Phase 3. Overall, 67% of drivers who were involved in back-of-queue incidents were engaged in some type of distracting task.

5.5 Relationship Between Speed and Back-of-Queue Behavior

A binary variable was created based on the threshold of ≤ -0.40 g to define a hard deceleration event. A logistic regression model was developed to evaluate the role of speeding in back-of-queue behavior (Table 5-1). Since both crash/near-crash and normal driving events were included, driver distraction could not be included at this stage.

Table 5-1. Data summary for the model

Variables		Coded as	Count	Mean	STD	Min.	Max.
Total number of events			229				
	Hard Deceleration	1	112				
	Soft Deceleration	0	117				
Event Type							
	Near-Crash	1	115				
	No Near-Crash	0	114				
Time of a day							
	Night	1	29				
	Day	0	200				
Pavement Condition							
	Wet	1	28				
	Dry	0	201				
Level of Service							
	Freeflow / LOS A and B	1	73				
	Not a Freeflow / LOS C, D, E and F	0	156				
Speed at Reaction Point			229	52.256	17.141	8.264	88.945

A logistic regression model was developed using the “glm” (generalized linear model) function in R 3.5.1. The status of hard versus normal deceleration was used as a dependent variable, and variables such as speed at the reaction point and other environmental factors were used as independent variables.

The results showed that for every unit increase in the freeflow speed of a vehicle at the reaction point, the probability or odds of a driver engaging in a hard deceleration increased by 1.04. The odds of a driver engaging in a hard deceleration were 7.37 times greater on wet pavement compared to dry pavement. In addition, drivers were also more likely to engage in a hard deceleration during nighttime driving compared to daytime driving. Table 5-2 shows the details of the model results.

Table 5-2. Model results

Variables	Estimate	Std. Error	t-statistic	p-value	Odds Ratio
(Intercept)	0.257	0.722	0.357	0.721	1.294
Speed at Reaction Point	0.036	0.019	1.870	0.061	1.037
Crash Type (No Near-Crash = 1, Near-Crash = 0)	-5.365	0.790	-6.793	0.000	0.005
Time of Day (Day = 0, Night = 1)	0.374	0.685	0.546	0.585	1.453
Weather (Dry = 0, Wet = 1)	1.998	0.646	3.091	0.002	7.371
Freeflow = 1, No Freeflow = 0	0.413	0.490	0.843	0.399	1.512

6. LANE MERGE MODEL

Lane closures in work zones require drivers in the closing lane to merge into an adjacent through lane before they enter the work zone area. A driver's merging behavior in the work zone merging area can be characterized by the distance between the start of the work zone area and the point where the driver begins to merge.

With increased seasonal traffic volumes, work zones become points of congestion that can lead to driver frustration and aggressive driving behavior (Hallmark et al. 2015). Aggressive driving often presents safety and efficiency concerns in work zones and 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 for as long as possible to avoid waiting in the queue. The presence of both kinds of drivers in the same facility may result in confusion and sometimes in aggressive driving.

A number of studies have focused on methods to improve merging operations in work zones. The early-merge and late-merge concepts are two methods in the literature that have been proposed to alleviate safety and capacity concerns in 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 closures in a work zone and concluded that the early-merge scenario was characterized by more consistent speeds and reductions in both queue lengths and queue stops compared to the late-merge scenario. It made merging smoother, decreased speeds upstream, 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 the flow of traffic at the merge points in the work zone. Queue lengths were decreased in both situations. The early-merge strategy was found to be a better option for moderate congestion. If the number of vehicles increased, however, this strategy could result in longer queues.

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

Weng and Meng (2011) characterized merging behavior in work zone merging areas using two models. The first estimated the desired merging location of drivers who were beginning to consider merging, and the second estimated the probability of a driver successfully merging into the current adjacent gap. A logit model was developed to determine the probability of merging. Real 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.

In the same study, Weng and Meng (2011) investigated drivers' merging behavior in work zone merging areas during the entire merging period, that is, from the start of the merging maneuver to the completion of the maneuver. The authors proposed a time-dependent logistic regression model that considered the possible time-varying effects of influencing factors, and a standard logistic regression model for the purpose of model comparison. The model comparison results showed that the time-dependent model performed better than the standard model because the former could provide higher prediction accuracy. The time-dependent model results showed that the merging vehicle's speed, the through lane lead vehicle's speed and the through lane lag vehicle's speed, the longitudinal gap between the merging and lead vehicles, the longitudinal gap between the merging and through lane lead vehicles, and the types of through lane lead and lag vehicles exhibit time-varying effects. Interestingly, both the through lane lead vehicle's speed and the through lane lag vehicle's speed were found to exhibit heterogeneous effects at different times during the merging period. Additionally, the merging vehicle has a decreasing willingness to complete a merging maneuver if the through lane lead vehicle is a heavy vehicle.

