Identifying Potential Workzone Countermeasures Using Connected-Vehicle and Driving Data

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16. Abstract

Work zones present an ongoing safety challenge to the road safety community. Traffic management in a work zone is done through movable, temporary elements, and the novelty and complexity of the situation can challenge even attentive drivers This project looked into identifying workzone countermeasures that might be implemented using V2I and I2V communication. An extensive literature review was done to identify state of the art in workzone safety interventions.Michigan crash data was analyzed and causal models were developed to identify region specific causes of workzone related crashes. It was found that driver drinking, driver distracted and driver over 65 years of age were over represented in workzone crashes as compared to non workzone crashes. Given the findings related to drunk and distracted driving, it was suggested that in vehicle alert system would be more effective in warning drivers of oncoming workzones and other vehicles, including queue lengths. It was found that infrastructure based connectivity and warning systems (I2V) could be more effective than vehicle to vehicle (V2V) because of higher market penetration rate and customizable messages on the part of MDOT.

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EXECUTIVE SUMMARY

Work zones present an ongoing safety challenge to the road safety community. Traffic management in a work zone is done through movable, temporary elements, and the novelty and complexity of the situation can challenge even attentive drivers. In the U.S., 576 (2%) fatalities occurred in work zones in 2010 (FHWA, 2015). For example, speed management and lane shifts can be challenging and can introduce safety issues in work zones. The advent of vehicle - communication affords a new opportunity to develop countermeasures for work zones. Infrastructure can monitor work-zone driving behavior and potentially provide adaptive or even targeted interventions to help drivers manage work-zone driving more appropriately.

This project looked into identifying work zone countermeasures that might be implemented using V2I and I2V communication. This work extends current data explorations taking place at UMTRI to use driving data to understand work zone behavior. At first, an extensive literature review was done to identify state of the practice in work zone safety interventions and their effect. Most countermeasures mentioned in literature were found to be directed towards speed management via dynamic and static messaging and signages, as well as other measures. However, the literature review indicated a lack of consensus on the effectiveness of different countermeasures. At the second stage, five years (2012-2016) of Michigan crash data were analyzed, and multivariate models were developed to understand the association of different external and driver related factors with work zone crashes as compared to non-work zone crashes. It was found that rear end crashes, sideswipes and angle crashes were the most common work zone crash types. Work zone crashes were found over represented in daylight conditions, during peak traffic hours, as well as during late night hours. Driver drinking, driver distracted and driver over 65 years of age were also over represented in work zone crashes as compared to non-work zone crashes. Presence of workers did not significantly change any work zone crash related characteristics.

At the next stage, video and trajectory data from Safety Pilot Model deployment database were parsed to retrieve work zone passes and to identify any possible differences in driver behavior in (i) work zones versus nonwork zones and (ii) before and after work zone signages were visible. No significant changes were noticed in any of the driver behaviors as measured by average speed and speed variability. However, it should be noted that the work zone passes identified in previous step did not have congestion or merging into traffic, neither did any of the passes get involved in crashes – therefore, there were no external event stimuli to instigate changes in driver behavior, and hence, to identify such behavior changes in this study. The driver behavior identified in this study is the baseline work zone driving behavior of drivers.

Given the findings related to drunk and distracted driving being overrepresented in work zone crashes and drivers' non-response to roadway signages, it was suggested that in-vehicle alert systems would be more effective in warning drivers of oncoming work zones and about positions of other vehicles, including queue lengths. Different possible methods of providing in-vehicle information – vehicle to vehicle (V2V), vehicle to infrastructure (V2I) communications and their different forms were assessed for effectiveness. It was found that because of higher market penetration rate, vehicle-to-infrastructure (V2I) warning systems could be most effective as compared to vehicle-to-vehicle (V2V) communications and because of its ability to tailor messages to suit the purpose and requirement of the users.

