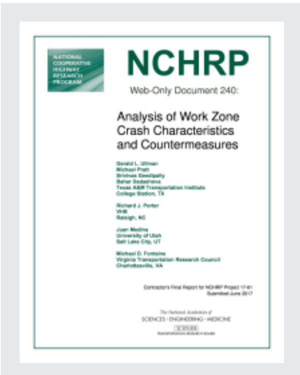
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Web-Only Document 240:
Analysis of Work Zone Crash Characteristics and Countermeasures

Analysis of Work Zone Crash Characteristics and Countermeasures

DETAILS

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SUMMARY

In this report, researchers have documented the results of multiple analyses focused on developing an improved understanding of work zone crash characteristics and countermeasure effectiveness. In-depth analyses of work zone crash narratives and other data sources above and beyond standard fields and codes in state and national crash databases yielded several useful insights into work zone factors associated with common types of crashes. Assessment of safety countermeasures used to combat rear-end collisions at interstate lane closure queues indicate that the countermeasures have a positive crash-reducing effect. Finally, an analysis of crashes at a national sampling of interstate work zones was not able to isolate the effects of individual roadway factors upon work zone crashes. However, general crash prediction models were computed that can assist practitioners in quantifying expected crash effects of work zones as a function of length, duration, and roadway traffic demand.

As has been hypothesized in previous studies, congestion and queues due to work zones were shown to be a significant contributor to crashes. In addition, the analyses also suggested that congestion contributed to a proportion of sideswipe collisions and collisions with barriers or other objects, due to last-second swerving to avoid running into the back end of a vehicle. Queues were found to be a significant issue associated with crashes at interstate and freeway work zones, and with two-lane highway work zones as well. Most work zones on two-lane highways involve the temporary closure of one travel lane, and the use of alternating one-way traffic control via flaggers, automatic flagger assistance devices (AFADs), or portable traffic signals. Queues of varying length are created at these work zones, can be unexpected by motorists, and so can result in occasional rear-end collisions.

Work vehicles entering/exiting the work zone were also found to be an issue in this assessment. Both rear-end collisions and sideswipe crashes could be attributed to this situation. In one of the databases analyzed in this research, 10% of the crashes on interstate/freeway facilities appeared to be the result of trucks attempting to enter or exit mainlane traffic to or from the work space.

Furthermore, work zones on non-freeway/interstate facilities appear to be creating challenges for drivers that were previously unknown or underestimated based on past analyses. Data from several crashes indicate that drivers became confused when approaching and entering work zones on non-accessed controlled facilities at intersections and driveways, especially in urban areas. Work zones on facilities which were normally divided and then converted to two-way operation in one of the directional roadways while the other direction was repaired or rehabilitated appear to be particularly problematic. Sight distance challenges were also noted for several crashes occurring at these types of work zones.

Two types of queue warning countermeasures, work zone ITS-based end-of-queue warning systems and portable transverse rumble strips, installed at interstate work zones when queues form indicate that the technologies can indeed reduce such crashes. Overall, the use of these countermeasures appeared to reduce crashes during periods of queuing and congestion by 53% to 60% from what would have been expected if the countermeasures had not been used. In addition, the crashes that did occur were significantly less severe when the countermeasures were deployed as compared to the no-countermeasure condition. Without the countermeasures deployed, 50% of the crashes occurring when queues were present involved injuries or fatalities; when the treatments were deployed, only 16% of the crashes involved injuries or fatalities.

Despite an extensive project identification and data collection/reduction effort, analysis of the multi-state database of work zones on interstate facilities did not yield statistically significant crash modification factors (CMFs) for individual work zone features such as lane widths, shoulder widths, lane closures, shoulder closures, median widths, lane shifts, or barrier use. One of the main reasons for this

was the lack of sufficient variability in these features across the projects available for analysis. There was considerable confounding of many of these features (e.g., reduced lane and shoulder widths together with barrier placed at the edge of the shoulder, etc.), which kept the research team from being able to extract useful CMFs from the data. Although the multi-state project analysis failed to provide individual work zone feature CMFs, the effort was successful in developing generic work zone safety performance functions (SPFs) for four and six-lane interstates, based on the national dataset generated. These SPFs have been computed for a defined set of base characteristics, and so can be useful in planning-level analysis of possible work zone safety impacts to be expected as a function of project length, duration, and roadway annual average daily traffic (AADT).

Based on the myriad of analyses undertaken on this project, it is recommended that research continue into ways to reduce the frequency and severity of rear-end (and sideswipe) collisions caused by queues and congestion at work zones, especially on higher-speed facilities. Research is also needed to develop better guidance, such as typical applications or improved signing, for work zone traffic control at intersections. Several of the crashes examined in detail under this study pointed to driver confusion and visibility issues when work zones were performed in the vicinity of intersections. New designs for barricades and channelizing devices may be necessary to further improve work zone safety at these locations. Increased emphasis should be made towards improving ingress and egress at work space access points within the work zone to reduce the frequency and severity of work vehicle/motorist crashes. Strategies such as eliminating work space access to and from high-speed travel lanes, innovative access point designs, and testing and evaluation of systems to warn approaching traffic when work vehicles are about to enter or exit the work space, should be pursued. Finally, agencies should begin to incorporate safety assessments into their work zone design and transportation management planning processes. An implementation guide developed as part of this research effort describes how this can be accomplished and provides guidance on the availability and applicability of available CMFs for this purpose.

CHAPTER 1 Background

Introduction

Work zone safety has been an area of concern to highway agencies, the construction industry, and the traveling public for nearly 40 years. A number of studies have been performed during that time to try and understand how the presence, design, and operation of work zones affect crash frequency and severity, manner of collision, and other crash characteristics. The earliest efforts to understand and predict the effects of work zones on crashes examined changes in crash rates (see *Graham et al. 1977*, *Wang and Abrams 1980*, as examples). Although researchers typically found that crashes did increase in work zones relative to pre-work zone conditions, the magnitude of the increases varied widely. Over time, odds ratio analyses using comparison sites and checks for comparability (*Ullman and Krammes 1991*), poisson/negative binomial regression models (such as *Venugopal and Tarko 2000*, *Khattak et al. 2002*, and *Chen and Tarko 2012*), and other analytical approaches (such as a quantitative risk assessment modeling approach proposed by *Meng et al. 2010*) were developed and applied. Even with more sophisticated analysis techniques, considerable variation has been found with regards to work zone effects upon crashes. Differences in work zone policies and procedures between agencies and regions likely explain some of the reasons for the inconsistent findings. Low sample sizes and regression-to-the-mean effects, and the inherent randomness in crash occurrence and outcome undoubtedly also contributed to some of the inconsistencies in the findings. Sample size effects are particularly prevalent in work zone safety analyses given the relatively short duration of many work zones, and the frequency at which the configuration of the work zone may change over the course of a project. Taken cumulatively, the studies typically indicate that work zones do result in more crashes relative to pre-work zone conditions. However, the magnitude of that increase has been difficult to predict. Several studies have also examined the effect of work zones on crash severity, utilizing a range of analytical techniques. In that most studies have shown total crashes to increase in work zones, a common research question has been whether the crashes that occur tend to be more severe or less severe than in pre-work zone conditions. Most studies have found that severe (fatal + injury) crashes have increased by a lower amount than have property-damage-only (PDO) crashes (examples include *Hargroves and Martin 1980*, *Richards and Faulkner 1981*, and *Garber and Zhou 2002*) or increased by a similar amount as PDO crashes (see *Ha and Nemeth 1995*, *Lindly et al. 2000*, and *Qin et al. 2007*). Even so, examples also exist where crash severity has increased by a greater percentage than has PDO crashes (such as *Burns et al. 1989*, *Ullman and Krammes 1991*, and *See et al. 2009*).

Meanwhile, other studies have strived to identify and evaluate the importance of various contributing factors or other causal indicators to better understand how such crashes can be mitigated. For example, several researchers have examined the spatial distribution of crashes within a work zone. Study results tend to indicate that the activity area is the predominant location for work zone crashes (as indicated by *Garber and Zhou 2002*, *Khattak and Targa 2004*, *Salem et al. 2006*, and *Akepati and Dissanayake 2011*). However, given that the activity area can often be the longest portion of the work zone relative to the advance warning, transition, and termination segments, such a finding is not unexpected. As might also be expected, a greater proportion of crashes occurring in the advance warning area tend to involve rear-end collisions, whereas sideswipe collisions tend to occur most frequently in the transition area. Overall, the literature indicates that rear-end collisions typically increase the most and are often the predominant type of work zone crash (as illustrated by *Rouphail et al. 1988*, *Hall and Lorenz 1989*, *Wang et al. 1995*, *Daniel et al. 2000*, *Mohan and Gautam 2002*). More recently, these increases in rear-end collisions have been shown to vary by type of work activity, time-of-day, and traffic volumes (*Ullman et al. 2008*).

However, despite the amount of previous research performed, it is difficult for practitioners to objectively incorporate the safety effects of various work zone design alternatives, operating strategies, and countermeasures into work zone impacts assessment and transportation management plan (TMP) development. For instance, the AASHTO Guide for Reducing Work Zone Collisions lists nearly 40 treatments and strategies that are believed to have the potential to reduce work zone collisions (*Antonucci et al. 2005*), but quantitative guidance as to the level of effectiveness of any of these treatments/strategies in a work zone environment is extremely limited. This makes it difficult for practitioners to effectively assess the cost versus safety tradeoffs of work zone design element choices, maintenance of traffic alternative analyses, or the provision of specific crash mitigation strategies.

Project Objectives

The objective of NCHRP 17-61 was to develop new information and comprehensive guidance on the characteristics of work zone crashes and the effectiveness of certain engineering, enforcement, education, emergency services, and public policy countermeasures intended to reduce work zone crash frequency and severity. To accomplish this, the following major efforts were undertaken:

- Assessment of data and findings from previous work zone safety study results to quantify, where possible, the effect of various work zone features, operational strategies, and potential safety countermeasures upon work zone crashes in terms of crash modification factors (CMFs);
- Assessment of existing non-work zone CMFs already developed for the AASHTO *Highway Safety Manual* (HSM) or included in the Crash Modification Factor Clearinghouse for their potential suitability for applying them to work zone situations;
- Mining of detailed crash databases for additional insights into work zone crash characteristics and work zone-related contributing factors;
- Analysis of the effects of multiple work zone design features upon crashes using a multi-state dataset of work zone projects on interstate, freeway, and multi-lane highways developed under this research effort; and
- Development of implementation guidance on how to utilize the information developed through this research effort to perform work zone safety impact assessments of alternative design decisions, operating strategies, and countermeasure deployments.

The results of the efforts regarding the first, second, and last bullet above have been packaged into a stand-alone implementation guide separate from this document. This report specifically addresses the results of the third and fourth bullet above.

Contents of this Report

This technical report documents the methodology and results of the various research activities performed on this project. Following this introductory chapter, Chapter 2 documents the results of analyses performed on detailed work zone crash report diagrams and narratives extracted from three existing crash databases: the Virginia Department of Transportation (VDOT) Roadway Network System (RNS) Crash database, the National Highway Traffic Safety Administration (NHTSA) National Motor Vehicle Crash Causation Survey (NMVCCS), and the combined NHTSA/Federal Motor Carrier Safety

Administration (FMCSA) Large Truck Crash Causation Study (LTCCS). Work zone crashes identified in each of these datasets were examined in detail to better define and understand the work zone-related contributing factors and sequences of events that resulted in those crashes.

Next, Chapter 3 presents the data, methodology, and results of an analysis of work zone crashes correlated to traffic operating conditions (specifically, periods of queuing and non-queuing) during nighttime temporary lane closures in Texas. Also included in this chapter is an evaluation of the crash-reducing effect of two types of work zone crash countermeasures, work zone ITS-based end-of-queue warning systems, and portable rumble strips (PRS) deployed transversely upstream of the temporary lane closure.

Chapter 4 provides documentation of an effort to develop predictive statistical models of work zone crashes as a function of several key design variables (lane width, shoulder width, barrier presence, and lane shifts) using a database of work zone project plans, traffic volume, and crash data from a sample of work zones across the U.S. The intent of the analysis was to establish useful work zone crash modification factors (CMFs) describing the proportional change in crashes attributable to the various factors. These CMFs could then be used when performing trade-off analyses of alternative work zone traffic-handling options and strategies for a particular project on a particular roadway segment.

Finally, Chapter 5 presents a summary of the key findings from these efforts and provides recommendations for additional research. A separate implementation guide describing the concept of work zone safety impact assessment, available CMFs, and estimation procedures, has also been produced as part of this research effort.

CHAPTER 2 Causal Assessments of Work Zone Crashes

Overview

Much of the work zone safety literature is based around methodologies that develop statistical associations between work zone crashes and work zone features. Knowledge on crash *causation*, including the road environment as one of many factors in the causal chain, is limited. Unlike fundamental, causal relationships, the 'signs' and 'magnitudes' of statistical associations may be an artifact of the database used for analysis. Data accuracy and completeness vary from jurisdiction to jurisdiction and few existing roadway and work zone databases contain all measureable variables. Therefore, the predicted 'outcomes' of statistically estimated models do not always transfer from location to location. One approach to addressing this challenge is to explore the crash-generation process for individual crashes as opposed to looking only at descriptive statistics for commonly available crash variables. These methods were historically used in studies of pedestrian and bicyclist crashes (see, for example, *Snyder and Knoblauch 1971*), but have also been applied to understanding work zone crashes (*Schrock et al. 2005*). The basic hypothesis is that examining individual crash reports and photographs to better understand factors leading to a crash, instead of relying solely on computer-automated 'slicing,' modeling, and summarizing of pre-coded data also holds promise for identifying common crash "causal types." For example, in the work zone context, crashes can be dissected and causality explored based on three factors as shown in Figure 1. Within a particular work zone crash type, one assesses the sequence of events pre-, during, and post-crash according to the following factors:

- Precipitating events: the specific nature of the failure in the function/event sequence that led to the collision
- Predisposing factors: specific environmental, human, or vehicle variables that influenced the function failure
- Target groups: human populations and/or kinds of vehicle types involved in the crash type

In this chapter, work zone crash information was extracted from three different datasets and examined using this approach to identify key characteristics that commonly found in work zone crashes. The first dataset was the VDOT RNS crash database, which is representative of databases available to most state DOTs.

Analysis of VDOT RNS Crash Data

The VDOT RNS crash database is constructed based on police crash report forms. Given that VDOT has responsibility for operating and maintaining all roadways outside of incorporated cities in the state, the work zone crashes extracted from this database included a range of roadway types.

Methodology

Work zone crashes (defined as those occurring within a defined work zone area) were extracted from the database for calendar years 2011 and 2012. In total, 6,774 crashes were identified as occurring in work zones during this time frame. The crash causes were analyzed by crash type since causes varied significantly among crash types. Only those crash types that comprised at least 10% of work zone crashes were examined in the analysis. This resulted in the consideration of only rear-end, angle, sideswipes, and fixed object run–off-road crashes. These crash types represent 94.8% of all coded work zone crashes over the two-year study period and are assumed to be a good representation of the work zone crash population.

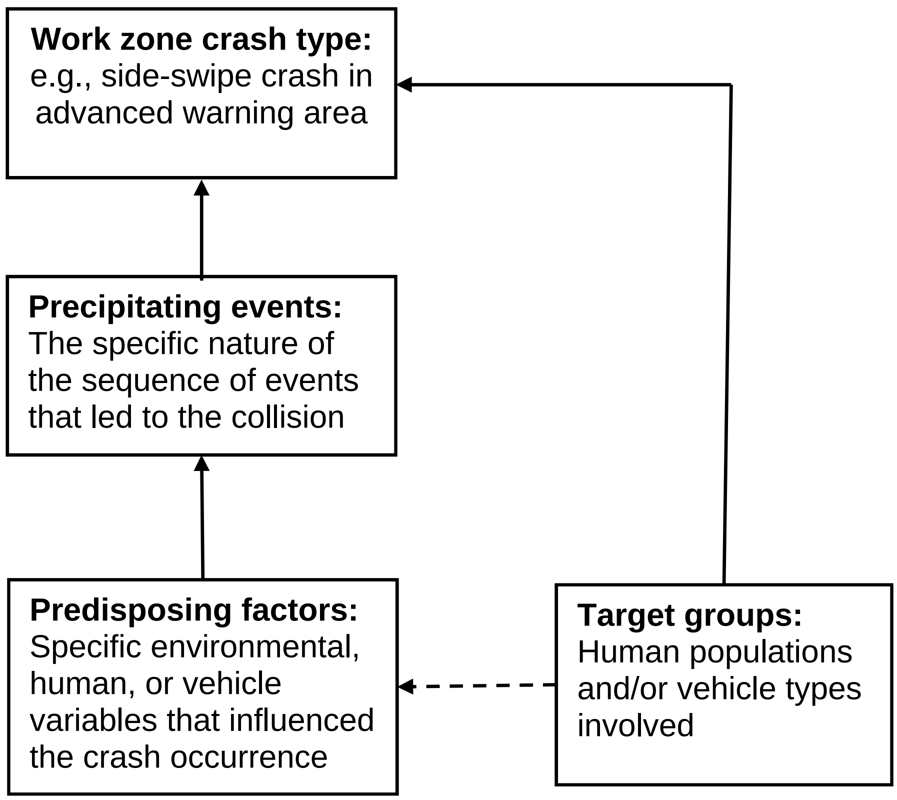


Figure 1. Illustration of dissecting work zone crashes into causal factors.

Crash report data fields and narrative descriptions provided by the responding officer, were used to assess the crash's relationship to the work zone. Crashes were categorized as "directly related" if their crash description, in tandem with the other crash report fields, indicated that the work zone influenced the likelihood of the crash in some capacity. Factors considered when determining if a crash fell into the directly related category included whether:

- A work zone vehicle or piece of equipment was struck
- The crash narrative directly referenced a work zone feature
- The crash narrative directly indicated that the work zone created changes in flow or speed
- The narrative indicated a specific driver response to the work zone

Even so, crashes determined to be directly related were not necessarily caused by the work zone and may have been only slightly influenced by the work zone's presence. Conversely, crashes not determined to be directly related could still have been influenced by the work zone, but the officer failed to capture this influence in the crash report. In many cases, the crash report contained insufficient information to make a determination as to the role, if any, that the work zone played in the crash.

Next, crashes were categorized based on their crash cause. The crash-causal categories were based on trends observed within the data while determining the crash's relationship to the work zone. For instance, crashes which involved stopping or slowing due to congestion created by the work zone were broken out as a category within the directly related data. The most common crash-causing categories identified in the dataset were:

- Stopping/ slowing due to work zone (including congestion and merging)
- Stopping/ slowing due to flagman, police officer, or work zone sign
- Changing lanes due to work zone lane closure or congestion
- Confusion due to work zone traffic control
- Limited sight distance due to work zone activities
- Work zone vehicle entering/exiting work zone
- Unauthorized work zone entry
- Avoiding crash with another vehicle or object
- Lost control, struck work zone device/barrier
- Unknown, but work zone device/barrier was struck

Other crash-cause categories that were identified but did not represent a significant percentage of the work zone crashes included: vehicle backing up, falling asleep/fatigued, improper work zone instruction (such as improper flagger operations), driver inattention, reckless driving, and uneven pavement.

Of the 6774 total work zone crashes occurring in the two-year study period, 6424 crashes belonged to the four primary crash types (rear-end, angle, sideswipe and fixed object- off road). Of these, 1480 (23%) were found to be directly influenced by the presence of a work zone (directly-related crashes), and these were examined in greater detail via crash diagrams and narratives provided by the investigating officer in order to develop common work zone features contributing to the crashes. It is still possible that the work zones may have contributed to some aspect of the remaining 77% of the work zone crashes, but insufficient information was available to make a direct determination.

Results of Analysis

The three most common crash-cause categories for each of four major crash types are displayed in Table 1. Each of these primary categories are described in greater detail in the sections that follow. Table 1 shows the number of crashes in each crash type that were determined to be directly related to the work zone using the criteria specified earlier. The percentage of crashes within each crash type that were determined to be directly related to the work zone are also shown (e.g., 18.1% of all recorded work zone rear-end crashes were determined to be directly related to the work zone based on the available data).

Table 1. Summary of Crash Causes Directly Related to Work Zone Presence

Crash Type	# of Directly Related Crashes	% of Coded Crash Type[a]	1st Most Common Cause	2nd Most Common Cause	3rd Most Common Cause
Rear-end	679	18.1%	Stopping/ slowing due to work zone presence (64.7%)	Stopping/ slowing for flagman, police officer, or work zone TTC (11.8%)	Changing lanes due to work zone TTC (8.5%)
Angle	160	15.1%	Changing lanes due to work zone TTC (22.5%)	Confusion due to work zone traffic control (21.3%)	Limited sight distance due to a work zone feature (11.9%)
Sideswipe – Same Direction	170	18.8%	Changing lanes due to the work zone (62.4%)	Work zone vehicle entering/exiting work zone activity area (5.3%)	Recovery from vehicles intruding into the work zone activity area (4.1%)
Fixed Object – Off Road	471	66.2%	Unknown, but work zone device/ barrier was struck (37.4%)	Lost control, struck work zone device/ barrier (23.4%)	Avoiding crash with another vehicle or object (14.6%)

[a] The percentage of crashes within each crash type that were determined to be directly related to the work zone

The following sections describe the specific circumstances and characteristics of the directly related crashes for each broad crash cause of each crash type shown in Table 1.

Rear-end Crashes

The most common crash-cause categories for directly-related rear-end crashes in Table 1 pertain to activities and events that require velocity and/or lane changes. It was determined that a large proportion of rear-end crashes occurred at lane closures, indicating that congestion created by vehicles merging at a work zone lane closure is a large contributor to increased rear-end crashes. Collectively, the three most common rear-end crash-cause categories displayed in Table 1 described 85% of the directly-related rear-end crashes in work zones. Definitions and further information about each of those common causes are provided below.

Common Cause #1: Stopping/ slowing due to work zone presence

This category included 439 crashes (64.7% of directly-related rear-end crashes) resulting from vehicles stopping/slowing due to some aspect of the work zone. This does not include crashes caused by stopping or slowing due to a flagman, police officer, or a work zone sign. Typical events or activities that were found to lead to this type of crash cause were the presence of work zone-induced congestion, merging situations, unexpected hazards in the travel lane, and confusion about the proper driving action to take.

Congestion. For rear-end collisions, 296 of the 439 crashes in this crash-cause category (65.1%) were related to congestion at the work zone. Only crashes that were attributed to abnormal congestion were included in this category. Crashes attributed to recurring congestion, such as congestion occurring during peak periods, were not included. The majority of these crashes (73.0%) occurred when a lane closure work zone was present, but were not directly attributable to merging actions.

Merging. Fifty of the 439 rear-end crashes in this category occurred while a vehicle was stopping or slowing due to merging maneuvers. This included crashes involving either:

- Congestion caused by merging at a lane closure or crossover (27 crashes, or 54% of the merging rear-end crashes)
- A vehicle slowing to allow another vehicle to merge at a lane closure (12 crashes, or 24%)
- A vehicle stopped in the closed lane waiting to merge at a lane closure (9 crashes, or 18%)
- An existing highway acceleration lane shortened by the work zone (2 crashes, or 4%)

Hazard. Twenty-six of the 439 rear-end crashes in this causal category (5.9%) were related to avoiding a work zone hazard in the travel lane. Typical hazards included equipment that had fallen into a travel lane, work zone channelizing devices that had fallen over or otherwise slid into an open lane, bumps, or roadway debris created by work zone activity.