Idewu and Wolshon (2010) discussed the development of the joint merge or alternating merge patterns to examine the patterns' effects on traffic flow. The joint merge pattern involves a two-sided taper in which both approach lanes are reduced simultaneously into a single lane, thereby eliminating an assigned lane priority. The results showed that merging speeds under this pattern 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. The authors also concluded that drivers were more cautious in their merging maneuvers because the joint merge pattern produced a more evenly balanced lane volume at the transition zone entrance.

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

6.1 Description of Data for Work Zone Merge Model

A lane merge model was developed to determine the characteristics associated with the point at which a driver merged before a lane closure. A merge was defined as a driver moving from a lane that is closing ahead into an adjacent open lane. If a driver changed lanes several times, only the final move into the open lane was included.

Time series traces from situations where traffic congestion was at levels 1 or 2 were considered for this model. Each row in the data set represented one trace driven by one driver. The study was focused on determining the effectiveness of static lane merge and dynamic (arrowhead) lane merge signs.

A lane merge was noted when the driver crossed the center line from the closing lane into the open lane. Figure 6-1 shows a typical lane closure scenario and the positions of signs before the end of the taper point for the work zone.

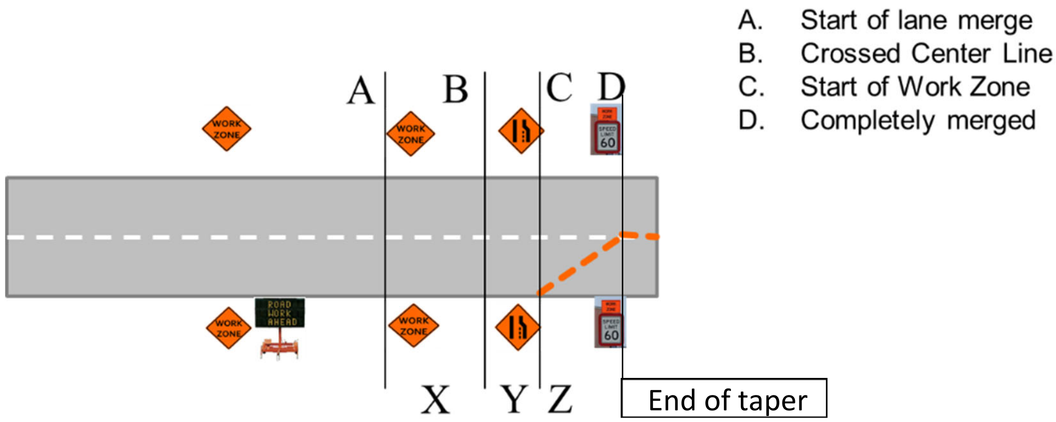


Figure 6-1. Lane merge scenario in work zone

6.2 Model Description for Work Zone Merge Model

A linear mixed effects model was used to account for dependencies among the observations. The dependent variable was the vehicle's distance from the taper point when the merge occurs. A random effect for the driver was introduced to account for dependencies among observations from the same work zone. Descriptive statistics for the model are shown in Table 6-1.

Table 6-1. Descriptive statistics

Variable	Description	Mean	STD	Min	Max
DistanceofLaneMerge	Dependent variable, distance of lane merge in m	-689.16	859.60	-3894.46	152.08
LateMerge	1 if it is a late merge scenario, 0 otherwise	0.09	0.29	0.00	1.00
Barrels	1 if barrels are present as channelizing device, 0 otherwise	0.66	0.48	0.00	1.00
Concrete	1 if Concrete is present as channelizing device, 0 otherwise	0.08	0.27	0.00	1.00
VerticalPanels	1 if channelizing device was Vertical Panels, 0 otherwise	0.25	0.43	0.00	1.00
NonForwardRelated	1 if driver glance was not forward related, 0 otherwise	0.08	0.27	0.00	1.00
CellPhone	1 if driver glance was on cell phone, 0 otherwise	0.04	0.19	0.00	1.00