CHAPTER 1. INTRODUCTION

1.0 Background

Like every other type of infrastructure, roads need to be maintained and repaired. Thus, drivers can expect to find countless work zones along the road network for this purpose. While a necessary reality of driving, work zones can present challenges for road users. There are two primary concerns regarding work zones: safety and congestion. In 2015, there were 642 fatal crashes in work zones across the United States (US; Fatality Analysis Reporting System, FARS, 2015). Work zones are also a significant source of “non-recurring” congestion; that is, congestion that does not occur regularly at a specific time and location. For example, in 2014, work zones accounted for about 10% of overall congestion (Federal Highway Administration, FHWA, 2017).

1.0.1 Objective

One potential way to address work zone-related concerns is to develop countermeasures designed to change driver behavior through messaging. Such countermeasures involve the use of signs, signals, and displays to convey a variety of relevant and timely information to drivers entering work zones. Much of the literature on messaging countermeasures in work zones addresses safety by encouraging appropriate vehicle speeds (speed management). However, the literature also includes countermeasures to reduce congestion through the provision of information to help drivers find alternate routing around work zones, direct them into proper lanes, and make them more aware of their surroundings. The objective of this study is to identify countermeasures based on connected vehicle communication system that can help work zone safety management.

1.0.2 Scope

This work extends current data explorations taking place at UMTRI to use driving data to understand work zone behavior. The scope of this study extends to understanding crash causation mechanisms in work zones and how connected vehicle communication system can be used to mitigate work zone crashes.

1.1 Statement of Hypothesis

The hypothesis of the study team is that advent of vehicle communication affords a new opportunity to develop countermeasures for work zones in that infrastructure can monitor workzone driving behavior and potentially provide adaptive or even targeted interventions to help drivers manage work-zone driving more appropriately.

CHAPTER 2. LITERATURE REVIEW

2.0 Introduction

To provide background for the project *Identifying Potential Work Zone Countermeasures Using Connected-Vehicle and Driving,* literature was reviewed on a broad range of topics related to safety and congestion in work zones. This report summarizes a subset of the larger literature that is focused specifically on messaging countermeasures. For the overall project, a set of search terms was identified through discussions among the project team. These terms were: work zone safety, speed management in work zones, connected vehicles and work zone safety, zipper and late merging in work zones, and improving safety and congestion in work zones. These terms were searched using the following databases: PsycINFO, TRID, Web of Science, ProQuest, and Google Scholar. Titles and abstracts were reviewed for relevance and those deemed appropriate by the project team were collected and entered into an electronic reference database (Zotero.com). Articles relevant to messaging countermeasures were then chosen from the database of articles and reviewed for relevancy for this report. Reference lists from the collected articles were also reviewed for additional literature. The identified studies were synthesized into four topics: work zone awareness, speed management, rerouting, and proper lane positioning and is presented below.

2.2 Literature Review

2.1.1 Work zone Awareness

Messaging countermeasures can be especially effective in making drivers more aware of the existence and characteristics of work zones (e.g. lane closures, speed limit differences, locations of active workers). Speed management countermeasures can increase safety by making drivers more aware of work zones, even if the measures are ineffective at reducing speeds (Hildebrand, Wilson & Copeland, 2005). To this end, Vadeby et al. (2016) recommended displaying information regarding work zones at the beginning of the work zone along with signs and other countermeasures, such as rumble strips or enforcement, so that drivers could be alerted to upcoming hazards, such as moving machinery, closed lanes, or road workers. Changeable message signs can be especially useful to drivers because they are often used to broadcast a wide variety of messages (Bai, Yang & Li, 2015; ENTERPRISE Program, 2014).

In addition, intelligent transportation systems applied to work zones, referred to as “smart work zones,” can be used to collect information about the characteristics of the work zone using sensors in real time, and then relay that information to oncoming drivers through message signs (Edara, Sun & Hou, 2013). Queue warning systems, for example, use sensors upstream of a work zone to alert drivers about traffic conditions through a series of portable changeable message signs (ENTERPRISE Program, 2014). One study measured driver perception of a smart work zone in Arkansas designed to provide real-time information to motorists (Luttrell et al., 2008). Of surveyed drivers, 82% reported that their ability to react to stopped or slowed traffic was improved and 49% reported that they were safer driving through the work zone because of the messages. Travel time delay data can also be useful information to increase a driver’s awareness of an upcoming work zone. In addition, some smart work zones, using Bluetooth sensors and computers to calculate delays, can provide this information to drivers so that they can better understand anticipated delays (Edara et al., 2013).