Other. Ten of the 439 rear-end crashes in this category (2.3%) were related to apparent driver confusion with the work zone TTC, according to the crash report narratives.

Common Cause #2: Stopping/slowing for flagman, police officer, or work zone TTC

This category included 80 crashes (11.8% of the directly-related rear-end crashes) occurring when vehicles stopped at the direction of a flagman, police officer, or work zone TTC. Traffic stopping for flaggers was responsible for 73 out of the 80 crashes (91.2%) in this category. It was not possible to ascertain whether driver distraction, poor sight distance to the advance warning devices or to the upstream end of the queue, or other factors contributed to these types of crashes.

Common Cause #3: Changing lanes due to work zone TTC

This category consisted of 58 crashes (8.5% of directly-related rear-end crashes) involving a vehicle actively in the process of, or just completing, a lane change maneuver due to the work zone TTC. Overall, 58.6% of these 58 crashes occurred in the advance warning area or transition area at a lane closure work zone.

Angle Crashes

As shown in Table 1, changing lanes is the most common cause for this type of crash. However, confusing work zone TTC or limited sight distance caused by a particular feature of the work zone also appeared to contribute substantially to angle crashes, particularly at intersections. Definitions and further information about the most common angle crash-causal categories are given below.

Common Cause #1: Changing lanes due to the work zone

This classification involved 36 crashes (22.5% of the directly related angle crashes) where a vehicle was actively in the process of changing lanes due to a work zone. This category includes crashes near the work zone taper where a vehicle must change lanes, discretionary lane changes in the advance warning area, often during congestion, and discretionary lane changes within the work zone activity area. The majority (61.1%) of crashes within this causal category occurred in the advance warning area or transition area of a lane closure work zone. While driver actions were not always documented consistently in the crash reports, it appears that failure to yield on the part of the merging vehicle was a common cause of crashes.

Common Cause #2: Confusion due to work zone traffic control

A total of 34 crashes (21.3% of the directly-related angle crashes) reflect crash report narratives where driver confusion about some aspect of the work zone was noted. All of these crashes occurred on non-interstate routes. Twelve of these crashes (35% of the 34 crashes) were attributed to confusion over unmarked lanes as a result of repaving or other roadwork. Meanwhile, eight crashes (24%) involved improper work zone instruction by either a flagman or a member of the work crew. Seven crashes (21%) involved a change in traffic patterns, causing the driver to be unaware that a lane or street was closed. In cases when a turn lane was closed, the driver was typically confused about if and how to properly execute the turn.

Common Cause #3: Limited sight distance due to a work zone feature

A total of 19 crashes (11.9% of directly-related angle crashes) were attributed to a decrease in sight distance or visibility due to a work zone obstruction such as construction equipment, construction vehicles (both parked and not parked), and/or TTC signs. Nine of these crashes (47%) occurred at a minor road stop-controlled intersection. In all of these cases, the stopped minor road vehicle could not see around the work zone obstruction and was hit by a major road vehicle. Six of the crashes (32%) were left-turn maneuvers that occurred at a four-lane signalized intersection where both parties had a green ball on the opposite approach, but the turning vehicle did not yield right of way because the driver's sight was obscured by some feature of the work zone.

Sideswipe - Same Direction

Similar to rear-end and angle crashes, 55.3% of directly-related same-direction sideswipe crashes occurred at a lane closure work zone, and another 20.6% of these types of crashes occurred in a crossover or short-duration or mobile work zone. In addition, work zone entry and exit of both authorized work zone vehicles and unauthorized vehicles were two significant causes for this crash type. Additional details regarding these crash-causal categories are given below.

Changing lanes due to the work zone

A total of 106 crashes (62.4% of the directly-related sideswipe crashes) involved a vehicle actively in the process of changing lanes within a work zone. This category includes sideswipe crashes that occurred in the advance warning and transition area of a lane closure, as well as sideswipe crashes within the work zone activity area where multiple lanes were available. About 54% of these crashes occurred in the advance warning area or transition area of a lane closure. Unfortunately, the narratives and diagrams were usually not sufficient to know for certain whether the sideswipe crashes occurred under uncongested or congested road conditions. It was also not possible to assess whether these crashes were due to a failure to detect adjacent vehicles in blind spots, or whether they reflected aggressive driving behaviors where one driver tried to force their way into a lane and the following vehicle attempted to keep the space in front of them too small for the merging vehicle. When multiple lanes were present in the activity area, a number of cases indicated that a vehicle traveling adjacent to barrier encroached on the adjacent lane

Work zone vehicle entering/exiting the work space

This category included nine crashes (5.3% of directly-related sideswipe crashes) involving work vehicles that were entering or exiting the travel lanes to or from work space. Eight of these nine sideswipe crashes occurred on interstates. This result suggests that work zone vehicles are finding it more difficult to merge into and out of interstate work zones than other facility types, possibly due to higher speeds.

Recovery from intrusions into the work zone activity area

This casual category included seven crashes (4.1% of directly-related sideswipe crashes) involving non-work vehicles unintentionally entering a work zone activity area, and then sideswiping vehicles in the adjacent travel lane as they attempted to recover back to the travel lane. The vehicle also typically struck cones and/or barrels during the vehicle's intrusion into or recovery from the activity area.

Fixed Object Run-Off-Road Crashes

This crash type exhibited the largest percentage of coded crashes determined to be directly-related work zone crashes in Virginia (66.2% as shown in Table 1). This is likely due to how directly-related work zone crashes were defined in this analysis. Any crash where a vehicle hit a work zone object was designated as a directly related crash. Unfortunately, many of the crash reports in this category only contained vague crash descriptions. Therefore, the most common crash causes for directly-related fixed object run-off-road crashes were "Unknown" or "Lost Control" (usually due to an unknown reason).

The analysis showed that 74.3% of interstate fixed object run–off-road road crashes (equal to 66.8% of these crashes on all facility types) occurred during a shoulder or median work zone. This is contrary to the other crash types which experienced the largest amount of crashes in lane closure work zones. Further information about the most common fixed object run–off-road road crash-causal categories are given below.

Unknown, but work zone device/ barrier was struck

This category included 176 crashes (37.4% of directly-related fixed object run-off-road crashes) involving either a collision with a work zone object or crashes that were determined to have possible connections to the work zone. However, a specific crash cause could not be determined from the crash report's narrative.

Lost control, struck work zone device/ barrier

This category included crashes attributed to the driver losing control of the vehicle and striking a device or barrier. Overall, this category represented 110 crashes (23.4% of the directly-related fixed object run-off-road crashes). Unfortunately, for 99 of the 110 crashes in this category, the reason for the driver's loss of control was not included in the crash report narrative. With regards to the specific items struck, 64 crashes (58.2% of the 110 crashes) occurred with concrete barrier, 29 crashes ((26.5% of the 110 crashes) occurred with crash cushions, and seven crashes (5.9% of the 110 crashes) involved impacts with a traffic control device.

Avoiding a crash with another vehicle or object

This category included 69 crashes (14.6% of directly-related fixed object run-off-road crashes) that were attributed to the driver swerving off the road in an effort to avoid a collision with another vehicle or object. Of these 69 crashes, 37 (53.6%) appeared to be caused by the vehicle trying to avoid what would have been a sideswipe crash, while 26 (37.7%) were the result of the vehicle running off the road to avoid a rear-end collision.

Collisions with Work Zone Vehicles

Work zone vehicles were the second most common object hit in the directly-related rear-end, angle, and sideswipe crashes (the first most common object hit was another vehicle in transport). Work zone vehicles were the third most common object hit across all the crash types, involved in 10.1% (149 crashes) of all directly-related crashes. Therefore, crashes involving work zone vehicles were further investigated. Table 2 indicates the location or action of the work zone vehicle during those crashes.

Crash protection/shadow vehicles at 1) lane closures or 2) mobile work zones were the most common type of work vehicle struck. These 57 crashes (which represented 38.3% of the work vehicle crashes) involved a vehicle fulfilling its function by protecting the work crews as a shadow vehicle (with or without a truck-mounted attenuator). The second most common situation where a work vehicle was struck was when a non-work zone vehicle intruded into the work space and struck a work vehicle, accounting for 37 crashes (24.8% of the work vehicle crashes). The third most common case involved work vehicles entering or leaving the work space, resulting in 27 crashes (18.1%) of the work vehicle-involved crashes.

Table 2. Location/Action of Work Zone Vehicles Involved in Crashes

Location/Action of Work Zone Vehicle	Number of Crashes Involving a Work Zone Vehicle	Percentage of Crashes Involving a Work Zone Vehicle
Work zone work vehicle struck by non-work zone vehicle intruding into the work zone activity area	37	24.8%
Shadow vehicle in work zone transition area struck by non-work zone vehicle	35	23.5%
Work zone vehicle struck while entering/exiting work zone activity area	27	18.1%
Shadow vehicle struck in mobile work zone	22	14.8%
Improper use/placement of vehicle or equipment	12	8.1%
Work zone vehicle struck while in transit within work zone	8	5.4%
Work zone vehicle hit another work zone vehicle or pedestrian within work zone activity area	8	5.4%

Summary of Findings of VDOT Crash Analysis

Table 3 highlights seven crash-causal trends that arose out of this analysis, and illustrate high-leverage opportunities for improving work zone safety nationally. These crash causes are summed across crash types in Table 3, and include crash causes that were not in the top 3 categories shown in Table 1. As a result some crash counts in Table 3 exceed what is shown in Table 1 if a characteristic was not in the top 3 presented earlier.

Table 3. Summary of Significant Crash Causes across Crash Types

Crash Cause	Number of Crashes Directly Related to Work Zone	Percentage of All Crashes Directly Related to Work Zone
Stopping/slowing due to congestion	356	24.1%
Changing lanes due to work zone	229	15.5%
Involved work zone vehicle	149	10.1%
Work zone vehicle entering/exiting work zone activity area	33	2.2%
Involved a flagman	73	4.9%
Confusion due to work zone traffic control	44	3.0%
Limited sight distance due to work zone	19	1.3%

- Overall, 24.1% of the directly related crashes occurred during work zone congestion. Of these, 73.3% (261 crashes) occurred on an interstate, with 57.0% (203 crashes) occurring during an interstate lane closure.

- The analysis also indicates that 15.5% of all directly related crashes were associated with lane changes at a work zone. Logically, lane change and congestion related crashes are closely linked. Congestion significantly shrinks the number of gaps large enough to allow effective merging.

- The analysis also found that 10.8% of directly related rear-end crashes occurred at work zones where flagger control existed. Unfortunately, the available data was not sufficient to assess whether improper advance signing, poor work zone location just beyond horizontal or vertical curvature, or improper flagging operations played a role in the crashes.

- Work zone vehicles entering/exiting the work zone activity area were also found to be an issue in this assessment. The analysis found that 57.6% (19 crashes) of crashes involving work zone vehicles entering/exiting crashes involved a shoulder or median work zone. This suggests that the work zone vehicle was attempting to merge or exit from a high-speed roadway, and additional attention should be paid to developing traffic control plans for ingress and egress from these sites.

- The narratives and diagrams pertaining to directly related crashes at work zones on primary/secondary roads suggest that driver confusion was more of an issue on these types of roadways than on interstates or freeways. This suggests that traffic control being utilized on these facilities may not be adequate in many cases to serve motorist positive guidance needs. It should be noted that these facilities typically have more access points than freeways, and navigation demands on drivers are often more difficult.

- Limited sight distance due to poor placement of work vehicles and equipment at intersections was noted as an issue for angle crashes. Changes in agency traffic control requirements that currently require closing lanes may need to be revised when the lane is a turning lane to better avoid creating sight distance challenges at intersections and driveways.

Analyses of the NMVCCS and LTCCS Databases

The other datasets examined for insights into work zone crashes were the NMVCCS and the LTCCS databases. In contrast to the VDOT police crash database, these datasets contained data specifically focused on developing crash causation and often had much more detailed documentation about site conditions. The NMVCCS database includes detailed information for crashes involving at least one light vehicle (gross vehicle weight less than 10,000 pounds) that was towed due to damage. Data were collected on-scene by trained staff as quickly as possible after the crash occurred and through detailed follow-up investigations and interviews. The NMVCCS investigated a total of contains 6,949 crashes that occurred between January 1, 2005 and December 31, 2007 collected at locations covering wide geographic regions and urbanization types in the U.S.

Similarly, the LTCCS database includes information for 1,070 crashes involving at least one large truck with a gross vehicle weight of more than 10,000 pounds and resulting in one or more fatalities or injuries. The crashes in the database occurred in 17 states from April 2001 through December 2003. Up to 1,000 crash-related variables are available for each crash. The data were collected on-scene and through follow-up efforts by trained staff from NHTSA’s National Automotive Sampling System (NASS) and State truck inspectors. The dataset includes variables indicating if the crash site was inside of a construction work zone, if the sequence of events involved work zone equipment, and if the crash involved a barrier.

NMVCCS Analysis

Methodology

NMVCCS records contain more than 600 variables that capture details related to the driver, vehicle, roadway, and the environment, including crash narratives, photographs, and diagrams collected at the crash scene. The NMVCCS database includes variables indicating whether there was a work zone present at the crash site and whether traffic barrier was present. For this analysis, there was particular interest in the events and factors that led to a crash, the roadway configuration in the work zone, and other significant factors, such as special weather conditions. Unfortunately, variables in the NMVCCS records do not include descriptions of the work zone signs, tapers, or special configurations at the time of the crash beyond what is observed from the photos and crash diagrams. Also, the survey does not contain information about the specific geographical location of crashes, making further investigation of details a difficult task.

Exploration of the data identified 178 crash records of events that occurred at or near work zones. These crashes were initially identified by filtering for traffic flow restrictions or interruptions due to work zone presence at the time of the crash. These crashes were segregated according to roadway type on which they occurred, and then analyzed focusing on identifying common crash “scenarios” that occurred in work zones on these types of facilities, resulting on an initial classification. Then, crashes were re-classified taking into account if they were directly related to a work zone.

Crashes were classified as directly related to a work zone if at least one vehicle interacted directly with work zone elements, such as temporary traffic control devices, modified geometry or physical roadway features, such as lane shifts or temporary lane drop-offs, or congested traffic conditions generated in part due to the presence of the work zone, as described in NMVCCS records. Therefore, for crashes classified as being directly related to a work zone, had the work zone not been in place, such interactions could not have occurred.

It is noted that for each subsection, labels common to both initial and re-classified diagrams have been included for the reader to link or track crashes between the two classifications.

Results of Analysis

Freeway/Interstate Crashes

Crash exploration and causal analysis began with crashes that occurred on segments with full access control (i.e., freeways and interstates), as this was expected to yield more uniform conditions than other roadway types and offer a context to further develop and test alternative in-depth crash analysis methodologies. A total of 65 crashes (36.5% of the 178 work zone crash records in the NMVCCS dataset) were coded as occurring at or near freeway work zones.

The 65 crashes were examined in order to classify them into categories by crash type and main contributing factors, as shown in Figure 2. Out of the 65 freeway work zone crashes, 10 were not related to vehicle-roadway interactions (e.g., roadway design, surface conditions) or direct vehicle-vehicle interactions. Instead, these crashes were related to external factors such as the physical condition of one or more drivers, the vehicle mechanical condition, or vehicle-debris interactions. The remaining 55 crashes were classified into four main groups:

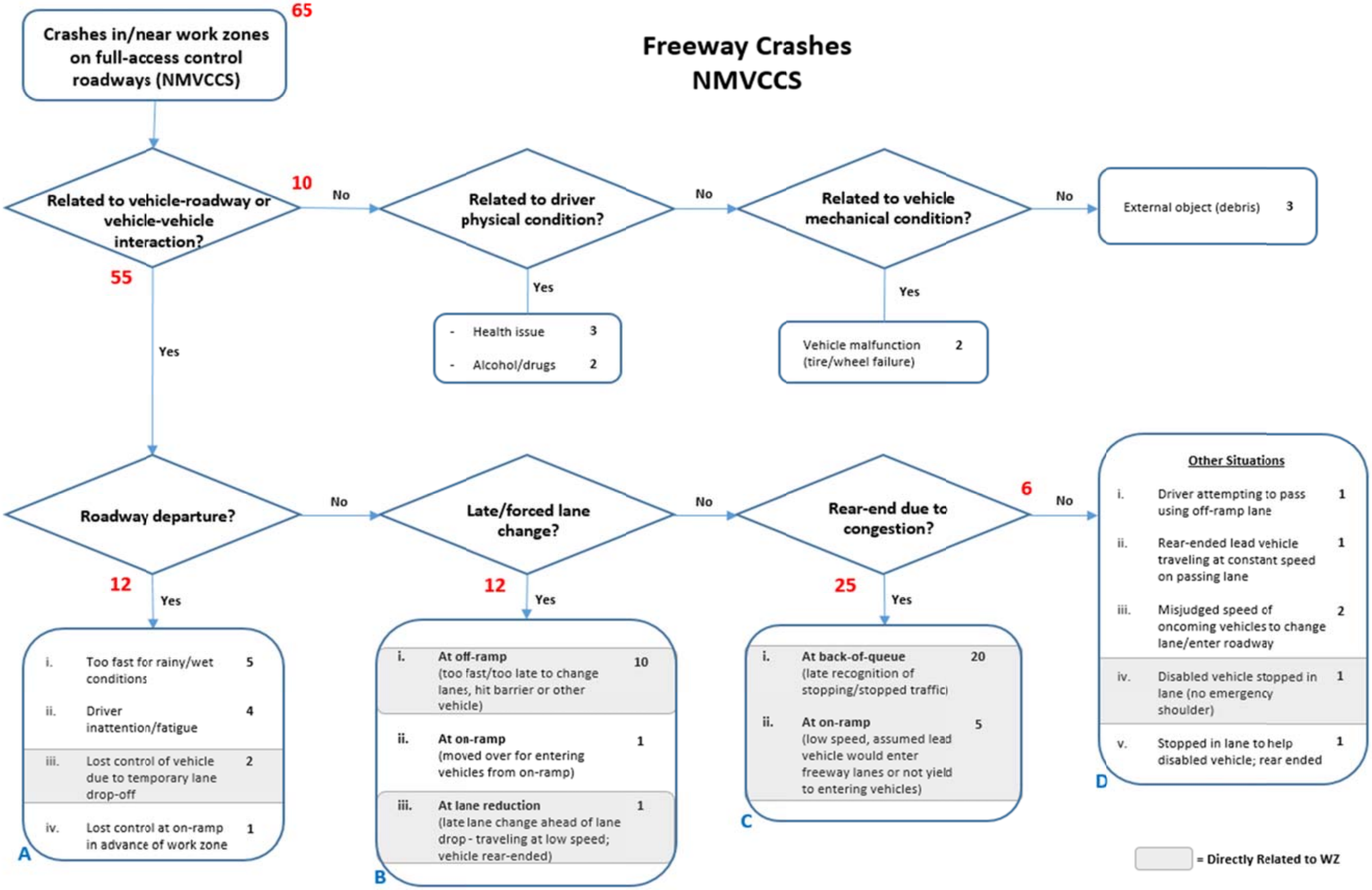


Figure 2. Initial classification of NMVCCS crashes in or near work zones on freeway/interstate roadways.

- Roadway departure
- Late/forced lane change
- Rear-end due to congestion
- "Other" situations

As expected, the classification with the highest frequency was the rear-end crashes due to congestion (25 crashes, or 45.5% of the 55 crashes). Further breakdown of these four groups is also given in Figure 3 with additional details of situations leading to the crashes.

In the roadway departure group there were 12 crashes (21.8%), further divided into four sub-groups. Only one sub-group could be directly related to the presence of a work zone and involved drivers losing control of the vehicle due to a temporary edge drop-off (two crashes, or 3.6%). The remaining three sub-groups were as follows:

- Vehicles traveling too fast for rainy/wet conditions (five crashes), with three of these crashes occurring while negotiating a curve
- Driver inattention/fatigue (four crashes)
- Losing control while traveling near an on-ramp in a work zone (one crash)

This last case occurred when a vehicle on an entrance ramp made a sudden lane change, entering the right through lane and sideswiping a through vehicle. It is noted that out of the three cases where drivers lost control of the vehicle while negotiating a curve, two cases were on entrance ramps that were not modified due to the work zone. In the remaining case, a vehicle traveled over standing water on a curved freeway section within the work zone, hydro-planed, and then lost control crossing a gravel median. It was not possible from the available documentation to ascertain whether the work zone somehow contributed to the presence of the standing water. Therefore, the visualization of the relation of crashes and work zones only includes the two crashes associated with the drop-off, as shown in Figure 3 in the category "changes in surface conditions".

In the group of "late/forced lane change" crashes, most occurred at or near exit ramps (10 out of the 12 crashes) when drivers lost control of the vehicle as they attempted to exit the roadway but were too close and/or traveling too fast at or near the exit gore point. Out of the 10 crashes near exit ramps, five of them occurred at locations where work zones were not visible in the crash photos or had no influence on the roadway configuration. The five remaining exit-ramp crashes were considered to be directly related to the work zone presence with shifted lanes (three cases), one of the two ramp lanes temporarily closed (one case), or the exit lane pavement was grooved and uneven (one case). In addition to the 10 crashes at exit ramps, one crash at an entrance ramp involved a truck causing other vehicles to depart the roadway. This occurred as the truck changed from the right to the left lane in anticipation of an entrance ramp while traveling on a two-lane freeway section upstream of any influence from the work zone. Lastly, the twelfth crash involved a vehicle making a sudden lane change just ahead of a lane drop and after a curved segment, causing others to suddenly decelerate and resulting in a rear-end crash. This crash was considered work zone related, but based on the crash report the main critical reason was driver distraction/inattention even though the drivers from the two vehicles stated that advance signs were not placed at a sufficient distance from the taper for the driver to properly react.