Variable	Description	Mean	STD	Min	Max
Distracted	1 if the participant was distracted, 0 otherwise	0.08	0.27	0.00	1.00
Female	1 if the participant was female, 0 otherwise	0.58	0.50	0.00	1.00
TwentyFourYounger	1 if the participant was younger than 24, 0 otherwise	0.13	0.34	0.00	1.00
TwentyFiveToSixtyFour	1 if the participant was between 25 to 64, 0 otherwise	0.66	0.48	0.00	1.00
Car	1 if the participant vehicle is a car, 0 otherwise	0.66	0.48	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	0.25	0.43	0.00	1.00
HeadToHead	1 if work zone configuration was head to head, 0 otherwise	0.51	0.50	0.00	1.00
LaneClosure	1 if work zone configuration was lane closure type, 0 otherwise	0.49	0.50	0.00	1.00
speedmps_new	Speed of vehicle at the lane merge point	27.51	2.72	21.77	35.28
SignsBeforeLaneMerge	Number of signs before the lane merge	3.10	1.25	1.00	9.00
DistanceFirstSign	Distance of first sign	-1452.48	872.46	-3569.60	0.00
Distancelanemergesign	Distance of lane merge sign	-1452.48	872.46	-3569.60	0.00
PresenceCMSLaneMerge	1 if CMS arrowhead Lane Merge sign is present, 0 otherwise	0.78	0.42	0.00	1.00
DistanceCMSLaneMerge	Distance of CMS arrowhead Lane Merge sign	-143.76	142.76	-378.55	287.72
Day	1 if daytime, 0 otherwise	0.87	0.34	0.00	1.00
Night	1 if Nighttime, 0 otherwise	0.08	0.27	0.00	1.00
Dusk/Dawn	1 if Dusk/dawn, 0 otherwise	0.05	0.22	0.00	1.00
PA	1 if State is Pennsylvania, 0 otherwise	0.64	0.48	0.00	1.00
NY	1 if State is New York, 0 otherwise	0.36	0.48	0.00	1.00
ModeratelyCongested	1 if moderately congested roadway, 0 otherwise	0.12	0.32	0.00	1.00
Clear/Cloudy	1 if weather is clear/cloudy, 0 otherwise	0.92	0.27	0.00	1.00
RainySnowy	1 if weather is Rainy/snowy, 0 otherwise	0.08	0.27	0.00	1.00
CMS	1 if CMS is present, 0 otherwise	0.43	0.50	0.00	1.00
SpeedFeedback	1 if Speed Feedback is present, 0 otherwise	0.23	0.43	0.00	1.00
EnforcementSign	1 if Enforcement Sign is present, 0 otherwise	0.06	0.25	0.00	1.00
NormalSpeedLimitSign	1 if Normal Speed Limit Sign is present, 0 otherwise	0.05	0.22	0.00	1.00
WorkZoneSpeedLimit	1 if Work Zone Speed Limit is present, 0 otherwise	0.82	0.39	0.00	1.00
StaticWorkZoneSign	1 if Static Work Zone Sign is present, 0 otherwise	1.00	0.00	1.00	1.00

6.3 Model Results for Work Zone Merge Model

The best fit linear mixed effects model for work zones on four-lane roadways is shown in Table 6-2.

Table 6-2. ANOVA results for the lane merge model for work zones on four-lane divided roads

Variable	Chisq	Df	Pr(>Chisq)	
speedmps_new	6.93	1.00	0.01	**
SignsBeforeLaneMerge	6.64	1.00	0.01	**
PresenceCMSLaneMerge	5.68	1.00	0.02	*
Barrels	2.01	1.00	0.16	
Rainy	2.51	1.00	0.11	
EnforcementSign	17.12	1.00	0.00	***

The table also shows the p-values for each of the included variables. Table 6-3 presents a breakdown of the estimates for these variables.

Table 6-3. Estimates of the parameters in the lane merge model for work zones on four-lane divided roads

Variable	Estimate	Std. Error	t value
(Intercept)	1211.6	821.78	1.474
speedmps_new	-70.18	26.67	-2.632
SignsBeforeLaneMerge	-153.17	59.42	-2.578
PresenceCMSLaneMerge	425.58	178.55	2.384
Barrels	228.43	161.04	1.418
RainySnowy	379.19	239.48	1.583
EnforcementSign	-1191.21	287.87	-4.138

The estimate for each variable represents the distance of a driver's lane merge from the start of the taper point (start of the work zone) in the presence of that variable. Drivers who are traveling over the mean speed for the work zone (based on the mean speed of all time series traces for the same work zone) merge later (i.e., closer to the work zone starting point). As the number of signs before a work zone lane closure increases, the distance of the lane merge from the start of the work zone also increases, meaning that drivers are more likely to merge earlier when more upstream signs leading to a work zone are present. The presence of a lane merge CMS in a work zone decreases the merge distance from the work zone starting point, meaning that drivers on average merge 425.6 meters later. This may be due to the fact that drivers are able to more clearly see the merge point and are not concerned about immediately moving into an open lane.

Drivers merge 228.4 meters earlier when barrels are present than when concrete or vertical panels are present. When speed enforcement signs are present, drivers merge about 1,191.2 meters sooner. When rain is present, drivers tend to merge 379.2 meters later. No impact was found for cell phone use or distraction.

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