Connected and automated vehicle technologies could potentially play an important role in developing advanced work zone messaging systems. At a basic level, autonomous vehicles can be “aware” of work zones by using video cameras to “read” signs and symbols in work zones (Seo, Lee, Zhang & Wettergreen, 2015). In addition to being sent through message signs, information about work zone characteristics can be sent directly to drivers. One form of connected vehicle technology allows the road infrastructure to send information to nearby vehicles; this is vehicle to infrastructure, or V2I communication (Office of the Assistant Secretary for Research and Technology, 2017). Another form of connected vehicle technology can communicate with other vehicles (V2V; National Highway Traffic Safety Administration, 2017). For example, Maitipe, Hayee, and Kwon (2011) designed a system through which connected vehicles could communicate with the work zone infrastructure to receive information regarding work zone conditions. Drivers of these vehicles could then make informed decisions about routing or driving behavior before entering the work zone. This system was subsequently improved to also receive information from other connected vehicles, which offered substantial improvement over the original design in terms of message broadcast range and congestion length coverage (Maitipe, Ibrahim, Hayee & Kwon, 2012). For drivers without connected or automated vehicles, even a smartphone-based warning system can help alert them to traffic conditions in a work zone (Rahman, Qiao, Li, Yu & Kuo, 2015). In a study on smartphone-based warning systems by Rahman et al. (2015), 80% of participants said that warning messages on their smartphones did not increase workload while driving and 75% of participants were interested in installing the work zone warning application on their smartphones. At the very least, these results indicate that there is interest in receiving information in more convenient ways than just through road signs. Collectively, literature in this section suggests that whether using standard messaging with signs or more advanced methods, messaging countermeasures in the work zone can help make drivers more aware of work zone activity and prepare accordingly, through speed reduction, rerouting, or moving to different lanes ahead of time.

2.1.2 Speed Management

In 2015, speeding was the primary cause of 181 fatal crashes within work zones in the US (FARS, 2015). Signs and displays can be used to help reduce speeding in work zones. Signs can be static, displaying a single unchanging message, or dynamic, displaying a variety of messages. Static speed limit signs are useful for making drivers aware of a speed limit in a work zone but should be limited to places where people are actively working; otherwise drivers might begin to ignore the signs because they may not think that they are relevant (Brewer, Pesti & Schneider, 2006). Speed limit signs can be outfitted with fluorescent orange borders or sheeting to increase visibility but studies show a limited benefit of this treatment for speed reduction (Hildebrand et al., 2005). Variable speed limit signs and changeable message signs provide a means for communicating real-time feedback to drivers on work zone speed limits based on the condition of the work zone. Despite this, studies suggest that dynamic signs are not significantly more effective in reducing average speeds in work zones than static speed limit signs; however, dynamic signs can help to reduce speed variance in the work zone (Hildebrand et al., 2005; Lin, Kang & Chang, 2004; McMurtry, Saito, Riffkin & Heath, 2009; Sommers & McAvoy, 2013). This latter finding may be important because crash rates are known to be positively correlated with increasing speed variance (Garber & Gadiraju, 1989).

Positioning of work zone speed limit signs is guided by MUTCD stipulations, in conjunction with field guidance documents developed by state DOTs. For example, guidelines on speed limit positioning for MDOT can be found at https://mdotcf.state.mi.us/public/tands/plans.cfm. However findings from research studies are not clear on optimal positioning of work zone speed limit sign. One study found the optimal location to be 575 feet upstream of work zone because this positioning gave drivers enough time to slow down to match upcoming traffic speed, but was not so early that it was disregarded by drivers by the time they reached the work zone (Bai et al., 2015). Another study, however, found that the optimal placement was about 246 feet upstream from the work zone (Hildebrand & Mason, 2014). These studies did not take any measurements between 246 and 575 feet, so no inferences can be drawn about distances in this range. More research is warranted to determine optimal speed limit sign placement for different type of work zones.