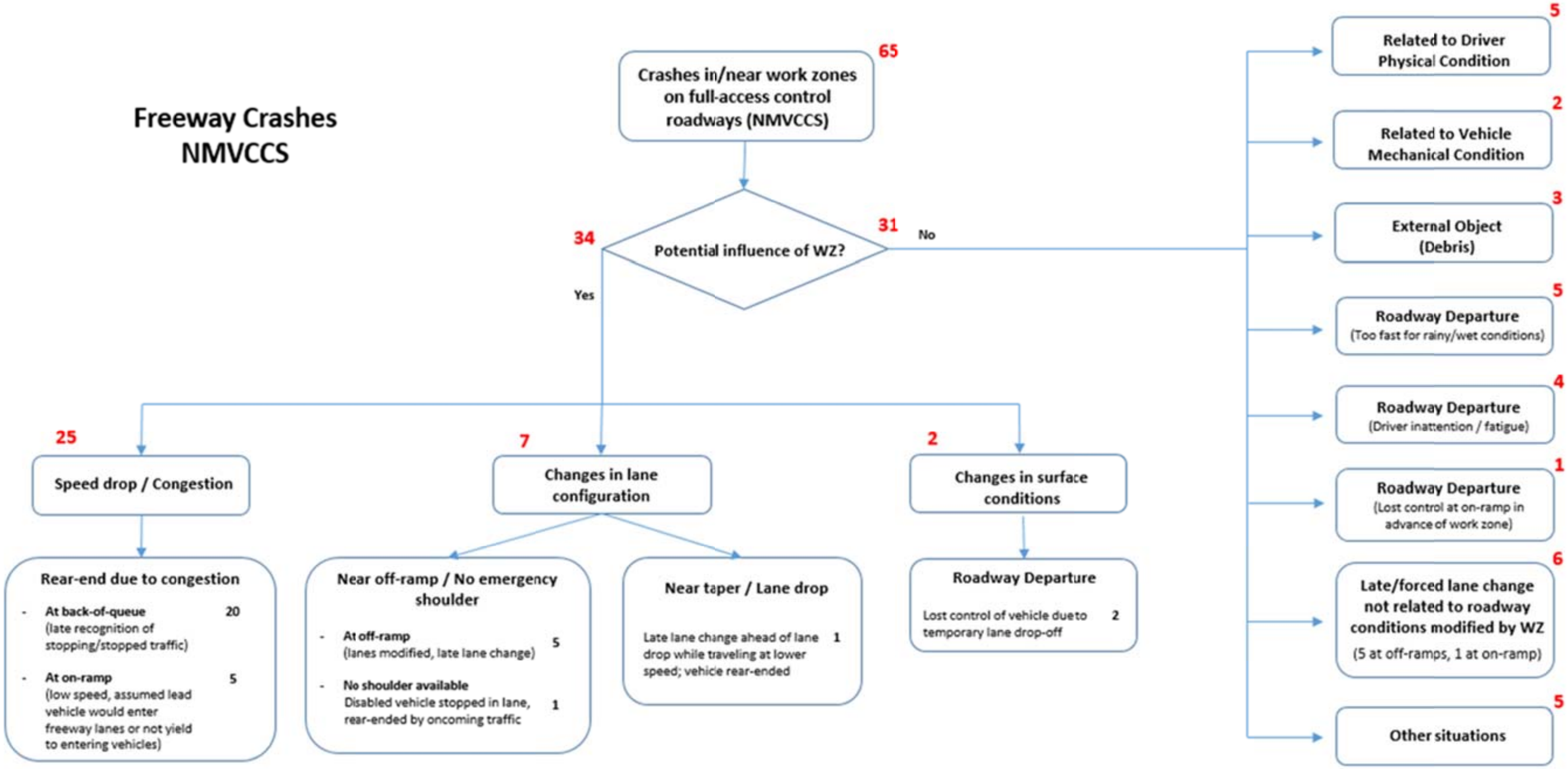


Figure 3. NMVCCS crashes in or near work zones on freeway/interstate roadways based on direct relation to the work zone.

Thus, a re-classification of the 12 crashes in this group, this time based on cases where work zones could have had an influence, results in six crashes being work zone related and another six grouped as having no clear work zone influence. Out of the six cases classified as work zone related, in four occasions the right lane leading to the off-ramp was shifted and had temporary concrete barriers (in one case the right lane was closed with cones), in one case the pavement on the right lane near an off-ramp was grooved, and in one case a late merge in advance of a lane drop caused a rear-end crash. These crashes are shown in Figure 3 in the categories “Near off ramp” and “Near Taper / Lane Drop.”

For the group of rear-end crashes due to congestion shown in Figure 3, in at least 19 of the 25 cases (76%), the crash report explicitly mentions that congestion was influenced by the work zone presence. In the remaining 6 cases, congestion was present and a connection between congestion and work zone presence was not explicit it but could be inferred from the report (the work zone was in all cases cited as a traffic flow interruption factor). A further breakdown of these crashes indicated that 20 of the 25 rear-end crashes (80%) occurred on segments without access points, where the drivers were distracted or failed to recognize slowing down/stopping traffic. Out of the five remaining crashes, four of them were related to yield maneuvers and inattentive drivers during stop-and-go conditions at locations adjacent to on-ramps. The fifth on-ramp crash occurred as a vehicle forcedly changed lanes from the ramp into the right lane and caused a rear-end crash but it was not related to stop-and-go conditions. Out of the five on-ramp crashes, two of them were in a work zone where the ramp was modified, and two others occurred where one of the main lanes was closed for construction. However, from the report pictures it seemed that modifications to the ramps in these two cases were not significant enough to cause significant challenges for drivers, and sudden speed reduction combined with driver inattention had more important roles in the crashes.

Lastly, six of the remaining crashes did not fit the previous classifications and were grouped in a classification called “other situations”, where only one of them may have been directly influenced by the nearby work zone. In this case, a vehicle became disabled in the right-most lane at a location without enough shoulder width for a driver to pull over (the shoulder was not available due to a work zone barrier). This crash was classified as related to “Changes in lane configuration” in Figure 3.

In summary, the 65 freeway crashes were re-classified based on the direct influence of work zones, as shown in Figure 3. A total of 31 crashes (48%) were likely not influenced by the work zone and 34 (52%) could be related to work zone presence in one of three ways:

- Rapid decrease in operating speeds or congestion due to the construction activities (74% of the 34 work zone-related crashes)
- Changes in lane configuration (21%)
- Changes in the roadway surface conditions (5%)

Based on the diagrams and photos from the crash records, it is noted that even though the 34 work zone related crashes did not necessarily occur on segments where the work space was located, the sequence of events leading to the crash was always initiated within the area of influence of a work zone, including the advance warning area.

Non-Freeway/Interstate Crashes

Crashes in non-freeway segments were identified by subtracting the freeway crashes (65) from the total work zone crashes initially found (178) in the NMVCCS records, for a total of 113 crashes. After eliminating a small number of records because some crashes were not at/near a roadway work zone (e.g., a building construction or no indication of a work zone), a total of 106 crashes on non-freeway segments remained for further examination.

An initial classification of the crashes is shown in Figure 4. Similar to freeway crashes, those not related to vehicle-roadway interactions (e.g., roadway design, surface conditions) or direct vehicle-vehicle interactions were identified first, resulting in 21 out of the 106 records. Further classification of the 21 crashes showed that they were related to driver physical condition, vehicle mechanical condition, and other factors such as reckless/aggressive driving, and an animal-related evasive maneuver that resulted in a single-vehicle crash.

Next, the 85 remaining crashes were examined to determine whether they were located at/near intersections. It was found that most non-freeway crashes were at intersections, with a total of 47 records. Even though the sample size in this evaluation is small, the ratio of intersection-related crashes to all sampled crashes was about 55% (47/55), which is not far from a national average of about 40% (*Choi, Eun-Ha, 2010*). Out of the 47 intersection-related crashes, 23 (49%) occurred at signalized and 24 (51%) at non-signalized intersections (stop-controlled and non-controlled). Further examination of the records showed whether at least one of the involved vehicles was turning left or right, or if all vehicles were traveling through the intersection. At signalized intersections, 10 crashes (43%) involved through vehicles only, eight of which had vehicles entering the intersection without the right of way (i.e., after the signal indication had changed to red) and the remaining two were rear-end crashes near the stop bar. All the 10 crashes with only through vehicles, however, were mainly attributed to driver performance errors such as inadequate surveillance and distraction, without clear influence of work zone elements.

The remaining 13 crashes at signalized intersections (57%) involved turning vehicles. A total of 12 out of those 13 crashes (92%) involved left-turning vehicles, and eight of those were associated with driver performance errors similar to those mentioned above for crashes with through vehicles only. However, in the remaining four crashes with left-turning vehicles, the presence of the work zone could have influenced the crash. In two cases, the left-turn lanes were closed and vehicles had to turn from through lanes. In one other case, left turns were prohibited but a vehicle proceeded to turn anyway. In still one final case, the through lanes were closed and vehicles were required to turn left. In each of these four cases, drivers turned left without having the right of way. The reports mentioned driver confusion and/or misjudgment related to the modified intersection layout, implying that it was more difficult for drivers to adequately judge acceptable gaps in the opposing traffic stream. One other crash involved a right-turning vehicle, but appeared to result from a driver misjudging the gap with the vehicle in front while turning, and so was not considered to be work zone related.

At unsignalized intersections and non-controlled entryways the proportion of crashes involving through and turning vehicles followed a similar trend. Out of 24 crashes, 12 (50%) involved a left-turn vehicle, two (8%) involved a right-turning vehicle, and remaining 10 (42%) involved only through vehicles. All 10 crashes with only through vehicles and the two crashes involving right-turning vehicles were not directly associated with work zone elements or characteristics, but rather to driver-related performance error elements. On the other hand, out of the 12 crashes involving left turns, four crashes (33%) were associated with driver performance errors but eight (67%) appear to have a more direct relation with work zone elements. These eight crashes include: five cases (63%) where the field of view for drivers turning left could have been reduced by construction equipment, temporary signs, or construction-related congestion; two cases (25%) where the work zone configuration and signs contributed to driver confusion resulting in vehicles turning left while oncoming traffic was approaching; and one case (13%) of a last-second decision to turn left and divert to avoid construction-related congestion that resulted in a crash with opposite-direction traffic.

Crashes that did not occur at intersections (38) were also classified into three specific sub-groups and one general sub-group that contained unique or less common cases. The first sub-group included rear-end collisions (18 crashes, or 47% of the non-intersection crashes). Of these, most (12 crashes, or 67% of the non-intersection rear-end crashes) occurred at the back of queue due to congestion, two other crashes (11%) occurred at/near a flagger directing traffic, and a few cases (22%) that involved working trucks stopped in a traveled lane and participating in construction activities.

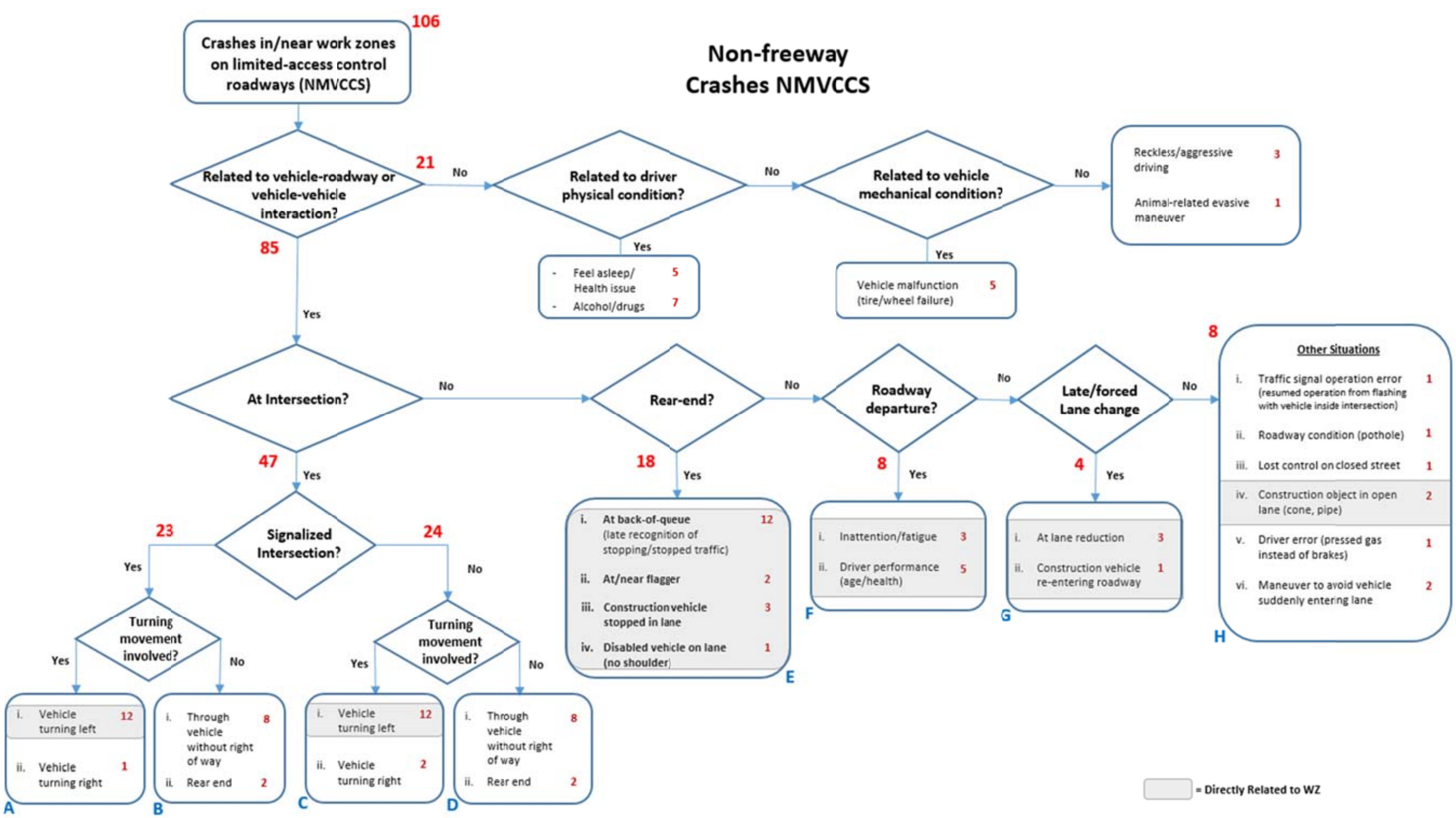


Figure 4. Initial classification of NMVCCS crashes in or near work zones on non-freeway/interstate roadways.

The second sub-group included roadway departure crashes (eight cases), where driver performance errors including inattention, health issues (two cases), and driver age (one case involving a young driver and one case involving an older driver) were contributing factors along with the construction zone being present. The crash involving a younger driver (18 years old) was speed-related, and the crash involving an older driver (79 years old) occurred at a location where the driver intended to turn left to the northbound lanes (which were closed) and had to use one of the two southbound lanes that was opened for this purpose (a temporary two-lane two-way operation). The driver became confused and in an attempt to U-turn and head back, he crashed into a vehicle on the southbound lane.

The third sub-group included four crashes with vehicles attempting late or forced lane changes at lane drops (three cases) and a construction vehicle re- entering the main travel lanes. These crashes were directly related to the presence of a work zone and also to driver distraction or inadequate action to change lanes.

Similar to freeway crashes, the potential effect of construction zones in the occurrence of each crash was also examined and resulted in the diagram shown in Figure 5. Out of the 106 crashes, in most cases (63 crashes, or 59%) the construction zone did not appear to have a clear role in the sequence of events that led to the crashes. The remaining 43 crashes (41%) could be related to work zones and were sub-grouped into the following categories (from largest to smallest):

- Crashes that occurred as a consequence of speed drop due to construction zone congestion, as indicated in the NMVCCS records (18 crashes, or 42% of the work zone-related crashes)
- Crashes that involved left-turning maneuvers (12 crashes, or 29%)
- Roadway departure due to poor driver performance and distraction (five crashes, or 12%)
- Late/forced lane changes (four crashes, or 10%) at lane reductions or due to construction vehicles re-entering to the main lanes
- Other situations (two crashes [5%])

LTCCS Analysis

Methodology

In addition to work zone crashes in the NMVCCS, work zone crashes in the LTCCS were also re-examined to determine if specific sequences of events were predominant in the crash descriptions. Initial screening of the records in the LTCCS showed a total of 77 crashes where a construction zone and/or a flow restriction associated with a work zone was present. Out of these 77 crashes, a total of 55 were identified on segments belonging to a rural or an urban freeway or interstate with full access control. The other 21 out of 22 remaining crashes occurred at facilities not classified as being part of a freeway section, and one crash was found not to be in close proximity or influenced by a work zone, and thus not considered further. The analysis of the freeway and non-freeway crashes from the LTCCS is described as follows.

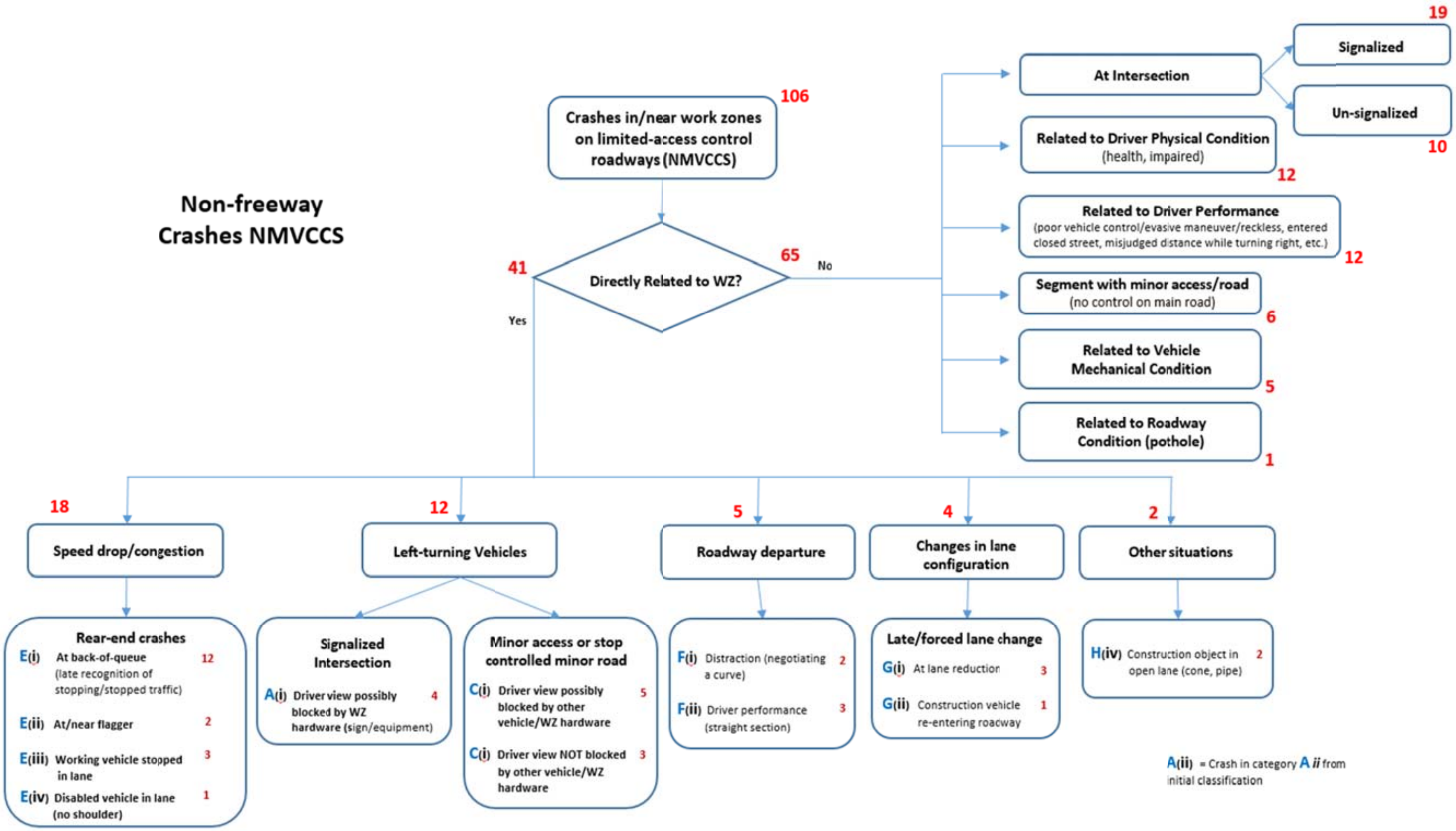


Figure 5. NMVCCS crashes in or near work zones on non-freeway roadways based on potential influence of the work zone.

Results of Analysis

Freeway/Interstate Crashes

The re-examination of the 55 crashes on urban and rural freeways resulted in the groupings by type of crash shown in Figure 6. Only one crash was not related to vehicle-roadway interactions (e.g., roadway design, surface conditions) or direct vehicle-vehicle interactions and it was attributed to brake failure.

From the 54 remaining cases, 35 (65%) were rear-end crashes and the majority of those (26 cases) occurred at or near the back of queue when drivers did not react on time to avoid making contact with stopped or slow moving vehicles. All 26 crashes at the back of queue were considered work zone related, as the congested conditions were generated or intensified by the presence of construction.

It is also noted that out of the remaining rear-end crashes, four cases involved vehicles re-entering the traveled lanes from the construction area. A closer examination of these records showed that three cases could be attributed to a driver decision error rather than a deficiency in the design of the construction area. However, one of these crashes could be related to the reduced field of view experienced by a truck driver entering the traveled lanes from a left-side (median side) work zone at the end of a section curved to the right. The truck driver expressed difficulty spotting oncoming traffic from that position, and made the decision to proceed resulting in the truck being impacted by another truck traveling in the left-most lane.

Other rear-end crashes included a daytime crash involving a trailer truck that impacted a slow moving (five mph) attenuator truck part of a moving lane closure on lane one out of five lanes (considered work zone related), two cases of disabled vehicles, one on the left lane without emergency shoulder (considered work zone related) and one outside of the traveled lanes on the right shoulder (not work related), one case of a driver over-reacting to barrels misaligned on a bridge (considered work zone related), and one case of an illegal maneuver when a driver aborted using an off-ramp and suddenly returned to the traveled lanes using the gore area (considered work related because the left lane of the two-lane freeway was closed).

One more category included seven crashes where vehicles performed a late/forced lane change. Three of these crashes occurred near the beginning of the taper closing a lane as drivers attempted to change lanes. However, even though the crashes were work zone related, from these crash records there was no indication of deficient work zone design or layout and crashes were mainly associated with driver performance or recognition errors. Similar conclusions were also reached from the remaining four late/forced lane change crashes, two of which occurred near the back of queue at congested construction areas, one near an off-ramp that was not modified by the work zone when a driver tried to change lanes from the right (exit) lane and hit an adjacent vehicle, and one rear-end crash as a driver initiated a late diverge maneuver to take an off-ramp.

Regarding the five roadway departure crashes, only two cases were directly related to temporary roadway characteristics. In other instances, truck drivers traveling on the right lane lost control of the vehicle when their tires dropped off the edge of the travel lanes because the shoulder had been converted to a temporary travel lane. The other roadway departure crashes involved drivers traveling too fast to negotiate an off-ramp and a curved segment near an interchange, both of which were not modified by the construction.

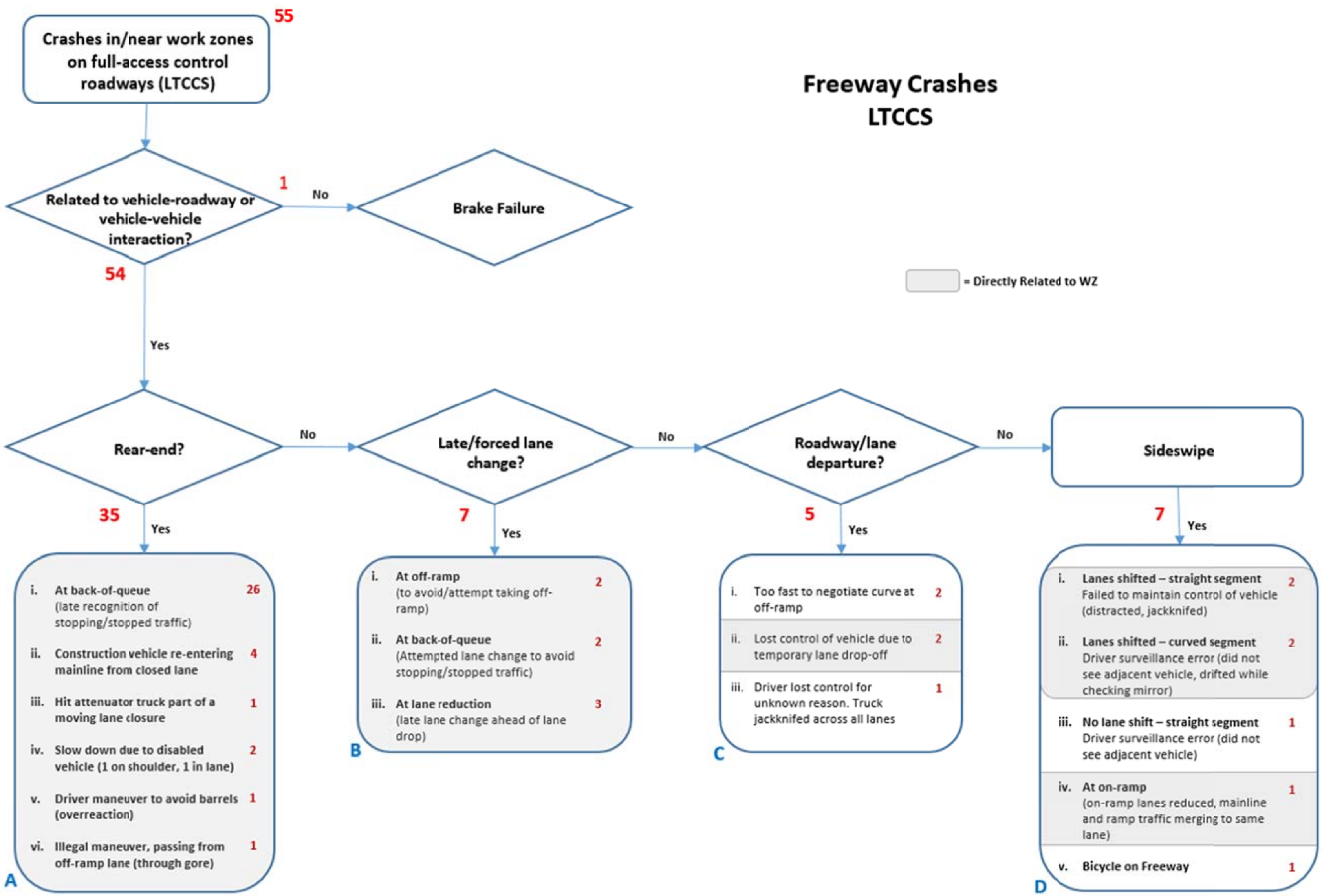


Figure 6. Initial classification of LTCCS crashes in or near work zones on freeway/interstate roadways.

In a separate category there were seven sideswipe crashes involving at least one truck. In five cases, the lane configuration was modified by construction, and for this reason were considered related to the work zone presence. There was one crash involving a bicyclist traveling unlawfully on the freeway involved in a crash, and another crash that appeared to be due to driver error in detecting a vehicle in an adjacent lane during a lane change maneuver on a tangent section unmodified by the work zone, and so both of these were not considered to be directly related to the work zone. In four of the seven cases, the traffic lanes were shifted, with two of the four crashes on curved segments. In one case the driver failed to see an adjacent vehicle and attempted to change lanes, and in the other case the driver was checking his mirror and the truck drifted out of the lane while negotiating the curve, sideswiping a vehicle. The two other crashes on straight segments involved driver inability to control the truck and jackknifed or drifted onto the adjacent lane because of internal distraction (lighting up a cigarette).

The last sideswipe crash occurred at the merge point (on ramp) between two interstates, where the right lane of one interstate and the left lane of another interstate merged into one lane. During construction, merging vehicles had to use the left lane (the right lane was closed with barrels) and the open lane was controlled by a temporary yield sign. The crash occurred as a truck traveling on the right lane and a vehicle merging from the only open lane sideswiped at the merge point.

A summary of the crashes classified as directly related to the work zone or not is shown in Figure 7. Based on the crash descriptions, diagrams, and photos most work zone crashes from the LTCCS were likely affected by the presence of a construction zone itself, with 47 of the 55 crashes in this sub-group. It is noted that direct comparisons of the crash breakdown between the LTCCS and the NMVCCS should be avoided since they were not conducted following the same guidelines and sampling methods.

Most of the crashes where construction could have affected the crash were related to sudden speed drops and congestion (28 crashes), and all of them except one occurred at or near the back of queue in congested conditions. Also, 17 crashes occurred at locations with changes in lane configurations, four of them near ramps, four involving construction vehicles re-entering the travel lanes, three near the beginning of a taper, four on segments with lanes shifted, one with a disabled vehicle on a section without shoulders, and one involving a driver overreaction to barrels near the traveled lane along a bridge. Lastly, two crashes were in a separate category where trucks lost control due to temporary lane drop-offs.

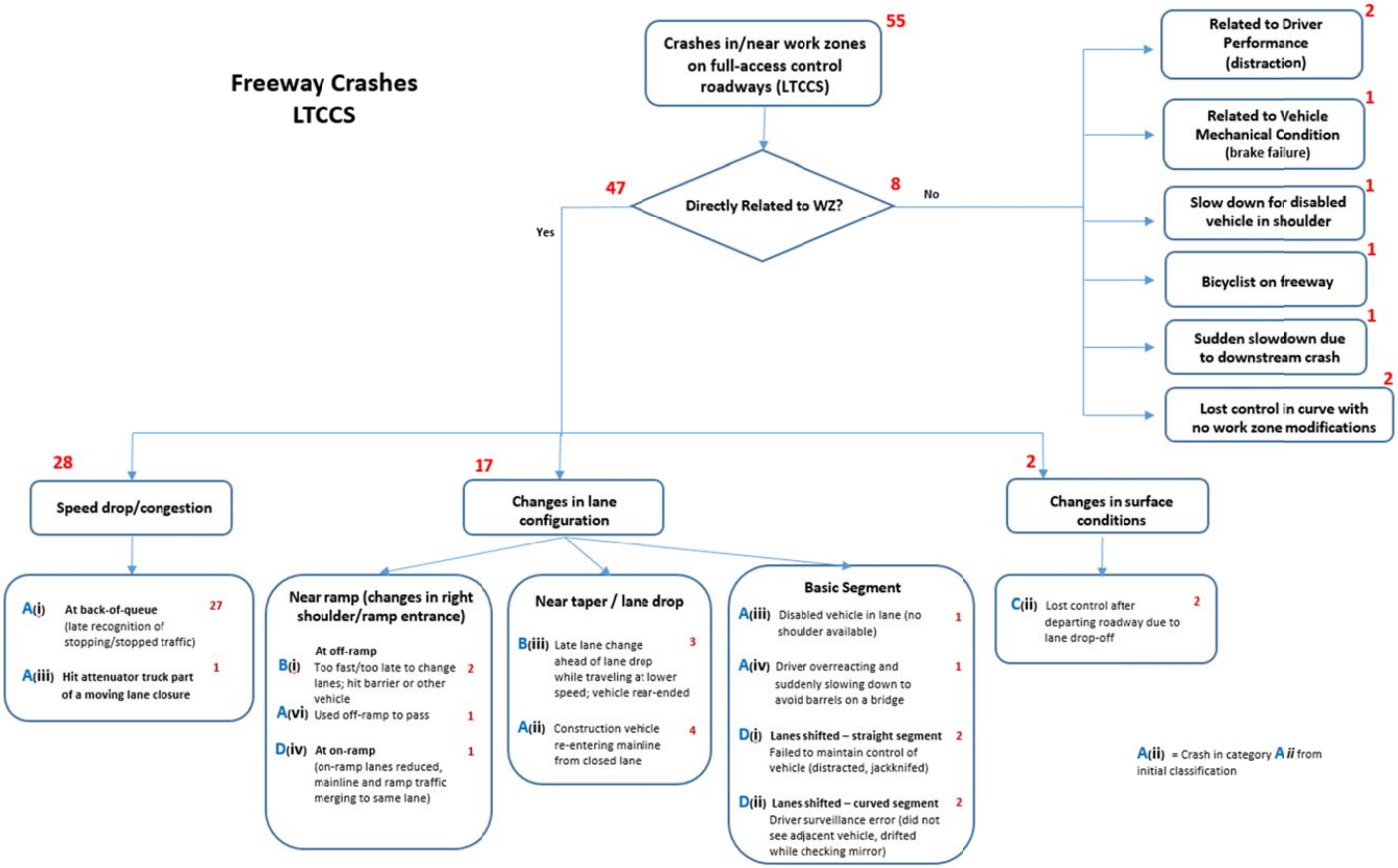


Figure 7. LTCCS crashes in or near work zones on freeways/interstates based on direct relation to the work zone.

Non-Freeway/Interstate Crashes

A total of 21 work zone crashes from the LTCCS records were identified and analyzed at facilities without full-access control. Following a similar format used for the freeway/interstate crashes, non-freeway/interstate crashes were first classified into vehicle-roadway or vehicle-vehicle interaction categories, as shown in Figure 8.

A total of eight crashes (38%) were not related to vehicle-roadway or vehicle-vehicle interaction but rather to the driver physical condition and/or the vehicle mechanical condition, and two of those were very specific situations where construction equipment hit workers inside the work space (and thus did not involve public road users).

The remaining 13 crashes were classified as follows: rear-end, roadway departure, at intersections, and sideswipe. As expected, the most common category was rear-end crashes, with a total of six crashes (46%). Three of those cases involved trucks rear-ending a vehicle in congested conditions, two cases involving trucks rear-ending a vehicle at locations where a flagger was directing traffic (one-lane two-way operation), and one case where a vehicle rear-ended a truck stopped in traffic. One of the two cases with a flagger directing traffic was attributed to driver distraction, but in the other case the report explicitly notes the lack of warning signs in advance of a curve that preceded the work zone. Moreover, this crash was a secondary crash following another rear-end collision at that location. The report also mentions that advance warning signs were added after this crash occurred to help prevent future incidents. It is also noted that the four rear-end crashes not involving a flagger were directly related to driver performance factors such as distraction or poor directional control.

Meanwhile, three roadway departure crashes were also identified, each with a distinctive characteristic. Whereas in two cases the driver lost control of the vehicle at a curved segment, in one occasion a driver overcompensated as he drifted to the right and almost hit a temporary concrete barrier next to the edge of the right lane, and in the other case the driver lost control of the vehicle at a section with uneven pavement due to resurfacing. The third case involved a head-on collision as an automobile departed the lane on a two-lane two-way roadway, crossed the double yellow line, and collided with an oncoming truck. It is noted that in normal conditions (no work zone) this was a four-lane divided roadway.

The third category included three sideswipe crashes at intersections, two of the crashes at unsignalized locations and one at a signalized location. The crash at the signalized location occurred at a four-lane undivided roadway, was categorized in the report as a driver decision error, and involved a left-turning truck not yielding to oncoming traffic. This work zone was not considered to have influenced the crash. At the unsignalized intersections, one of the crashes involved a driving error by an older driver (82 years old) turning left from a four-lane divided road with channelizing drums onto an uncontrolled access road and being impacted by opposing through traffic. The second crash involved an illegal maneuver by the driver not stopping and yielding to crossing traffic. Even though the driver stated that barrels blocked the stop signs, from the diagram and photos it does appear that one of the stop signs was clear from any obstruction. Whether the driver’s eye height or location relative to the barrels actually obscured the stop sign could not be determined from the available crash data.

Lastly, an additional crash was identified in the sideswipe category, as a distracted driver could not react on time to avoid hitting stopped vehicles, changed lanes to avoid a rear-end crash, entered opposite direction travel lanes, and was sideswiped by an oncoming truck.

A re-classification of these non-freeway crashes based on the direct relation to the work zone is shown in Figure 9. As expected, the largest group was crashes related to speed drop/congestion (seven crashes), followed by changes in lane configuration (two crashes), changes in surface conditions (one crash), and at an intersection (one crash). It is also noted that a final category (grayed out in Figure 9) includes the two incidents where workers were hit by construction equipment inside the work space and did not involve public road users.

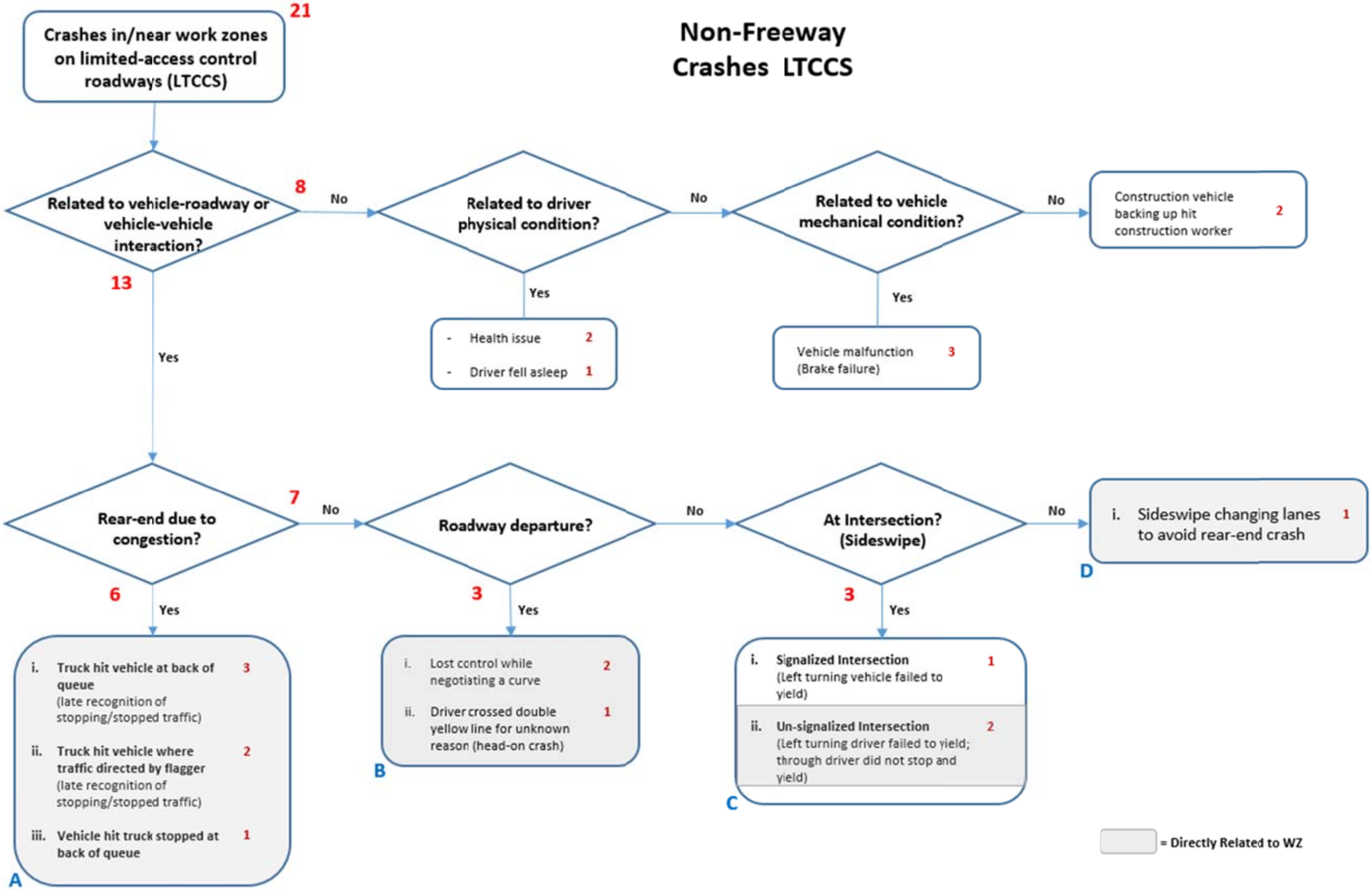


Figure 8. Initial classification of LTCCS crashes in or near work zones on non-freeway/interstate roadways.

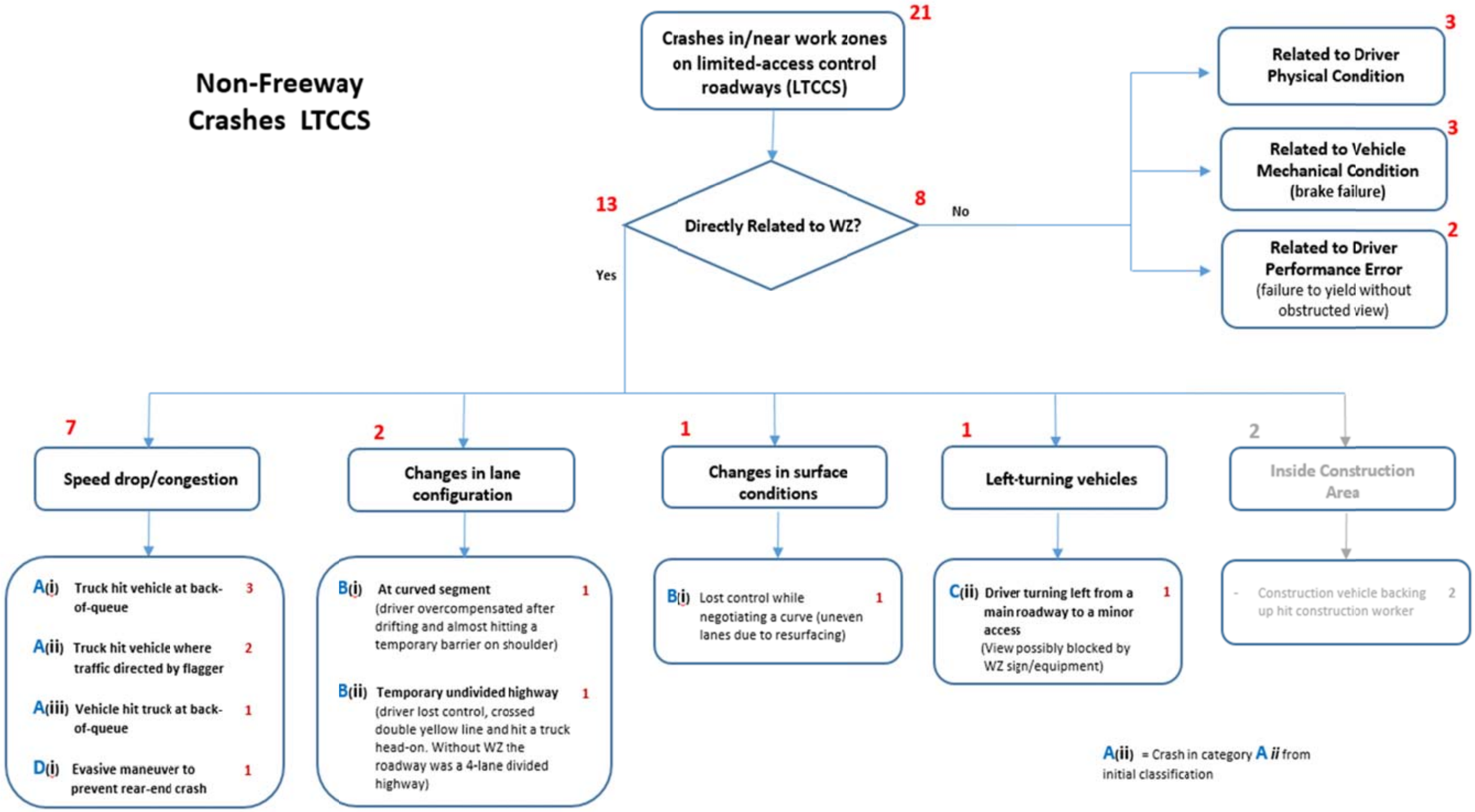


Figure 9. LTCCS crashes in or near work zones on non-freeway/interstate roadways based on potential influence of the work zone.

Summary of Findings from the NMVCCS and LTCCS Analyses

A breakdown of the freeway and non-freeway crashes grouped by main categories and subcategories for each of the two databases is shown in Table 4. Overall, ***back of queue rear-end crashes*** related to speed drop/congestion were by far the most common type and represented about 48% of all work zone related crashes (64 of the 133 crashes). Rear-end crashes at the back of queue were also the single largest contributor for both freeway and non-freeway categories in both NMVCCS and LTCCS databases.

Congestion due to construction activities and/or roadway changes were in most cases explicitly mentioned as contributing factors for the rear-end crashes. Additional major contributing factors were mostly driver-related, in particular driver distraction, inattention, and failing to recognize stopped or decelerating traffic.

The second largest category was vehicle ***crashes at or near freeway off-ramps*** (eight crashes). In these cases, access to off-ramps was modified within the construction zone in a variety of ways: reduced number of deceleration lanes, length of deceleration lane, or temporary barriers and other roadway hardware. In general, these crashes were coded as involving driver performance errors when trying to exit (or trying to avoid exiting) and while traveling too fast or attempting a late lane changing maneuver. Similar to rear-end crashes, the work zone presence was relevant because it modified the off-ramp, increased congestion, and narrowed the available width for drivers to maneuver.

The next largest category included ***crashes at or near a taper or a lane drop*** (seven crashes). These crashes occurred on both freeway and non-freeway facilities, and involved both passenger vehicles as well as trucks. All of these cases were associated with the late recognition or a late maneuver in advance of the lane reduction, and most of these crashes resulted in rear-end crashes not due to congestion but to the late maneuver.

Another significant category observed at non-freeway facilities involved six crashes that were associated with ***vehicles turning left onto minor roads that were not controlled from the main road***. These maneuvers required drivers to judge available gaps in oncoming traffic before proceeding. Based on the analysis of available data, it is possible that these crashes were influenced by limited driver visibility due to work zone hardware or equipment. Examples of such hardware/equipment included construction equipment in the left-turn lane of opposing traffic, vertical panels dividing traffic on a two-lane, two-way road, and congestion in one lane blocking the view of traffic approaching in adjacent lanes.

Five crashes involving ***construction vehicles re-entering the travel lanes*** comprised the fifth most common category. Speed differentials between main lane traffic and trucks entering from the work space were a significant factor in these cases, with vehicles rear-ending the construction trucks. In one instance in particular, a truck was rear-ended as it re-entered from the median lane on a segment curved to the right. From this angle, the truck driver stated that he had reduced visibility of oncoming traffic, which contributed to the crash occurrence.