Speed monitoring displays serve a different role in speed management than speed limit signs. These displays indicate both the speed limit within a zone and the actual speed of drivers' vehicles as they approach the work zone. If the system detects that a driver is traveling over the speed limit, the display will start to flash. There is conflicting evidence as to whether these speed displays are effective in lowering driver speeds. Some investigators have reported that speed monitoring displays that are in place for an extended period of time have an impact on lowering speeds and speed variance, even after the removal of the displays (e.g., Brewer et al., 2006; Pesti & McCoy, 2001). Others, however, have reported that speed monitoring displays are only effective when combined with some method of enforcement (Benekohal, Hajbabaie, Medina, Wang & Chitturi, 2010; Lee, Azaria & Neely, 2014). Consistent with this latter approach, Hildebrand and Mason (2014) used a mock police vehicle placed near the speed monitoring display. They found a significant reduction is speed closer to the posted speed limit. However, over the long-term, this effect disappeared presumably because drivers realized that the police car was not real and no actual enforcement was occurring. These researchers suggested that a speed monitoring display combined with actual enforcement would likely be the best way to maintain the speed reductions. Speed photo enforcement vans (law enforcement vehicles parked along the road that have the ability to display an oncoming driver's speed and the posted speed limit, as well as photographing drivers who are speeding), are part of a similar system that can monitor and display speeds while also providing the threat of enforcement; these have been shown to be effective for speed reduction in work zones (Benekohal et al., 2010; Fang, 2006). Unfortunately, these vans are expensive to operate and are not a legal method of enforcement in many states. Finley (2015) suggested that while law enforcement is an effective way to reduce speed limit in work zones, if personnel are not available then speed display trailers or portable changeable message signs with radar can be substituted.

2.1.3 Routing

A primary concern with work zones is that they produce traffic congestion. One way to help reduce congestion in work zones is to divert drivers onto alternate routes. Routing countermeasures for work zones are designed to give relevant information about alternative routes that are timed appropriately so that drivers can make decisions about taking other routes. The effectiveness of the routing countermeasures are often measured using traffic diversion rate information gathered using portable surveillance on the work zone route and alternative routes (Edara et al., 2013). In one study examining a bridge work zone (Edara et al., 2013), a changeable message sign was used to provide alternate route information. A total of 47% of drivers who used the bridge to commute regularly reported that the changeable message signs influenced their decision to use an alternative route. Travelers using the bridge were also asked about the value of changeable message signs as compared to other sources of information; 87% reported that the message signs were at least as valuable as other sources. In another work zone study in Texas, a message sign displayed traffic delay times and provided alternate route information (Luttrell et al., 2008). Results indicated that traffic volumes were reduced by 10% during congested periods. In a study in the District of Columbia using a similar system, a 52% reduction in traffic volume was found (Luttrell et al., 2008). Some researchers have proposed that delay times and alternate route information sent directly to connected vehicles could be a potentially effective way to reduce congestion in work zones (Genders & Razavi, 2015; Maitipe et al., 2012). Such information could also interface with a vehicle's built-in navigation system to facilitate the use of alternate routing, but more research is needed to determine how drivers' would use and think about this system.