Table 4. Summary of NMVCCS and LTCC Crashes where the Work Zone Influence was Likely

Category	Sub-category	NMVCCS		LTCCS		Total
		Freeway	Non-freeway	Freeway	Non-freeway	
Speed drop/ congestion	At back of queue (driver distraction / inattentive / failed to recognize stopping traffic)	20	12	27	5	64
	At/near on-ramp	5				5
	Moving lane closure			1		1
	At/near flagger		2		2	4
	Working vehicle stopped in lane		3			3
	Disabled vehicle in lane - no shoulder	1	1	1		3
Changes in lane configuration	Near off-ramp (modified ramp access)	5		3		8
	Near on-ramp (on-ramps lanes reduced)			1		1
	At lane drop / Near taper	1	3	3		7
	Construction vehicle re-entering roadway		1	4		5
	Lanes shifted - curved segment			2		2
	Lanes shifted - straight segment			2		2
	Drifted towards a temporary barrier on a curved segment, then overcompensated				1	1
	Divided Highway temporarily operated as undivided (2-lane 2-way)				1	1
	Bridge - Driver overreacted to barrels in shoulder			1		1
Changes in surface conditions	Temporary lane drop-off	2		2		4
	Uneven lanes				1	1
Left-turning vehicles	Signalized Intersection		4			4
	Minor access or stop controlled minor road view possibly blocked by WZ hardware		5		1	6
	Minor access or stop controlled minor road view not blocked by WZ hardware		3			3
Roadway Departure	Straight segment - Driver performance error		3			3
	Curved segment - Distracted drivers		2			2
Other	WZ hardware in open lane (cone, pipe)		2			2
Total		34	41	47	11	133

New Insights Gained Through the Analyses

The combined results of the analysis of the three different databases illustrate the significance of work zone-induced congestion upon crash potential. Certainly, work zone congestion is a major contributor to rear-end collisions, as previous research has found or hypothesized. Depending on the database considered, work zone-induced congestion was found to contribute to between 24% and 70% of work zone crashes. The analysis also shows that the presence of congestion may also contribute to sideswipe crashes at entrance ramps and at upstream ends of queues as drivers swerve to avoid running in to the back of the vehicle in front of them. The analyses also suggest that work zone congestion also contributes substantially to roadway departure fixed object crashes with barriers or work zone hazards as drivers swerve to avoid rear-end collisions. Although this issue is most commonly associated with freeway/interstate work zones, it does show up on other roadway types as well. For instance, the analysis of the VDOT crash database found that 11% of the rear-end collisions occurred at work zones where flaggers were being used. In most locations, flaggers are used predominantly on two-lane highways for alternating one-way traffic control or for intermittent stop control to manage construction vehicle access points. Although, typically not considered a “congestion” issue, work zones that periodically require temporary stoppages in traffic flow were found to contribute substantially to work zone rear-end collisions.

Analysis of the NMVCCS and LTCCS databases also suggest that ramp junctions at interstate/freeway work zones also create challenges for drivers and contribute to work zone crashes. Often, ramp geometrics must be temporarily degraded (reduced acceleration/deceleration lanes, reduced ramp widths, etc.) in order to accommodate construction activities. Unfortunately, this analysis could not associate the type or magnitude of the ramp degradation with the magnitude of increased crash risk. However, work zone designers should acknowledge in their decisions that temporarily degrading ramp designs will likely increase crashes.

Work zone vehicles entering/exiting the work zone activity area were also found to be an issue in this assessment. Both rear-end collisions and sideswipe crashes in the three databases could be attributed to this issue. In the LTCCS database, 10% of the crashes on interstate/freeway facilities appeared to be the result of trucks attempting to enter or exit main lane traffic to or from the work space. Improving work zone ingress/egress should be made a greater priority for agencies and contractors.

Finally, the analyses of the three databases highlighted that work zones on non-freeway/interstate facilities are creating challenges for drivers that were previously unknown or underestimated. Data from several crashes examined in these analyses indicated that drivers became confused when approaching and entering work zones on non-accessed controlled facilities at intersections and driveways, especially in urban areas. Work zones on divided facilities that were temporarily converted to two-way operation in one of the directional roadways, while the other direction was repaired or rehabilitated appear to be particularly problematic. Improved training on how to properly design and implement TTC for approaches to these types of work zones may be needed. In addition, sight distance challenges were noted for several crashes occurring at these types of work zones. Obstructions created by the presence of work equipment too close to an intersection or driveway were cited as a contributor in a number of crash narratives, as was the presence of certain temporary traffic control devices. In one instance, type 3 barricades placed in the opposing left-turn lane at a signalized intersection limited the ability left-turning traffic coming from the other direction to see approaching through lane traffic during the permissive green phase. Thus, improved training for designing and implementing TTC at both signalized and unsignalized intersections appear to be needed based on this analysis.

The fact that these trends were observed in all three databases, despite the fact that they were created for different purposes and cover very different levels of detail and geography, is particularly noteworthy. Such correlations across the databases adds credibility to the significance of these issues in work zones nationally.

CHAPTER 3 Effects of Queuing and Crash Countermeasures at Interstate Work Zone Lane Closures

Overview

The analyses of the work zone crash datasets described in Chapter 2 verify the perceptions held by many practitioners that queues and congestion are a key contributor to rear-end collisions in work zones, especially on high-speed facilities such as freeways and interstates. Meanwhile, as noted in Chapter 2, multiple studies have shown rear-end collisions to be the predominant type of crash occurring in work zones, and often the type of crash that increases most significantly when a work zone is installed on a roadway segment. Unfortunately, past studies have not been able to quantify how significantly a queue caused by a work zone increases crash risk. Conceptually, the greater the amount of time that a queue is present at a location, the greater the chance for a crash caused by a queue to occur. Similarly, a higher number of vehicles encountering a queue over a given duration would be expected to lead to a greater chance of a crash than if fewer vehicles encountered that same queue. The ability to predict the expected increase in crashes that a queue would create would be valuable to work zone designers and project engineers as they make decisions about when to close travel lanes, how long to allow them to be closed, and whether to employ countermeasures to reduce the risk of those crashes occurring.

With regards to countermeasures available to reduce crash risks due to traffic queues at work zones, many agencies hire law enforcement personnel and vehicles to deploy within or upstream of the work zone. In one study, researchers found that the presence of enforcement (as could be best recalled by the project engineer) resulted in a 41.5% reduction in crashes overall relative to work zones where enforcement was not present (*Chen and Tarko 2012*). However, traffic conditions during the times of enforcement were not available and so could not be incorporated into the analysis. More recently, researchers have analyzed the effect of work zone ITS technology combined with portable rumble strips (PRS) upstream of temporary (a single work shift) work zone lane closures <u>where traffic queues were anticipated to occur during some portion of the work shift</u> (*Ullman et al. 2016*). In their analysis, they concluded that the combination of the real-time end-of-queue warning system (EOQWS) and PRS resulted in a 44% reduction in crashes from what would have occurred had the technologies not been used. In addition, severe crashes and rear-end crashes both appeared to be reduced, consistent with expectations.

A major limitation of that analysis, however, was that the actual presence or absence of queues during those temporary lane closures were not considered. Although queues were anticipated during each of the lane closures examined, differences in traffic demands from one day to the next and other factors did result in some lane closures not experiencing traffic queues, and the duration of the lane closures when queues did exist varied from location to location and by day of the week. Fortunately, the corridor from which the data was taken was also instrumented with Bluetooth readers that were configured to measure current point-to-point travel times. The data can provide an estimate of times and locations when and where traffic queues had developed at the temporary work zone lane closures, and were used to examine the effect of queues due to the lane closures affected crashes. In addition, the effect of using portable EOQWS and PRS upon crashes during periods of queuing and periods of non-queuing were also examined.

Methodology

Description of the Study Corridor

The Interstate 35 (I-35) Central Texas Expansion Project is a seven year, $2.1 billion highway expansion project currently underway along 96 miles within the Waco District, located between Austin and Dallas. The corridor carries between 55,000 and 111,000 vehicles per day, of which 25% to 35% are truck traffic, with higher percentages of trucks during the nighttime hours. The main purpose of the project is to widen the highway to six lanes in rural areas. The project additionally involves improving the freeway infrastructure and changing the current two-way frontage roads into one-way frontage roads. Most of the work is performed alongside the current freeway or protected by barriers in the median, but occasionally, lane closures are necessitated for some construction activities. To reduce the traffic disruption from these activities, the Texas Department of Transportation (TxDOT) mandated that the temporary lane closures only be performed at night, between the hours of 7 PM and 7 AM. However, traffic volumes are still substantial enough for queuing to occur in some locations on some nights. Given that most of the corridor is rural, queues are unexpected at night by motorists, which raised safety concerns about rear-end collisions within TxDOT.

Description of the Queue Warning Crash Countermeasures

Because of practical concerns of using traditional work zone ITS technologies that are placed on the roadside and left for the duration of the project, a highly-portable EOQWS concept based on easily-deployable radar speed sensors (to minimize calibration requirements) was selected. The sensors are linked wirelessly to a central data processing unit, as are one or more portable changeable message signs (PCMSs). System logic evaluates the status of the sensors, and automatically displays an appropriate queue warning message based on the distance from the sign to the location of closest sensor detecting slowed or stopped traffic (see Figure 10). In one configuration, sensors are placed at the lane closure merging taper and then at 0.5, 1.5, and 2.5 miles upstream of the taper. A portable changeable message sign is placed 3.5 miles upstream of the taper. For lane closures where longer queues are expected, additional sensors are placed 3.5, 4.5, 5.5, and 6.5 miles upstream of the taper, and a second PCMS is positioned 7.5 miles upstream of the taper. The concept requires minimal calibration (sensors simply need to be aimed towards oncoming traffic properly) and so could be easily incorporated into the setup of the temporary traffic control for the lane closure each night it was needed, and quickly removed the next morning.

Another technology of interest to TxDOT was the use of PRS. Although rumble strips in general do not typically have a dramatic effect on vehicle speeds in work zones, it was hypothesized that the tactile and auditory stimuli they provide could be beneficial in gaining the attention of distracted drivers approaching a work zone lane closure. Until recently, transverse rumble trip applicability to work zones was limited to long-term deployments because a portable and reusable rumble strip did not exist. However, one vendor developed a rumble strip product which could be quickly put down and picked up and which was reported to be able to remain in place relatively well under traffic (*Heaslip et al. 2010*). The PRS do require periodic attention to ensure that they remain in place. For this application, the PRS were put down as part of the temporary traffic control for the lane closure in the evening, and then picked back up when the temporary traffic control was picked up. The PRS were installed before and after the PCMS, shown as the transverse dotted lines in Figure 10. Figure 11 illustrates the selected product deployed approaching a work zone on I-35.

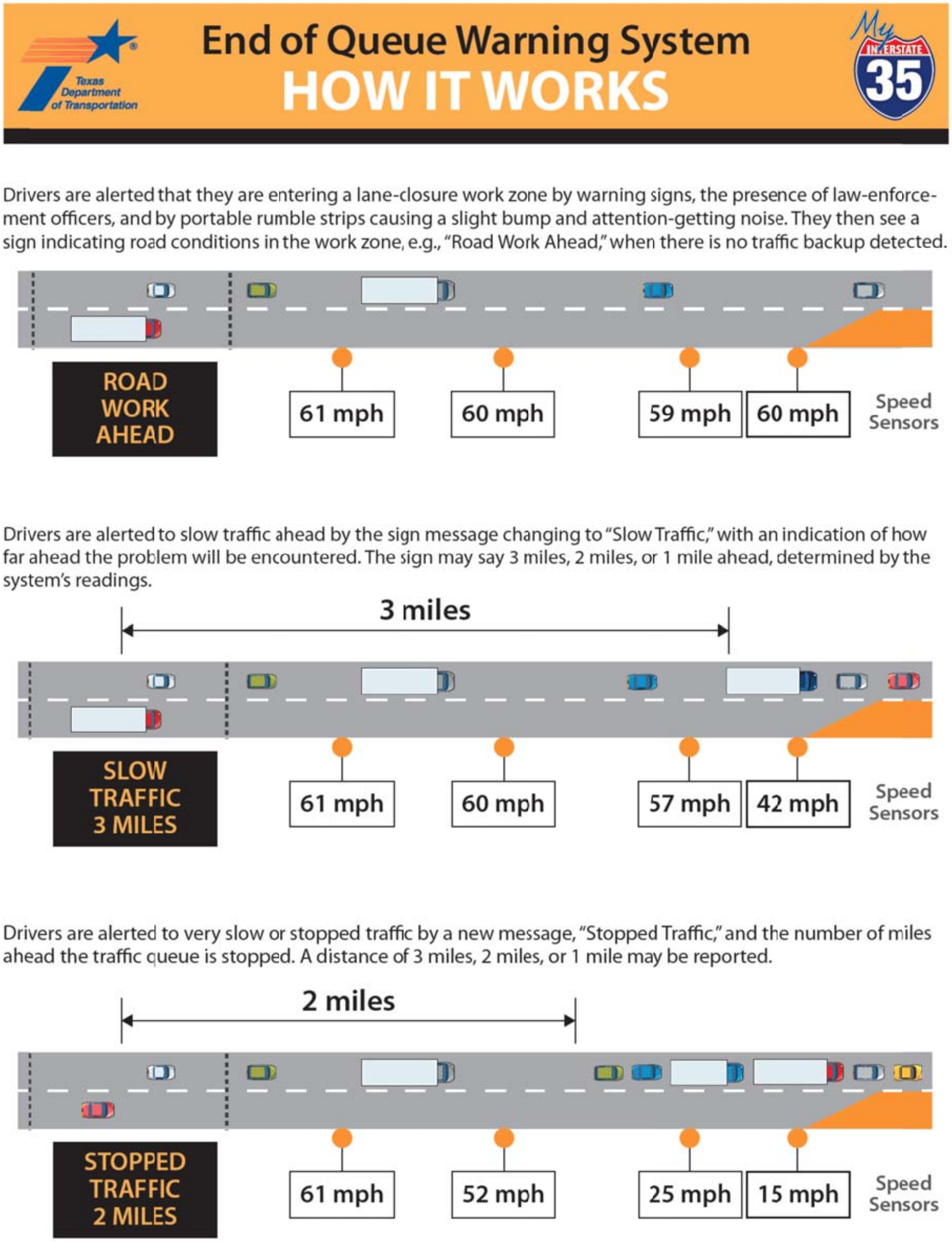


Figure 10. Conceptual operation of the portable queue warning system.

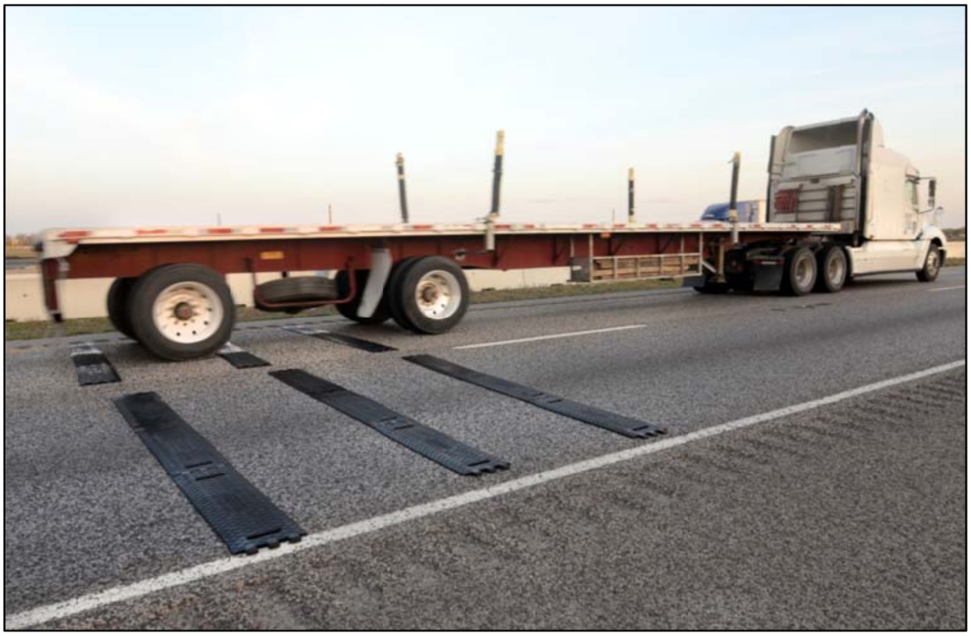


Figure 11. Portable rumble strips used upstream of temporary lane closures on I-35.

Description of the Analysis Methodology

Since 2012, a queue prediction analysis was undertaken for all lane closures proposed by contractors in the corridor. This analysis compared the expected traffic demand during the hours of the closure to the expected traffic capacity of the closure and determined if queuing was probable. For all lane closures since the beginning of 2013, TxDOT mandated that PRS be deployed irrespective of whether or not a queue was expected. For lane closures predicted to cause queuing, TxDOT additionally mandated that the portable EOQWS be deployed in conjunction with PRS to provide maximum possible warning to drivers of potential queued conditions. In 2012, no traffic safety treatments were deployed, and temporary nighttime lane closures during that year provided a controlled baseline for comparison to the 2013-2016 data, for which every lane closure had traffic safety treatments of some kind deployed. For this analysis, over 400 nights of lane closures without safety treatments deployed, and another 700 nights of lane closures with safety treatments, were analyzed.

Determining When Traffic Queues Were Present

Queuing was determined using Bluetooth sensors deployed along the I-35 corridor. These sensors ping Bluetooth-enabled electronic devices in passing vehicles and associate timestamps with the unique Bluetooth device identifiers. When a sensor downstream encounters the same unique identifier, it likewise associates a timestamp and the travel time through the roadway segment can be calculated for that vehicle. This travel time data is then aggregated and averaged every fifteen minutes, and the results used to detect queuing that may have occurred at specific locations along the corridor.

Each of the lane closures had mile markers associated with its start and end points. Each of the Bluetooth sensors are similarly geo-located within the corridor. For each closure on each night, Bluetooth segments were identified that encompassed the lane closure and approximately three to five miles upstream. Data for these segments on that night were extracted from the archived database and used to assess whether the travel time through that segment increased by enough to suggest that queuing had developed. If it had, the duration when queuing was present was also estimated. To accomplish this, the travel times over the analysis segment of each lane closure was graphed over time (aggregated into 15-minute time intervals). Each graph was then reviewed manually to assess if and when queues were present at the lane closure during each 15-minute interval. This manual process looked for regions where average travel times increased by at least 120-seconds (labeled as "mountains" in Figure 12) across two consecutive 15-minute time periods. The 120-second threshold was selected because the majority of the lane closures were approximately two miles in length. Recognizing that vehicle speeds normally dropped 5-10 mph while traversing the lane closure even if no queuing was present, it was estimated that travel times would not increase more than this 120-second threshold due solely to a speed reduction of this magnitude across the two miles. Conversely, even a small (i.e., 0.25 mile) queue forming at the lane closure merge taper would be enough to increase travel times by enough (in conjunction with the reduced speeds through the lane closure) to exceed the 120-second threshold.

The hours and portions thereof when queuing was determined to exist at each nighttime lane closure were then recorded, and the other hours of the lane closure were designated as non-queuing times for that lane closure. Consequently, there existed the following six major categories of conditions available for analysis for the set of nighttime lane closures examined:

- hours when queues were present and no safety treatments were deployed
- hours when no queues were present and no safety treatments were deployed
- hours when queues were present and only PRS were deployed
- hours when queues were not present and only PRS were deployed
- hours when queues were present and EOQWS and PRS were deployed
- hours when queues were not present and EOQWS and PRS were deployed

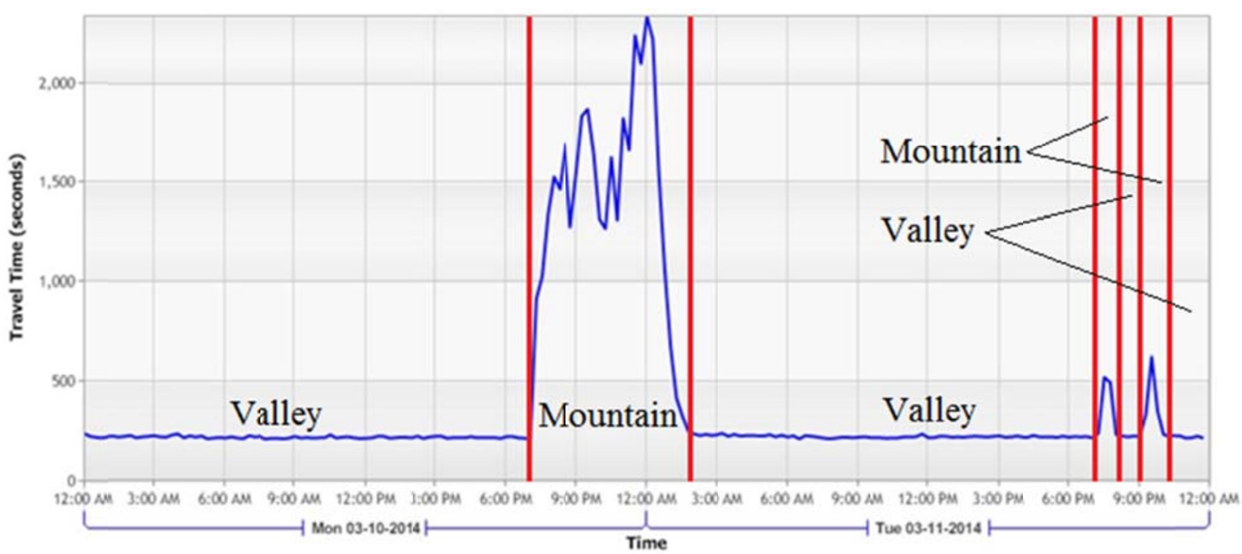


Figure 12. Illustration of the manual queue detection process for each temporary nighttime lane closure segment.

Generally speaking, queues only developed for a portion of the nighttime lane closures when queuing did occur, and for many of the nights, no queues at developed at the lane closures. As a result, the dataset was heavily weighted towards non-queuing hours. Table 5 provides a summary of the hours associated with each of the above six categories. On nights when a traffic queue did form at a lane closure, the queue typically lasted three to five hours before dissipating. The data for the no safety treatments-queued conditions and the only PRS-queued conditions actually represents approximately 120 lane closures each, and the both EOQWS & PRS deployed – queued conditions comes from approximately 206 lane closures.

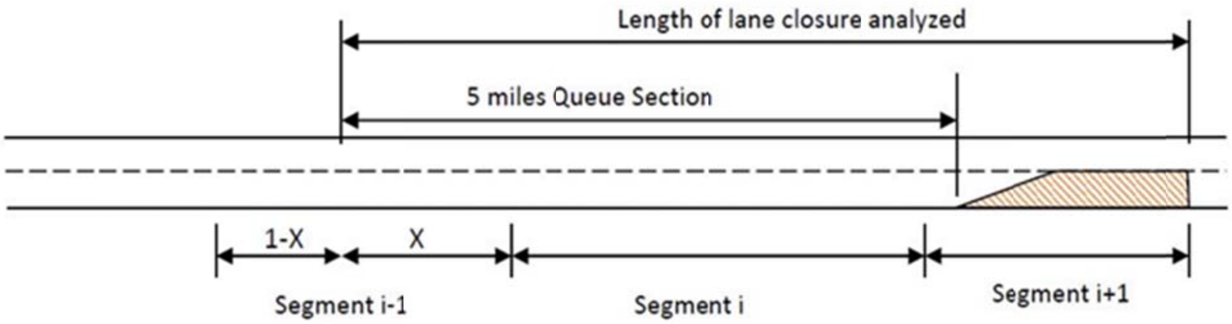
Table 5. Sample Sizes

Analysis Category	Total Hours
No safety treatments - queued conditions	491.5
No safety treatments - non-queued conditions	3941.5
Only PRS deployed - queued conditions	491.5
Only PRS deployed - non-queued conditions	2674.5
Both EOQWS & PRS deployed - queued conditions	1763.5
Both EOQWS & PRS deployed - non-queued conditions	827.5

Safety Analysis Methodology

As stated previously, the location of lane closures changed continuously throughout the corridor as contractors worked on and completed various tasks within each project. The fact that the lane closures when no safety treatments were deployed were not necessarily at the same locations as those where PRS only or the combined EOQWS and PRS treatments were deployed meant that it was not appropriate to simply compare crashes occurring under each of the above six categories. Therefore, the analysis approach ultimately adopted was to compare expected baseline crashes (had the work zone and nighttime lane closures not been present in the corridor) to crashes that actually occurred during each of the six categories of interest. To accomplish this, the corridor was divided into a set of discrete homogenous segments and Empirical-Bayes analysis methodologies applied for years 2003-2009, using the Enhanced Interchange Safety Analysis Tool (ISATe) (*Bonneson et al. 2013*) which is based on models published in the 2014 supplemental document to the HSM. The result of that analysis was an expected number of crashes/year in each segment. The average proportion of crashes occurring during the same nighttime hours that lane closures were allowed during construction was then calculated from the calibration data, and applied to each of the segments to obtain the expected nighttime crashes/year for that segment. Dividing these yearly values by 365.25 yielded an expected number of crashes/night within each segment along the entire corridor.

To estimate the expected crashes per night (ECN) for each lane closure included in the dataset, a lane closure section was selected that included the closure length itself plus a section that extended five miles upstream of the beginning of the lane closure. The ISATe segments corresponding to the lane closure and upstream section was determined, and the expected number of crashes from the ISATe analysis corresponding to that lane closure section determined. In cases where the lane closure section began or ended within one of the discrete homogenous segments, the expected crash/night value was adjusted based on the proportion of the segment overlaid by the lane closure section. Figure 13 illustrates the estimation process. Finally, the expected crashes per night were then further subdivided according to the proportion of crashes occurring each hour per night to yield an expected number of crashes during each hour per night within that lane closure section.



$$ECN_{\text{lane closure section}} = x*ECN_{\text{Segment i-1}} + ECN_{\text{Segment i}} + ECN_{\text{Segment i+1}}$$

where,
ECN = Expected Crashes/Night
Segment i = i^{th} Homogeneous segment in corresponding ISATe model
X = Proportion of ISATe segment within the analysis section

Figure 13. Method of estimating expected crashes per night within lane closure analysis section.

Results

As shown in Table 5, the nighttime lane closures during 2012 when no safety treatments were being deployed experienced many more hours of non-queued traffic conditions than queued conditions. Likewise, the number of hours when PRS only were deployed when no queues were present was greater than the number of hours when only PRS were deployed and queues formed. This was to be expected, as TxDOT attempted to deploy both the EOQWS and PRS on nights when queues were expected to form when the lane closures were deployed. However, due to the stochastic nature of traffic demands on any given night, there were occasions when queues did form when only PRS were deployed. Conversely, the dataset for the combined EOQWS and PRS deployment conditions consisted of more hours of queued conditions than hours when no queues were present.

Table 6 present the expected baseline crashes that would have occurred during the hours and locations in each category if the work zone and lane closures had not occurred, as well as the actual crashes occurring during those hours at the lane closure locations. One sees that the number of crashes occurring during hours when queues were present were substantially greater than the baseline expected crashes, whereas the actual crashes were only somewhat greater than baseline during hours when queues were not present. The increase is particularly evident for the no safety treatment condition, which experienced 18 crashes during hours and locations where only 3.152 crashes would have normally occurred if no work zone or lane closure were present. This represents the equivalent of a 471% increase in crashes from what would have normally been expected in those locations during those times if the work zone and lane closures had not occurred. One sees that crashes are much higher than would have been expected with no work zone and lane closures during times when only PRS were deployed or both EOQWS & PRS were deployed and queues were present. However, the proportional increases are substantially smaller than for the no safety treatment condition. During queued conditions when only PRS were deployed, actual crashes were 277% higher than would have been expected if no work zone or lane closure had occurred. During queued conditions when EOQWS & PRS were deployed, actual crashes were 331% higher.

Table 6. Expected and Actual Crash Results

Analysis Category	Crashes Expected if No Work Zone & Lane Closure	Actual Crashes During Lane Closures
No safety treatments - queued conditions	3.15	18
No safety treatments - non-queued conditions	22.61	29
Only PRS deployed - queued conditions	3.45	13
Only PRS deployed - non-queued conditions	13.69	18
Both EOQWS & PRS deployed - queued conditions	4.17	18
Both EOQWS & PRS deployed - non-queued conditions	9.14	10

The relative effect of the two safety treatments under both queued and non-queued conditions can be computed using an odds ratio analysis as outlined in available guidance on computing crash modification factors (*Gross et al. 2010*):

$$CMF_{Treatment} = \frac{\frac{TA_{Treatment}\,TE_{No\ Treatment}}{TE_{Treatment}TA_{No\ Treatment}}}{\left(1 + \frac{1}{TE_{No\ Treatment}} + \frac{1}{TE_{Treatment}} + \frac{1}{TA_{Treatment}}\right)}$$

$$SE(CMF_{Queue}) = \sqrt{\frac{CMF_{Treatment}{}^{2}\left(\frac{1}{TA_{Treatment}} + \frac{1}{TE_{No\ Treatment}} + \frac{1}{TE_{Treatment}} + \frac{1}{TA_{No\ Treatment}}\right)}{\left(1 + \frac{1}{TE_{No\ Treatment}} + \frac{1}{TE_{Treatment}} + \frac{1}{TA_{Treatment}}\right)}}$$

Where,

$CMF_{Treatment}$ = crash modification factor representing the proportional effect of the treatment upon crashes during nighttime lane closures for the particular traffic condition of interest (queued or non-queued)

$SE(CMF_{Treatment})$= standard error of $CMF_{Treatment}$

$TA_{Treatment}$ = total crashes actually occurring when the treatment was deployed for the particular traffic condition of interest (queued or non-queued)

$TA_{No\ Treatment}$ = total crashes actually occurring when the treatment was not deployed for the particular traffic condition of interest (queued or non-queued)

$TE_{Treatment}$ = total crashes expected when the treatment was deployed for the particular traffic condition of interest (queued or non-queued)

$TE_{No\ Treatment}$ = total crashes expected then the treatment was not deployed for the particular traffic condition of interest (queued or non-queued)

Table 7 presents the CMFs associated with the PRS only treatment and the EOQWS and PRS combined treatment for both traffic conditions. During hours when no traffic queues were present, neither the PRS only nor the combined EOQWZ and PRS treatment resulted in a statistically significant CMF (although the values were both slightly less than 1). Conversely, during hours when a traffic queue was present, both treatments yielded significant reductions in crashes relative to what would have been expected had the treatments not been deployed. Interestingly, the PRS only treatment achieved essentially the same crash reduction as the EOQWS and PRS combined, yielding 60.3% and 53.2% reductions in crashes, respectively. In other words, deploying both the EOQWS and PRS together had almost the same effect as did deploying PRS only when traffic queues were present.

It should be noted that there may be some bias in the data and these results since the PRS only condition was deployed when queues were not expected, whereas the EOQWS and PRS together were deployed where queuing was expected. It is possible that some of the queuing for the PRS only deployments may be due to unusual traffic conditions such as incidents or unusually high traffic volumes on a particular night, and so comparison to the baseline queued condition may overstate the effect of the treatment.

Table 7. Effects of Safety Treatments

Safety Treatment	Traffic Condition	Crash Modification Factor	Standard Error	P-Value
Only PRS deployed	Non-queued	0.890	0.377	0.771
	Queued	0.397	0.265	0.023
EOQWS and PRS deployed	Non-queued	0.717	0.353	0.424
	Queued	0.468	0.301	0.078

Aggregating the results across both treatment types, it also appears that utilizing the safety treatments reduced the severity of crashes that did occur at these nighttime lane closures. As shown in Figure 14, 50 percent of the crashes occurring during hours when a traffic queue was present during a nighttime lane closure but no safety treatment was deployed involved injuries or fatalities (i.e., were considered severe crashes), whereas only 16.1% of the crashes during hours of traffic queuing when the safety treatments were deployed were of the severe category. For comparison purposes, the percentage of crashes occurring during hours when no traffic queues were present that were of the severe variety were essentially the same, 28.6% and 31.0% with and without safety treatments deployed, respectively.

Discussion

It is important to be cautious when interpreting the results of this analysis. Although the dataset itself is comprised of several hundred nights of temporary lane closures, it does only represent a single corridor with multiple projects that were ongoing simultaneously over several years. In addition, although the results of the analysis did yield statistically significant conclusions, the number of crashes included in the analysis is very limited (as shown in Table 5). Finally, the location of the crash relative to the traffic queue was not examined as part of this analysis. It is likely that not all crashes occurring during the queued traffic conditions occurred at the upstream end of the queue. Rather, some of the crashes may have been lower-speed rear-end and sideswipe collisions within the queued section. Despite this limitation, though, the results of the analysis do provide useful insights into the magnitude of increases in total crashes due to work zone lane closures when queues are and are not present.

This analysis focused strictly on the total crash reduction effectiveness of the two safety treatments being deployed during nighttime lane closures on the I-35 corridor. However, both types of treatments have unique cost and deployment characteristics that also need to be taken into consideration when deciding what type of safety treatment to deploy. PRS tend to have lower capital cost requirements than EOQWS, but have higher deployment and retrieval costs. PRS require workers to be out in the travel lanes for deployment and retrieval, which increases safety risks (EOQWS are deployed on the roadside and typically do not require workers to be out in a travel lane). Consequently, practitioners must weigh these considerations in addition to the costs of the treatments when making decisions on which treatment (if any) to utilize on a given project.

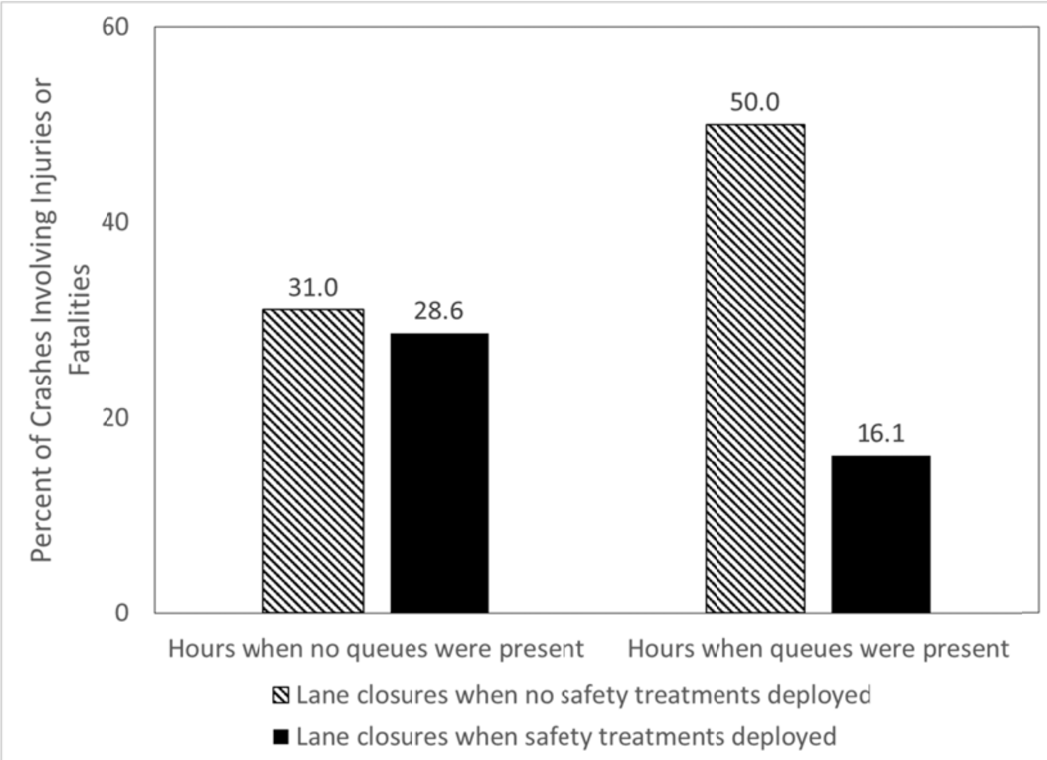


Figure 14. Effect of safety treatments upon crash severity during hours of queuing and non-queuing.

The results of this analysis also illustrates the importance of good traffic impact analyses during transportation management planning as well as throughout the duration of the project. As the results imply, deploying these safety treatments at locations where queues are not anticipated to develop would not likely yield much of a safety benefit, and may actually increase safety risks for workers (especially for PRS deployments that require workers to be out in the travel lanes). In essence, the costs of providing, deploying, and retrieving these treatments at locations where queues are not anticipated will not likely be offset by a reduction in crashes. However, given that queues and congestion at work zones was found to be such a major contributor to crashes, the importance of these results in quantifying the potential crash reduction effects of these countermeasures is substantial.

CHAPTER 4 Statistical Modeling of Work Zone Features Upon Crashes

Overview

Another focus effort under this research project was to gather the appropriate crash, roadway, and work zone feature data at a robust number of work zones nationally, and use state-of-the-art crash analysis techniques to produce CMFs that describe how certain high-priority features affect crashes. Many efforts have been undertaken in recent years to use statistical modeling techniques to develop predictive and explanatory models of work zone crashes (for example, see *Khattak et al. 2002*, *Srinivasan et al. 2008*, or *Sun et al. 2016*). For the most part, those efforts have focused on major work zone exposure indicators such as project length, location, and duration. In some instances, driver and weather factors have also been examined. One study did explore the various work zone design elements (lane and shoulder widths or closures, addition of positive protection to separate work activities from travel lanes, lane shifts and splits, etc.) that affect crashes (e.g., *Chen and Tarko 2012*), but was limited to a sample of work zones within a single state.

A national survey of practitioners was conducted under phase I of this project to determine which work zone features were of greatest interest for purposes of estimating their safety impacts. Factors that were of primary interest in this effort were the following:

- Number of lanes open and closed through the work zone
- Widths of travel lanes through the work zone
- Widths of shoulders (inside and outside) through the work zone
- Whether barrier was placed at the edge of the shoulder (or immediately adjacent to the travel lanes if there was no shoulder)
- Locations of any lateral lane shift

Additional factors (presence of work zone intelligent transportation systems, use of enforcement, use of rumble strips, etc.) were also of interest, but examples of their use were not identified in the final dataset obtained through this effort. Although it is possible that some of these may have been present at one or more of the projects, no documentation or indication to that effect was uncovered during the data collection phase of this effort.

Database Development

With the assistance of the project panel, other contacts, and project information posted online, the research team queried various state departments of transportation (DOTs) to obtain information about ongoing construction projects. The research team was ultimately able to obtain data describing projects in the States of Ohio, Texas, Utah, Virginia, and Washington. The following data sources are needed to obtain a complete description of a construction project:

- Work zone drawings, including maintenance of traffic plans (to show the locations of longitudinal barriers throughout the work zone) and typical cross sections (to obtain the key cross-sectional variables such as lane and shoulder width). These drawings are needed for both the “before” period and each phase of the “during” period.

- Narratives, notes, and logs describing work zone operations and layouts.

- Aerial photographs, which were obtained from Google Earth.

- Construction schedule, including Gantt charts that provide the start date, end date, and duration of each construction phase.

- Traffic volumes.

- Crash data, for both the “before” and “during” periods.

- Stationing and mileposts that are used for linear referencing in both the work zone drawings and the state’s traffic volume and crash databases.

Among these sources, the work zone drawings required the largest amount of effort. The research team reviewed the work zone drawings to divide each construction project into homogeneous segments based on the cross-sectional widths provided in the typical cross sections in the construction plans, and then subdividing these segments where needed because of other noteworthy changes in characteristics. This process was conducted for both the “before” period and each of the construction phases in the “during” period. The process yielded a database containing one record for each roadway segment in each phase of construction. For example, if a freeway construction project consisted of three phases of work activity, each segment of the freeway would be represented four times in the database (before, phase 1, phase 2, and phase 3).

Beginning and ending mileposts were carefully tracked and recorded because homogeneous segment break points were not always identical across the construction phases. Additionally, the work zone drawings were typically referenced in terms of stations while the state databases for crashes and volumes were typically referenced in terms of mileposts. The research team maintained a visual record of the stations and mileposts along each construction project by plotting pins on aerial photographs in Google Earth (see Figure 15). The research team also used aerial photographs to obtain information about ramp entrance and exit presence and length on each segment.

The research team obtained construction schedules from several sources. Some of the construction projects in the database were simple, short-term projects like pavement rehabilitation, and did not have multiple phases. For these projects, the starting and ending dates were adequate to define the “during” period, and these dates were often available on public project information pages on the state DOT web sites. The research team was also able to obtain lists of project and their starting and ending dates from some state DOT contacts. For the more complex projects that had multiple phases, the research team obtained scheduling documents from state DOT contacts. These documents included Gantt charts and contractor notes. It must be noted that the accuracy of these sources is affected by the contractors’ and state DOT’s ability to maintain accurate, current descriptions of activities as they actually occurred. The research team was limited to using the construction plans and Gantt charts as the best-available descriptions of project activity.

After extracting the geometric data from the work zone drawings and the phase durations from the construction schedules, the research team merged these data with the traffic volume and crash databases that were provided by the state DOTs. The assembled database contained the data elements listed in Table 8.

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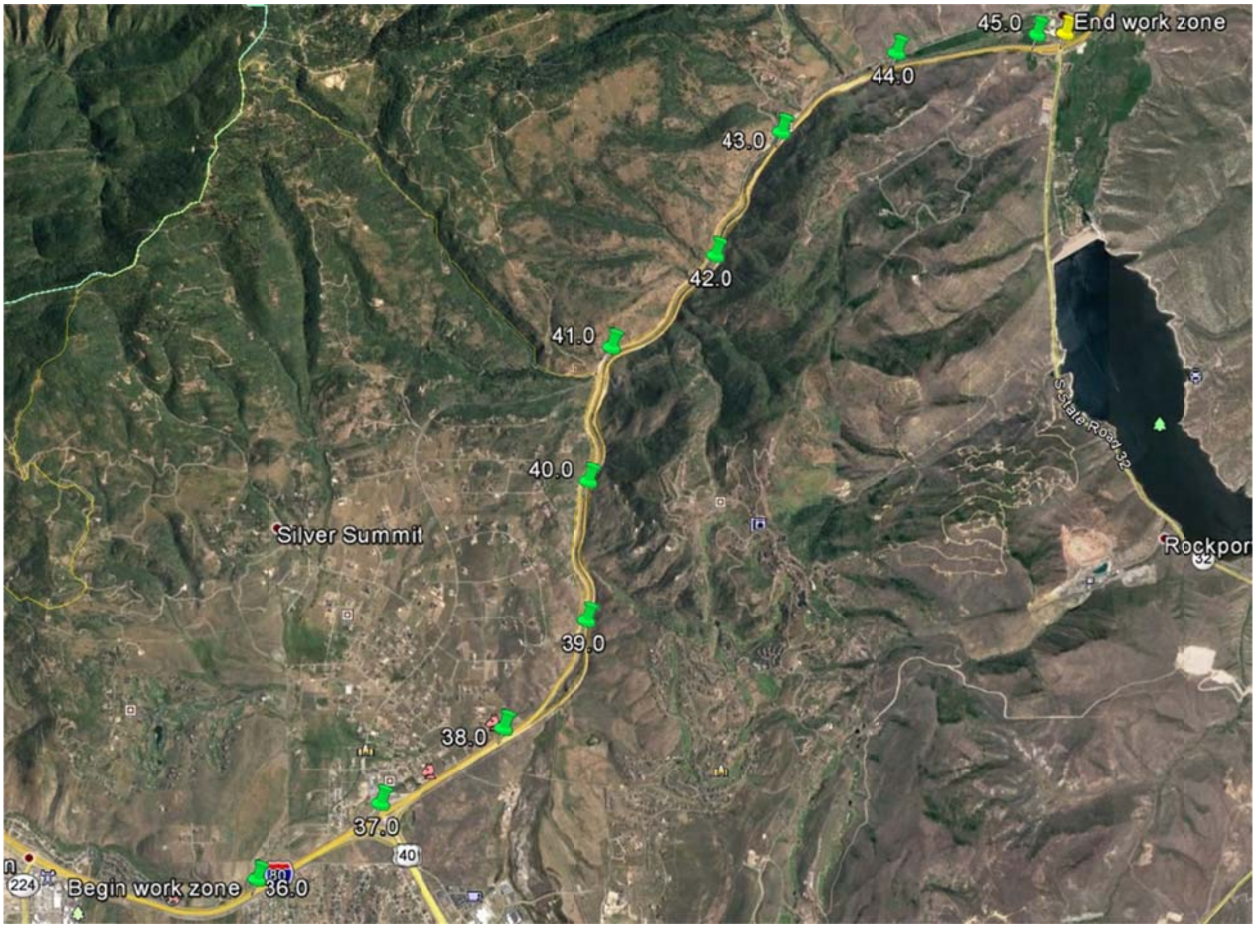

Figure 15. Work Zone Linear Referencing.

Table 8. Work Zone Database Elements

Category	Data Element	Source
Schedule	Period (before, during phase number)	Gantt charts, contractor notes, state DOT web sites
	Phase duration	
Geometry	Number of lanes and lane closures	Work zone drawings, aerial photographs, street-level photographs
	Lane width	
	Shoulder width	
	Median width	
	Longitudinal barrier length and offset	
	Horizontal curve presence	
	Lane shift presence	
	Lane add or drop presence	
	Crossover presence	
	Ramp entrance or exit presence	
	Ramp speed-change lane presence (speed-change lane versus lane add/drop)	
	Ramp speed-change lane length	
	Ramp side (left or right)	
Volume	Traffic volumes	State databases, state DOT web sites
Traffic control	Speed limit	Work zone drawings, contractor notes, street-level photographs
Crashes	Crash location and date	State databases
	Crash type (multiple-vehicle or single-vehicle)	
	Crash severity (K, A, B, C, PDO)	

A brief description of each project in the database is provided in Table 9. Some of the projects involved adding capacity, others involved repaving or rehabilitation, and others involved changes like adding shoulders or improving drainage. All of the projects were located on freeways. Some of the projects required lane closures, while others did not.

Table 10 provides sample sizes for the database in terms of several measures – length, time duration, number of mile-months, and total crash count. The crashes included in the database are crashes that occurred on the freeway mainline segments; crashes on ramps, collector-distributor roads, or frontage roads were not included. In terms of mile-months, roughly half of the dataset is represented by the Texas projects, and roughly 60% of the dataset corresponds to “before” conditions. Overall, AADTs ranged between 5,000 and 70,000 vehicles per day (vpd) on the four-lane segments and between 50,000 and 150,000 vpd on the six-lane segments.

The ranges of the key geometric variables are presented in terms of minimum, mean, and maximum values in Table 11. Cross-sectional width is generally smaller, and barrier lengths are generally larger, in the during periods than in the before period. These trends are consistent with typical work zone maintenance-of-traffic practices, which involve narrowing cross-sectional widths and adding temporary barriers to separate traffic from work areas. Meanwhile, Table 12 presents the pre- and during-work zone average crash rates by state, collision type, and severity. Overall, one sees that average crash rates increased in Ohio, Texas, and Virginia, but were down slightly at the work zones examined in Utah and Washington. Interestingly, single vehicle crash rates decreased on average at work zones (relative to pre-work zone conditions) in all of the states, whereas multi-vehicle crash rates were slightly higher. Based on the differences in average before and during work zone PDO crash rates, it appears that work zone crashes tended to be more severe in Ohio, Utah, and Virginia, but less severe in Texas and Washington**.**

Table 9. Construction Project Descriptions

State	Project	Number of Lanes		Description
		Before	During	
Ohio	I-75	4	4	Widening from 4 lanes to 6
Texas	I-35 West	4	4	Widening from 4 lanes to 6
	I-35 Waco	4	4	Widening from 4 lanes to 6
	I-35 Lorena	4	4	Widening from 4 lanes to 6
	I-35 Bruceville-Eddy	4	4	Widening from 4 lanes to 6
	I-35 Troy	4	4	Widening from 4 lanes to 6
	I-35 Salado	4	4	Widening from 4 lanes to 6
Virginia	I-64 Low Moor	4	3	Drainage installation, grading, and paving
	I-95 Hanover County	6	6	Bridge replacement and ramp construction
	I-81 Christiansburg	4	4	Truck climbing lane construction and median and shoulder upgrade
	I-95 Richmond	6	6	Bridge rehabilitation
	I-95 Dumfries	6	5	Shoulder improvements and auxiliary lanes
Washington	I-90	4	4	Asphalt lane and shoulder paving
	I-82	4	4	Repaving asphalt pavement
Utah	I-15 Beaver	4	2	Paving
	I-70 Sevier	4	2	Concrete cutting and pouring works
	I-80 Summit	4	2	Concrete pavement reconstruction
	I-80 Summit	4	2	Barrier replacement
	I-80 Tooele	4	2	Concrete maintenance
	I-80 Summit	6	4	Barrier and lighting installation

Table 10. Sample Sizes

State	Period	Average AADT	Length, mi	Duration, months	Number of mile-months	Total crash count
All	All	47329	660	10807	8176	7652
	Before	43977	134	6628	6019	4512
	During	56687	526	4179	2157	3140
Ohio	All	54382	35	214	429	617
	Before	55112	7	130	320	332
	During	52235	27	84	109	285
Texas	All	59925	409	9284	4228	5191
	Before	59354	44	5593	2547	2599
	During	60788	365	3691	1681	2592
Utah	All	17714	137	309	1886	410
	Before	17790	49	268	1683	387
	During	17086	88	42	204	23
Virginia	All	79354	48	780	775	1156
	Before	79087	18	432	648	932
	During	80714	30	348	127	224
Washington	All	17888	32	220	857	278
	Before	17874	16	206	821	262
	During	18206	16	14	36	16

Table 11. Geometric Variable Ranges

Period	Statistic	Cross-sectional width, ft					Barrier length, mi	
		Non-traversable median	Total median	Lane	Right shoulder	Left shoulder	Right	Left
Before	Min.	2.0	8.0	12.0	5.0	4.0	0.0	0.0
	Mean	12.6	41.4	12.0	10.4	5.6	0.1	0.9
	Max.	400.0	410.0	12.0	18.0	12.0	2.5	13.0
During	Min.	2.0	2.0	11.0	0.0	0.0	0.0	0.0
	Mean	14.8	40.2	11.9	8.6	6.2	0.1	0.5
	Max.	400.0	405.0	12.5	17.0	14.0	5.6	13.0

Table 12. Crash Rate Comparison Between Pre- and During-Construction Periods

State	Period	Crash rate (crashes per million vehicle-miles)							
		Total	By Collision Type		By Crash Severity				
			MV	SV	K	A	B	C	PDO
OH	Before	0.35	0.530	0.470	0.000	0.018	0.060	0.096	0.825
	During	1.26	0.611	0.389	0.004	0.025	0.084	0.102	0.786
TX	Before	0.56	0.633	0.367	0.007	0.018	0.098	0.142	0.735
	During	0.81	0.666	0.334	0.005	0.014	0.084	0.143	0.754
UT	Before	0.52	0.217	0.783	0.021	0.006	0.088	0.088	0.798
	During	0.39	0.304	0.696	0.000	0.000	0.087	0.174	0.739
VA	Before	0.60	0.761	0.239	0.002	0.067	0.071	0.152	0.708
	During	0.64	0.764	0.236	0.005	0.049	0.159	0.082	0.703
WA	Before	0.38	0.519	0.481	0.008	0.019	0.118	0.137	0.718
	During	0.30	0.545	0.455	0.000	0.091	0.000	0.182	0.727
All	Before	0.55	0.613	0.387	0.006	0.027	0.090	0.137	0.740
	During	0.80	0.663	0.337	0.005	0.018	0.088	0.136	0.753

Statistical Analysis Methodology

The research team then focused on developing a cross-sectional statistical model describing crash frequency in a given segment before and during work zone as a function of various geometric and work zone variables. The effort started with a model functional form described as follows:

$$N_i = N_{base,i} \times CMF_1 \times CMF_2 \times \ldots \times CMF_n;\ i = 4 \text{ or } 6 \text{ lanes}$$

Where,

N_i	=	predicted annual average crash frequency for model i (i =4 or 6 lanes
$N_{base,i}$	=	predicted annual average crash frequency at base conditions as described below
$CMF_1, CMF_2, \ldots CMF_n$	=	crash modification factors for various road segment features (1, 2, …, n)

The predictive model calibration process consisted of the simultaneous calibration of four-lane and six-lane freeway models and CMFs using the aggregate model. Note that the number of lanes is the lane count during the pre-work zone (before) conditions. The simultaneous calibration approach was needed because all CMFs were common to four-lane and six-lane freeways. Fixed state-effects were used to capture the differences between states that are not possible with just the variables in the model. Work zones were allowed to have different state fixed effects than the normal roadway segments.

Different functional forms were examined with various combinations of variables and the form presented below reflects the findings from several preliminary regression analyses.

$$N = N_{base} \times CMF_{lw} \times CMF_{lsw} \times CMF_{rsw} \times CMF_{ls} \times CMF_{mw} \times CMF_{ib} \times CMF_{ob} \times CMF_{lc}$$

with,

CMF_{lw} = $e^{b_{lw}(W_l - 12)}$
CMF_{lsw} = $e^{b_{lsw}(W_{ls} - 6)}$
CMF_{rsw} = $e^{b_{rsw}(W_{rs} - 10)}$
CMF_{ls} = $e^{b_{ls} I_{ls}}$
CMF_{mw} = $(1.0 - P_{ib}) e^{b_{mw}(W_m - 2W_{ls} - 48)} + P_{ib} e^{b_{mw}(2W_{icb} - 48)}$
CMF_{ib} = $e^{b_{ib} I_{ib}}$
CMF_{ob} = $e^{b_{ob} I_{ob}}$
CMF_{lc} = $e^{b_{lc} I_{lc}}$

where,

CMF_{lw} = lane width CMF
CMF_{lsw} = left shoulder width CMF
CMF_{rsw} = right shoulder width CMF
CMF_{ls} = lane shift CMF
CMF_{mw} = median width CMF
CMF_{ib} = inside (median) barrier CMF
CMF_{ob} = outside (roadside) barrier CMF
CMF_{lc} = lane closure CMF
W_l = average lane width, ft
W_{ls} = average left shoulder width, ft
W_{rs} = average right shoulder width, ft
I_{ls} = lane shift presence indicator variable (= 1.0 if present, 0.0 if absent)
W_m = median width, ft
W_{icb} = distance from edge of inside shoulder to barrier face, ft
I_{ib} = inside barrier presence indicator variable (= 1.0 if present, 0.0 if absent)
I_{ob} = outside barrier presence indicator variable (= 1.0 if present, 0.0 if absent)
I_{lc} = lane closure presence indicator variable (= 1.0 if present, 0.0 if absent)

Three types of models were developed. In the first model, for both "before" and "during" conditions, the intercept and ADT coefficients are forced to be the same but the CMFs are allowed to be different. This means, for base conditions (i.e., 6-ft inside shoulder, 10-ft outside shoulder, 60-ft median width including inside shoulders, no barriers, no lane closure or lane shift), the work zone will behave similar to a normal road:

$$N_{base} = L \times n \times e^{b_0 + b_{adt} \ln(AADT) + b_j state}$$

where,

L = length of work zone segment,
n = time (in months)/12,
AADT = annual average daily traffic on the segment,
state = state in which the project was located if not in Texas, and
b_j = calibration coefficient for variable j.

The research team also tried describing the segment length as a variable instead of an offset (i.e., instead of L, it is used as L^{β}). The β parameter value was equal to 0.99 for the pre-work zone (before) period and 1.01 for the during work zone period. Thus, it was concluded that the segment length should be used as an offset rather than as a variable.

In the second model, for both "before" and "during" conditions, the intercept and ADT coefficients are forced to be the same but an added effect of work zone is introduced and the CMFs are different. This means, for base conditions (i.e., 6-ft inside shoulder, 10-ft outside shoulder, 10-ft median width, no barriers, no lane closure or lane shift), the work zone will still have more crashes than a normal road.

$$N_{base} = L \times n \times e^{b_0 + b_{adt}\ln(AADT) + b_{wz} + b_j state}$$

In the third model, for "before" and "during" conditions, the intercept and ADT coefficients are allowed to be different in addition to different CMFs. This means, for base conditions (i.e., 6-ft inside shoulder, 10-ft outside shoulder, 10-ft median width, no barriers, no lane closure or lane shift), the work zone will still have more crashes than a normal road plus the crash trend is different with the change in ADT (i.e., crash risk also changes).

$$N_{base\_wz} = L \times n \times e^{b_{0\_wz} + b_{adt\_wz}\ln(AADT) + b_j state}$$

The inverse dispersion parameter, K (which is the inverse of the over dispersion parameter k), is allowed to vary with the segment length. The inverse dispersion parameter is calculated using:

$$K = L \times e^{k}$$

where,

K = inverse dispersion parameter
k = calibration coefficient for inverse dispersion parameter

The mixed nonlinear regression procedure (NLMIXED) in the Statistical Analysis System (SAS) software was used to estimate the proposed model coefficients. This procedure was used because the proposed predictive model is both nonlinear and discontinuous. The log-likelihood function for the NB distribution was used to determine the best-fit model coefficients.

Modeling Results

Table 13 through Table 15 present the results of the analysis using each of the three models described above. Unfortunately, researchers were unable to develop statistically valid estimates of any of the geometric variables that were of primary interest in this analysis under any of the three modeling approaches. A few of the variables yielded parameter estimates that appeared reasonable and were within expected range, but were not statistically significant. For example, depending on the model results used, the effect of a lane shift on crashes equated to a CMF of between 1.165 and 1.185, comparable to a CMF value of 1.213 for lane shifts reported elsewhere (*Chen and Tarko, 2012*). Conversely, parameter values for other variables were highly counter-intuitive. For example, the marginal effects of increasing lane widths in work zones in model 1 was positive, suggesting that crashes increased as lane widths increased. Similarly, model 1 results regarding the effect of median and shoulder widths indicate that these variables have little effect upon work zone crashes, despite the fact that both have an effect upon crashes in normal (non-work zone) environments as illustrated by the roadway segments used in this analysis as well as the CMFs that have been developed for use in the HSM (see Figure 16 and Figure 17).

Table 13. Results of Analysis for Model 1

Variable	Parameter	Estimate	Standard Error	Pr > |t|
Intercept (for 4-or 6-lane facilities)	$b_{0,4}$	-12.795	1.113	<.0001
	$b_{0,6}$	-12.603	1.153	<.0001
AADT	b_{adt}	1.410	0.102	<.0001
Dispersion (for 4-or 6-lane facilities)	k_4	2.124	0.113	<.0001
	k_6	0.701	0.177	<.0001
Lane width	$b_{lw,during}$	0.120	0.198	0.543
Left shoulder width	$b_{lsw, pre}$	-0.029	0.038	0.443
	$b_{lsw, during}$	-0.004	0.012	0.763
Right shoulder Width	$b_{rsw,pre}$	-0.109	0.050	0.030
	$b_{rsw,during}$	-0.019	0.017	0.259
Lane shift	b_{ls}	0.163	0.152	0.284
Median width	$b_{mw, pre}$	-0.001	0.001	0.315
	$b_{mw, during}$	-0.002	0.002	0.235
Inside barrier	$b_{ib, pre}$	-0.197	0.143	0.168
	$b_{ib, during}$	0.105	0.125	0.402
Outside barrier	$b_{ob, pre}$	-0.606	0.655	0.355
	$b_{ob, during}$	0.256	0.171	0.134
Lane closure	b_{lc}	0.473	0.576	0.412
State fixed effects for pre-construction conditions	$b_{WA, pre}$	1.101	0.415	0.008
	$b_{VA, pre}$	-0.716	0.204	0.001
	$b_{OH, pre}$	0.306	0.251	0.223
	$b_{UT, pre}$	0.783	0.231	0.001
State fixed effects for during-construction conditions	$b_{WA, during}$	0.644	0.364	0.077
	$b_{VA, during}$	-1.022	0.210	<.0001
	$b_{OH, during}$	0.649	0.190	0.001
	$b_{UT, during}$	-1.935	0.749	0.010

Researchers did find that the state in which the work zone was located had a significant effect upon crashes in both the pre-work zone and during-work zone conditions. Relative to the work zones from Texas (which was defined as the base case in the model), projects in Ohio and Washington experienced a greater propensity for crashes than those in Texas both pre- and during the work zones, whereas project locations in Virginia experienced fewer crashes pre- and during-work zones. Somewhat counterintuitively, project locations in Utah experienced a greater propensity for crashes than the Texas locations in the pre-work zone condition, but fewer crashes in the during-work zone condition.

Table 14. Results of Analysis for Model 2

Variable	Parameter	Estimate	Standard Error	Pr > |t|
Intercept (for 4-or 6-lane facilities)	$b_{0,4}$	-12.509	1.130	<.0001
	$b_{0,6}$	-12.318	1.167	<.0001
ADT	b_{adt}	1.344	0.105	<.0001
WZ added effect	b_{wz}	0.683	0.207	0.001
Dispersion (for 4-or 6-lane facilities)	k_4	2.143	0.113	<.0001
	k_6	0.712	0.177	<.0001
Paved width in each direction	$b_{pw, pre}$	-0.017	0.025	0.490
	$b_{pw, during}$	-0.009	0.008	0.278
Lane shift	b_{ls}	0.144	0.147	0.326
Median width	$b_{mw, pre}$	-0.001	0.001	0.388
	$b_{mw, during}$	-0.004	0.002	0.049
Inside barrier	$b_{ib, pre}$	0.292	0.200	0.146
	$b_{ib, during}$	-0.144	0.154	0.350
Outside barrier	$b_{ob, pre}$	-0.129	0.629	0.837
	$b_{ob, during}$	0.185	0.171	0.280
Lane closure	b_{lc}	0.554	0.577	0.337
State fixed effects for pre-construction conditions	$b_{WA, pre}$	0.634	0.374	0.090
	$b_{VA, pre}$	-0.783	0.228	0.001
	$b_{OH, pre}$	0.548	0.250	0.029
	$b_{UT, pre}$	0.449	0.243	0.065
State fixed effects for during-construction conditions	$b_{WA, during}$	0.707	0.362	0.051
	$b_{VA, during}$	-0.920	0.195	<.0001
	$b_{OH, during}$	0.646	0.164	<.0001
	$b_{UT, during}$	-1.954	0.731	0.008

The state-by-state effects likely reflect a wide range of other, unmeasured variables affecting crashes in the pre- and during-construction conditions and which interacted and confounded with the work zone variables of interest, yielding the lack of statistical significance of those variables in the model. In addition, the lack of statistical significance of the work zone variables of interest is also due in large part to the limitations of the available projects from which the dataset was developed. Although the research team desired to locate projects that spanned a good range of values for each of the variables of interest, the reality was that the projects available for analysis did not provide this range for most of the variables. In addition, changes in several of the variables were correlated, confounding their effects. For example, projects where a full inside shoulder was retained while the outside shoulder width was reduced were not available (the reverse of this condition was similarly not available). Likewise, projects where travel lanes were narrowed but where median and outside shoulders were maintained were not available. From a practical perspective, it makes sense why this confounding would occur. Typically, projects are completed in a manner that maximizes contractor productivity while maintaining traffic to the minimum requirements put forth by the owner agency. It would not make sense for the agency or the contractor to create work zones with some of the combinations of values of the variables listed above because they would not have a positive effect on productivity or efficiency, and in some cases could actually detract from that.

Given that the lane width and shoulder widths were not statistically significant, the total pavement width in each direction was used as a variable instead, in models 2 and 3. The base condition for this variable is 40 feet for 4-lane segments and 52 feet for 6-lane segments.

Table 15. Results of Analysis for Model 3

Variable	Parameter	Estimate	Standard Error	Pr > |t|
Intercept (normal) (for 4- or 6-lane facilities)	$b_{0,4,pre}$	-11.231	1.270	<.0001
	$b_{0,6,pre}$	-9.438	1.551	<.0001
ADT (normal)	$b_{adt,pre}$	1.248	0.116	<.0001
Dispersion (normal) (for 4- or 6-lane facilities)	$k_{4,pre}$	2.537	0.188	<.0001
	$k_{6,pre}$	0.350	0.144	0.016
Intercept (work zone) (for 4-or 6-lane facilities)	$b_{0,4,during}$	-10.036	2.829	0.000
	$b_{0,6,during}$	-9.987	2.851	0.001
ADT (work zone)	$b_{adt,during}$	1.164	0.256	<.0001
Dispersion (work zone) (for 4-or 6-lane facilities)	$k_{4,during}$	2.005	0.128	<.0001
	$k_{6,during}$	1.595	0.269	<.0001
Paved width in each direction	$b_{pw, pre}$	-0.027	0.024	0.253
	$b_{pw, during}$	-0.006	0.008	0.429
Lane shift	b_{ls}	0.148	0.152	0.329
Median width	$b_{mw, pre}$	-0.002	0.001	0.077
	$b_{mw, during}$	-0.004	0.002	0.090
Inside barrier	$b_{ib, pre}$	-0.183	0.187	0.330
	$b_{ib, during}$	-0.071	0.156	0.648
Outside barrier	$b_{ob, pre}$	1.423	0.633	0.025
	$b_{ob, during}$	0.168	0.171	0.327
Lane closure	b_{lc}	1.291	0.615	0.036
State fixed effects for pre-construction conditions	$b_{WA, pre}$	0.166	0.382	0.665
	$b_{VA, pre}$	-1.836	0.284	<.0001
	$b_{OH, pre}$	0.319	0.221	0.150
	$b_{UT, pre}$	0.363	0.248	0.143
State fixed effects for during-construction conditions	$b_{WA, during}$	0.501	0.439	0.254
	$b_{VA, during}$	-0.917	0.191	<.0001
	$b_{OH, during}$	0.606	0.175	0.001
	$b_{UT, during}$	-1.927	0.719	0.008

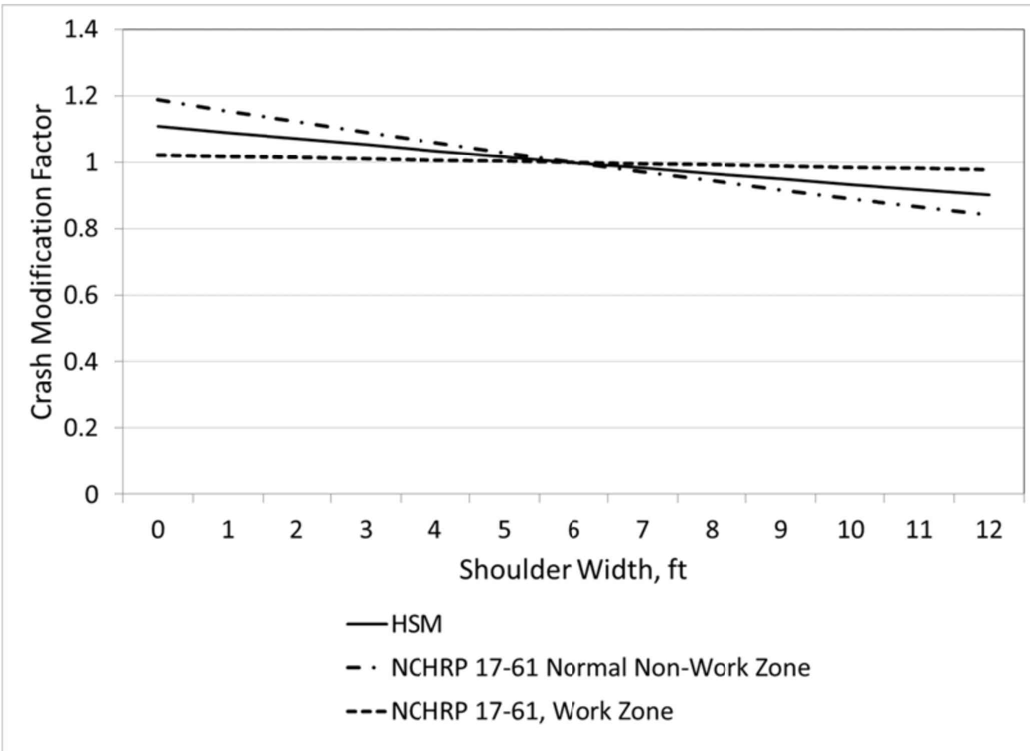

Figure 16. Estimated effects of median shoulder width before and during the work zones at the test sections (based on model 1) as compared to the HSM CMF.

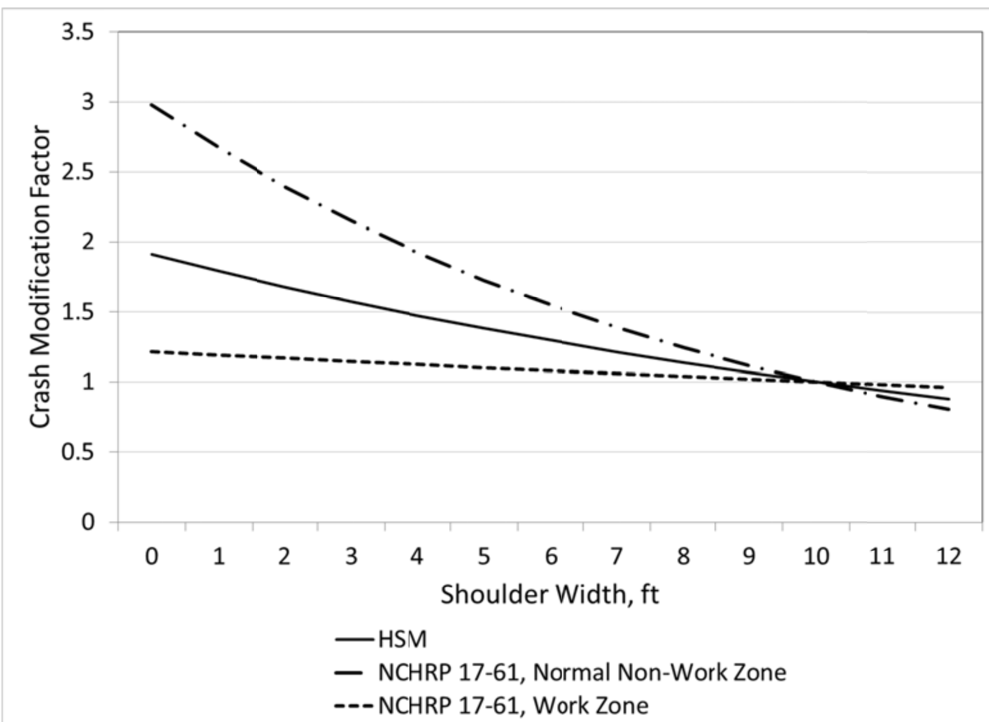

Figure 17. Estimated effects of outside shoulder width before and during the work zones at the test sections (based on model 1) as compared to the HSM CMF.

Because of the lack of statistical significance of the work zone variables computed in this analysis and the likely reasons for this as outlined above, the research team concluded that the best sources of estimates of the potential effect of these variables upon work zone crashes will continue to be the CMFs included in the HSM for permanent roadway conditions, as well as some of the CMFs included in the CMF Clearinghouse.

Although this analysis did not yield specific CMFs for the individual variables, the results do provide general models that can be used by practitioners who do not have site-specific data or other means of estimating the number of crashes expected to occur in their interstate/freeway work zones. These models can serve as a generic safety performance function (SPF) describing the basic effect of a work zone upon crashes. Using the parameters for the intercept and AADT from Table 15 (model 3), the following functions are recommended:

$$\text{4lanes (work zone)}: N_{base} = L \times n \times e^{-10.036+1.164\ln(AADT)}$$
$$\text{6lanes (work zone)}: N_{base} = L \times n \times e^{-9.987+1.164\ln(AADT)}$$

The base work zone conditions for the models are:

- Pavement width = 40 feet in each direction for 4-lane segments and 52 feet in each direction for six-lane segments (equal to 12-ft lanes, 6-ft inside shoulder, and 10-ft outer shoulder)
- No lane shifts present
- No lane closures present
- Median width of 60 feet, which includes the inside shoulder width of 6-ft in both directions
- No longitudinal barriers present

These equations are plotted in Figure 18 and Figure 19 (labeled as NCHRP 17-61, Work Zone). Also plotted in those figures for comparison purposes are the combined safety performance functions for normal conditions included in the HSM (both Rural and Urban), and the results of the statistical models from Table 14 and Table 15 for the pre-work zone (NCHRP 17-61, Normal Non-Work Zone) conditions from the project locations in this study. The model structure and parameters for model 3 provided the best fit of the data for the work zone conditions on both the four-lane and six-lane facilities, and for the pre-work zone conditions on four-lane facilities. However, for pre-work zone conditions on six-lane facilities, the model 2 structure worked better.

Overall, one sees that the models for normal conditions match the HSM functions for normal roadway very well, providing reasonable confidence about the validity of the project locations and data. For the four-lane roadways, the function from this study for the pre-work zone conditions falls between the rural and urban functions. This result was as would be expected, as the project locations came from both rural and urban facilities nationally. For the six-lane roadways, the pre-work zone function for this study mimicked fairly closely the urban six-lane roadway function from the HSM. This again was consistent with expectations, as the six-lane roadway project locations used in this study came from primarily urban areas.

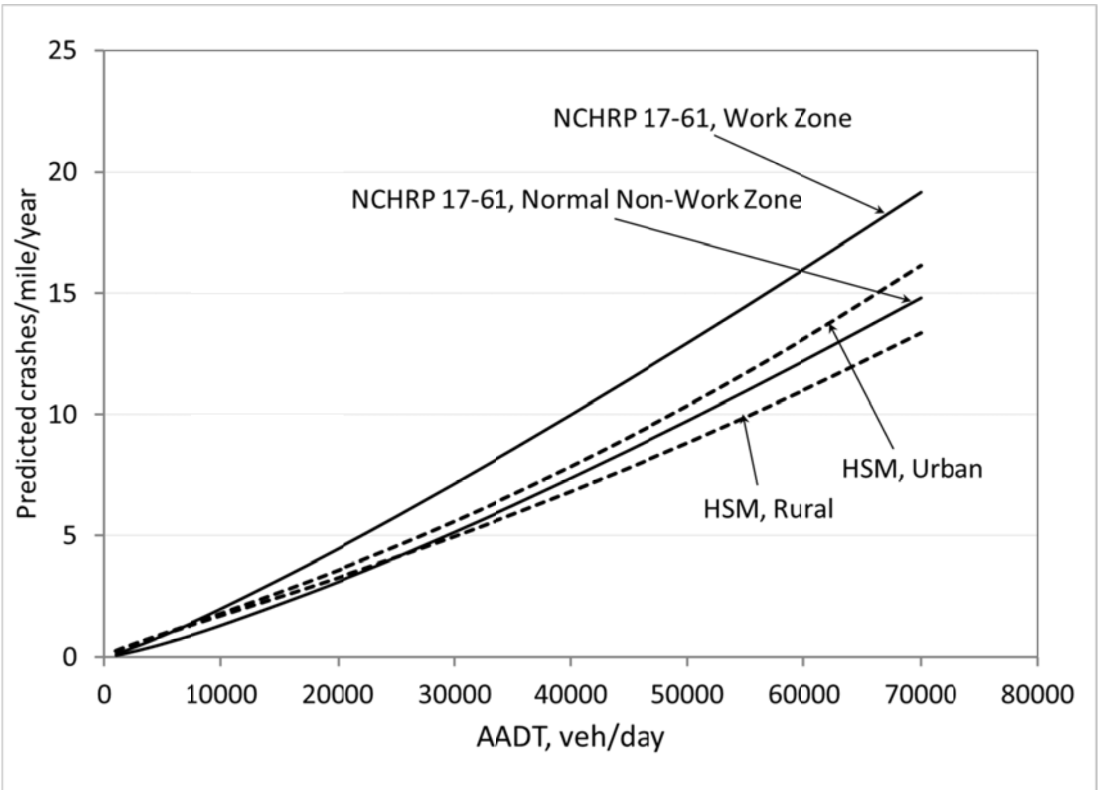

Figure 18. Predicted crashes on 4-lane freeway segments.

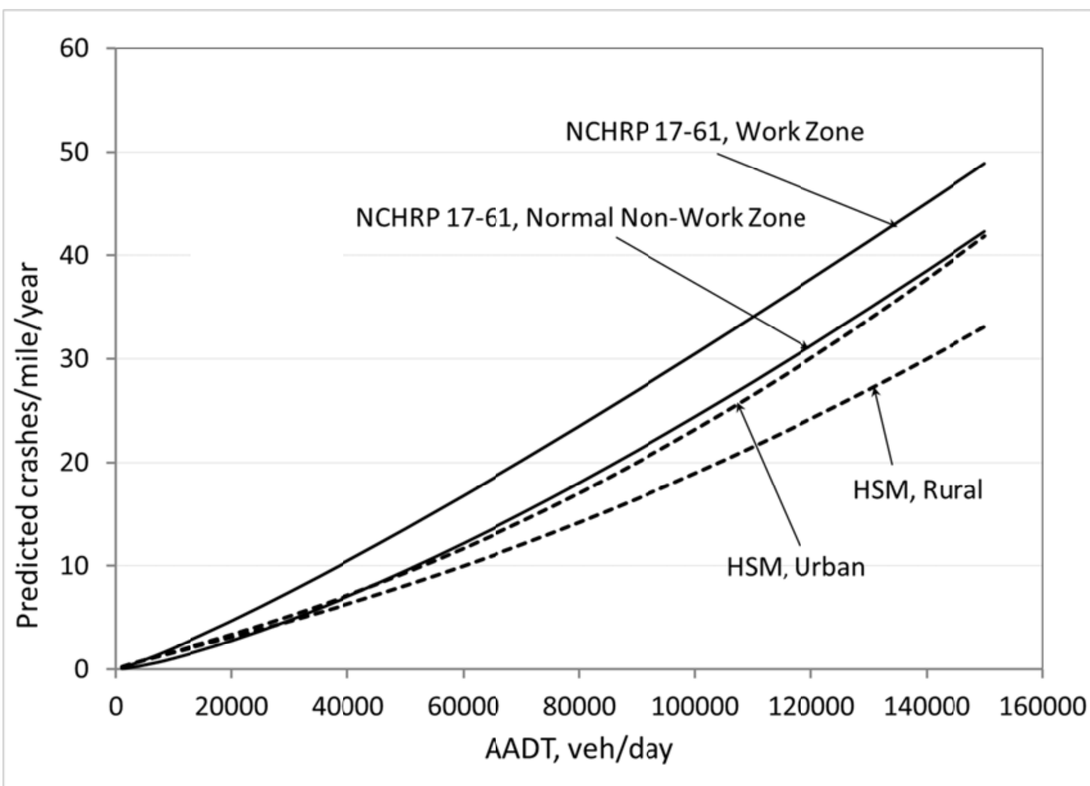

Figure 19. Predicted crashes on 6-lane freeway segments.

Relative to pre-work zone (normal) conditions, Figure 18 and Figure 19 also show that the presence of a work zone on a roadway segment increases the number of crashes expected to occur on that roadway segment as compared to the crashes expected if a work zone is not present. Because of how the models were constructed, the analysis results also suggest that the effect of a work zone upon crashes is nonlinear. Specifically, work zones are predicted to result in a smaller proportional increase in crashes from pre-work zone conditions on higher AADT facilities than on lower AADT facilities. This is illustrated graphically in Figures 20 and 21.

In absolute terms, though, the number of additional crashes per mile per year that are associated with work zone presence still does increase as AADT increases. Expressed as a work zone CMF, the resulting equations are as shown below.

4-lane facilities:

$$WZCMF_{4-lanes} = \frac{e^{-10.036+1.164\ln(AADT)}}{e^{-11.231+1.248\ln(AADT)}}$$

6-lane facilities:

$$WZCMF_{6-lanes} = \frac{e^{-9.987+1.164\ln(AADT)}}{e^{-12.318+1.344\ln(AADT)}}$$

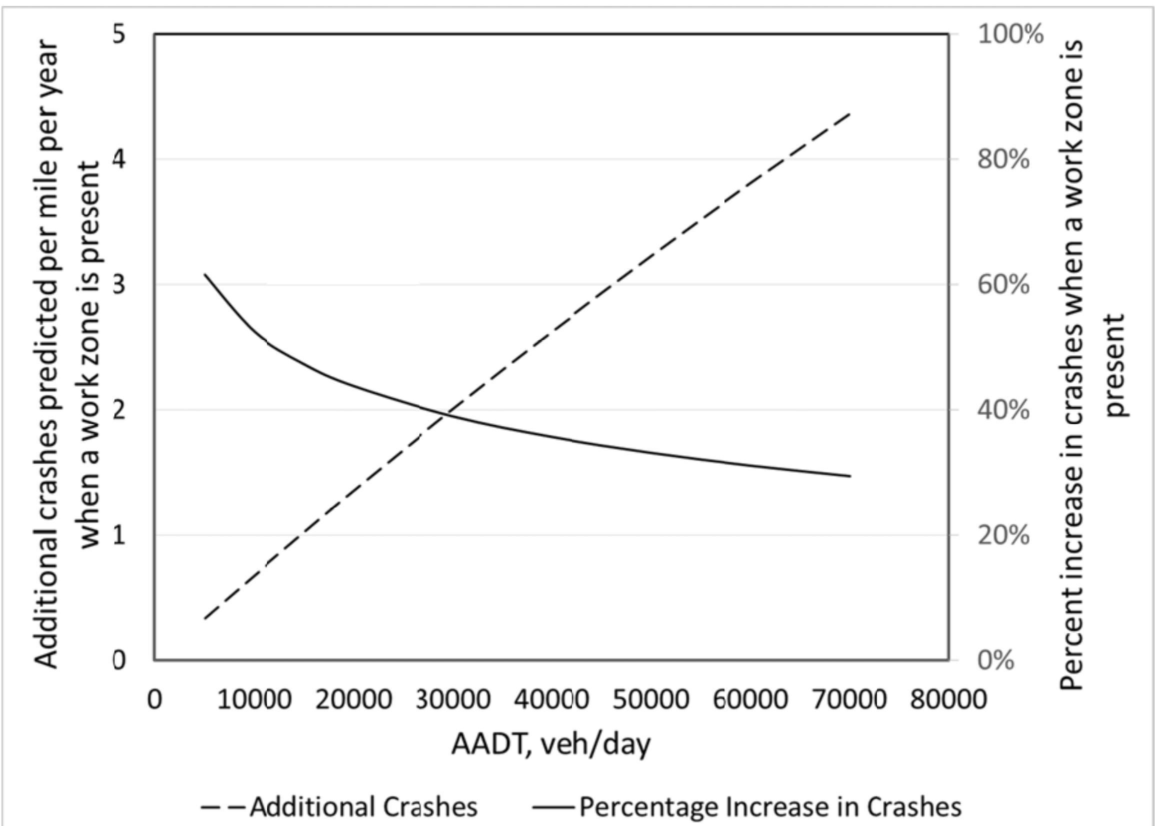

Figure 20. Average effect of work zones upon crashes predicted on 4-lane freeway segments.

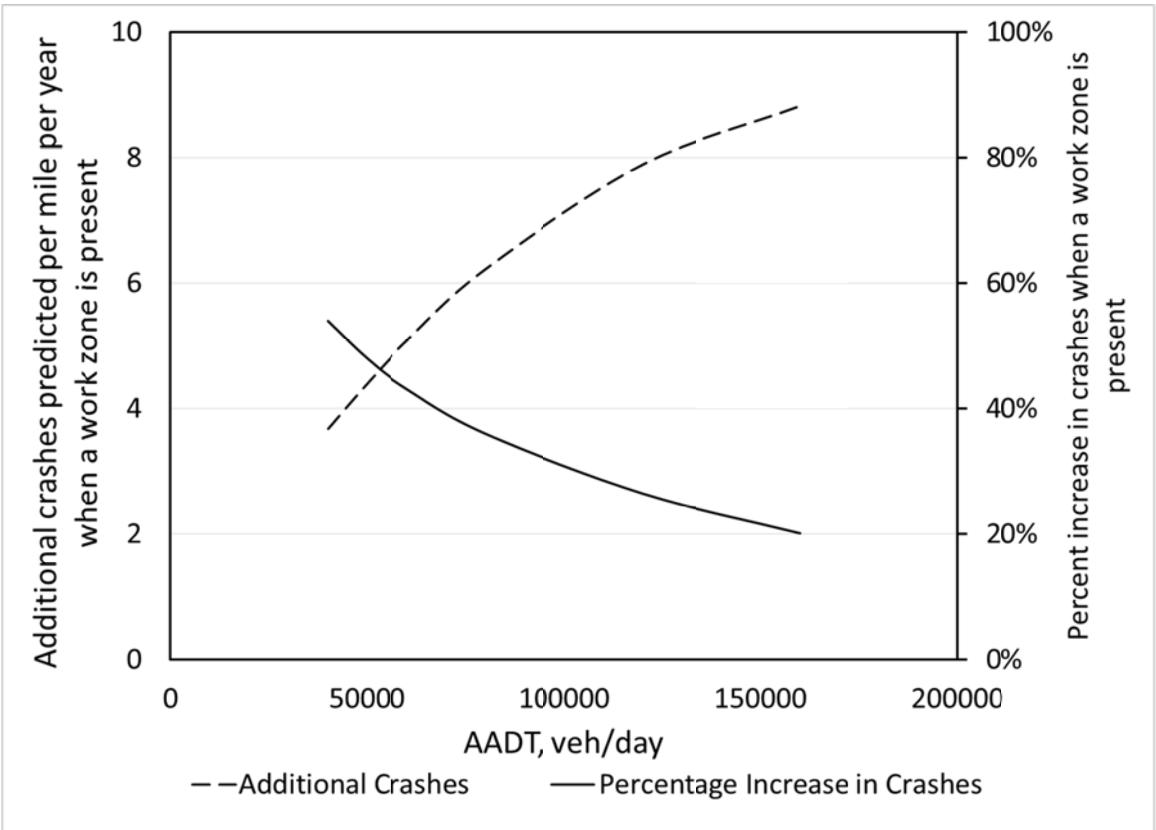

Figure 21. Average effect of work zones upon crashes predicted on 6-lane freeway segments.

A practitioner who already has a baseline estimate of crashes normally occurring on the section of road where a work zone is planned could calculate the appropriate expected work zone CMF for that section and apply it to the baseline to estimate the number of crashes expected during the work zone.

SUMMARY AND RESEARCH RECOMMENDATIONS

Summary

In this report, researchers have documented the results of multiple analyses focused on developing an improved understanding of work zone crash characteristics and countermeasure effectiveness. In-depth analyses of work zone crash narratives and other data sources above and beyond standard fields and codes in state and national crash databases yielded several useful insights into work zone factors associated with common types of crashes. Assessment of safety countermeasures used to combat rear-end collisions at interstate lane closure queues indicate that the countermeasures have a positive crash-reducing effect. Finally, an analysis of crashes at a national sampling of interstate work zones was not able to isolate the effects of individual roadway factors upon work zone crashes. However, general crash prediction models were computed that can assist practitioners in quantifying expected crash effects of work zones as a function of length, duration, and roadway traffic demand. The following is a summary of the key findings in this report:

- As has been hypothesized in previous studies, congestion and queues due to work zones were shown to be a significant contributor to crashes. The presence of queues and congestion was found to be a key contributor to rear-end collisions in each of the three different databases described in Chapter 2. In addition, the analyses also suggested that congestion contributed to a proportion of sideswipe collisions and collisions with barriers or other objects, due to last-second swerving to avoid running into the back end of a vehicle.

- Although queues were found to be a significant issue associated with crashes at interstate and freeway work zones, the VDOT analysis also found them to be associated with two-lane highway work zones as well. Most work zones on these types of roadways involve the temporary closure of one travel lane, and the use of alternating one-way traffic control via flaggers, AFADs, or portable traffic signals. Queues of varying length are created at these work zones, can be unexpected by motorists, and likely contribute to the rear-end collisions that occur.

- Work vehicles entering/exiting the work space were also found to be an issue in this assessment. Both rear-end collisions and sideswipe crashes in the three databases could be attributed to this situation. In the LTCCS database, 10% of the crashes on interstate/freeway facilities appeared to be the result of trucks attempting to enter or exit main lane traffic to or from the work space.

- Work zones on non-freeway/interstate facilities do also appear to be creating challenges for drivers. Data from several crashes examined in these analyses indicated that drivers became confused when approaching and entering work zones on non-accessed controlled facilities at intersections and driveways, especially in urban areas. Work zones on facilities which were normally divided and then converted to two-way operation in one of the directional roadways while the other direction was repaired or rehabilitated appear to be particularly problematic. Sight distance challenges were also noted for several crashes occurring at these types of work zones. Obstructions created by the presence of work equipment too close to an intersection or driveway were cited as a contributor in a number of crash narratives, as was the presence of certain temporary traffic control devices. In one instance, type 3 barricades placed in the opposing left-turn lane at a signalized intersection limited the ability left-turning traffic coming from the other direction to see approaching through lane traffic during the permissive green phase.

- The analysis of EOQWS and PRS as countermeasures to reduce collisions at interstate work zones when queues form indicate that the technologies can indeed reduce such crashes. Overall, the use of these countermeasures appeared to reduce crashes during periods of queuing and congestion by 53 to 60% from what would have been expected if the countermeasures had not been used. In addition, the crashes that did occur were significantly less severe when the countermeasures were deployed as compared to the no-countermeasure condition. Without the countermeasures deployed, 50% of the crashes occurring when queues were present involved injuries or fatalities; when the treatments were deployed, only 16% of the crashes involved injuries or fatalities.

- Interestingly, the data indicates that the use of the PRS alone resulted in the same crash reduction as the combined EOQWS + PRS treatment, suggesting that there was little additional benefit to using both countermeasures together. However, it is important to reiterate that there were differences in where the PRS only and EOQWS + PRS treatments were deployed which may be partially responsible for these results. The two technologies also have significantly different capital and operational costs associated with their use. Practitioners should carefully weigh these differences when deciding whether to use either (or both) of these countermeasures.

- Despite an extensive project identification and data collection/reduction effort, analysis of the multi-state database of work zones on interstate facilities did not yield statistically significant CMFs for individual work zone features such as lane widths, shoulder widths, lane closures, shoulder closures, median widths, lane shifts, or barrier use. One of the main reasons for this was the lack of sufficient variability in these features across the projects available for analysis. There was considerable confounding of many of these features (e.g., reduced lane and shoulder widths together with barrier placed at the edge of the shoulder, etc.), which kept the research team from being able to extract useful CMs from the data.

- Although the multi-state project analysis failed to provide individual work zone feature CMFs, the effort was successful in developing generic work zone SPFs for four-lane and six-lane interstates, based on the national dataset generated. These SPFs have been computed for a defined set of base characteristics, and so can be useful in planning-level analysis of possible work zone safety impacts to be expected as a function of project length, duration, and roadway AADT.

- In lieu of using the work zone SPFs directly, the analyses also yielded a basic work zone CMF for the base characteristics that can be used where an estimate of crashes normally occurring on a segment of roadway is already available.

Research Recommendations

The findings from this research effort have also yielded the following recommendations:

- Research should continue into ways to reduce the frequency and severity of rear-end (and sideswipe) collisions caused by queues and congestion at work zones, especially on higher-speed facilities. The analysis of the EOQWS and PRS indicate that they may be quite effective countermeasures, but the evaluation performed under this study was limited to a single interstate corridor. In addition, the effects of EOQWZ separate from PRS could not be evaluated at this time.

- It is recommended that the adequacy of existing training for work zone traffic control relative to arterials and intersections be examined, and improvements to that training be made where appropriate. Several of the crashes examined in detail under this study pointed to driver confusion and visibility issues when work zones were performed in the vicinity of intersections. Efforts should also be made to ensure that the improved training be readily available to municipalities, counties, and contractors who typically have primary responsibility for this on the job site.

- Increased emphasis should be made towards improving ingress and egress at work space access points within the work zone to reduce the frequency and severity of work vehicle/motorist crashes. Strategies such as eliminating work space access to and from high-speed travel lanes, innovative access point designs where they cannot be avoided, and testing and evaluation of systems to warn approaching traffic when work vehicles are about to enter or exit the work space, should be pursued.

- Agencies need to begin to incorporate safety assessments into their work zone design and transportation management planning processes. An implementation guide developed as part of this research effort describes how this can be accomplished and provides guidance on the availability and applicability of available CMFs for this purpose. Examples highlighting how those analyses might be performed are also included in the guide.

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ABBREVIATIONS AND ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Official
AFAD	Automatic Flagger Assistance Devices
CMF	Crash Modification Factor
ECN	Expected Crashes per Night
EOQWZ	End-of-Queue Warning System
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carriers Safety Administration
HSM	Highway Safety Manual
ISATe	Enhanced Interchange Safety Analysis Tool
ITS	Intelligent Transportation Systems
LTCCS	Large Truck Crash Causation Study
NASS	National Automotive Sampling System
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NMVCCS	National Motor Vehicle Crash Causation Survey
PCMS	Portable Changeable Message Signs
PDO	Property Damage Only
PRS	Portable Rumble Strips
RNS	Roadway Network System
SAS	Statistical Analysis System
SPF	Safety Performance Function
TMP	Transportation Management Plan
TTC	Temporary Traffic Control
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
VDOT	Virginia Department of Transportation
VPD	Vehicles Per Day
VTRC	Virginia Transportation Research Council