2.1.4 Proper Lane Position

In many cases, work zones require that one or more lanes be closed to allow work to be safely conducted, creating the potential for increased congestion. One way to mitigate some of the congestion and driver uncertainty when approaching a work zone is to notify drivers about which lanes are closed before drivers reach the point where they must merge, so that they can potentially merge earlier. There is little research on how messaging can assist with proper lane positioning. Conventional strategies involve the placement of static signs to direct drivers to the proper lane position before a lane closure. Different state Departments of Transportation may use different configurations of merge signs, but it is not likely that the differences impact congestion. For example, Long, Qin, Konur, Leu, Moradpour and Wu (2016) tested the Missouri Department of Transportation's sign configurations against the configuration in the Manual on Uniform Traffic Control Devices, and found no significant difference in travel time between the two types in a simulation testing different sign configurations. Intelligent, or adaptive, lane merge control strategies can be more effective than conventional strategies. For example, a system developed by Yulong and Leilei (2007) used multiple variable message signs across a work zone to indicate upcoming lane closures and different points where drivers could pass. This system can be modified to the real-time conditions of the work zone, depending on where the active road work is taking place. Dynamic merge systems can use changeable message signs to instruct drivers on where they are allowed to merge before a lane closure; these can be modified based on traffic conditions. Such a system used in a Michigan work zone helped reduce dangerous merges by a factor of 3, a considerable reduction (Luttrell et al., 2008). Queue warning systems can also be combined with lane selection messages to indicate to drivers which lanes are closed (Pesti et al., 2008).

CHAPTER 3. WORK ZONE CRASH DATA AND CONTEXT ANALYSIS

3.0 Introduction

Navigating work zones and work zone traffic present a consistent challenge to all drivers, as is evident from the increasing number of work zone crashes across the nation - between 2014 and 2015 nationwide, work zone related crashes increased by 7.8% (FHWA 2017). Work zone crashes are also slightly more likely to involve fatal injuries as compared to non-work zone crashes (0.7% of all work zone crashes vs 0.5% of all non-work zonenon-work zone crashes in 2015) (FHWA 2017). In Michigan, of all fatal crashes in 2015, 0.9% were work zone crashes which increased to 1.7% in 2016 (National Work zone Safety Information Clearinghouse 2017).

Addressing work zone crashes and fatalities require understanding of the context in which the crashes happened and how the crashes differ in character and context from non-work zonenon-work zone crashes. Multiple studies have looked into work zone crashes versus nonwork zone crashes to identify factors that distinguish these two type of crashes (Liu et al. 2016, Harb et al. 2006). These studies can be classified into three categories based on their focus – (i) crash rate or frequency of work zone crashes, (ii) work zone environment (including roadway environment) and (iii) driver behavior related to the work zone crashes. Findings from literature on the first category (work zone crash rate/frequency) indicate that presence of work zones tends to increase crash frequency while crash occurrences are positively correlated with traffic volume, length of the work zone, work zone duration and the work zone being in urban areas. Results from the work zone environment related studies indicate that work zone crash severities are related to having higher posted speed limits and in dark but lighted conditions. Further, work zone crashes are more likely to happen in clear weather and more likely to involve trucks as compared to other vehicles. The third category, driver behavior related studies, mostly point to speeding, speed variability, improper following distance, drunk driving, distraction and ignoring traffic control signs as causal factors for work zone crashes.

In this chapter we look at the same three categories of work zone crash data analysis for Michigan within the purview of data availability (for example, not having data on work zone length and duration restricts our ability to estimate any effect of these factors on work zone crashes or their frequencies). The focus of this chapter is to understand the trends and patterns of Michigan specific work zone crashes and to identify their causal factors before effective countermeasures can be proposed. The first part of the chapter deals with comparison of work zone versus non-work zone crashes based on crash characteristics, roadway environment and external factors like weather, time of day etc. as well as the driver characteristics. The same analyses are then extended to compare work zone crashes with worker present versus work zone crashes without worker present to understand if presence of workers significantly alter any crash charateristics.

The second part of the chapter presents multivariate models for the probability of being in a freeway work zone crash versus being in a freeway non-work zone crash for single and multi vehicle crashes based on work zone environment, driver characteristics and vehicle type. The single vehicle crashes are defined as run off road crashes and crashes with any fixed objects (or pedestrians/animals etc.) within the work zone. For the multiple vehicle crashes, crashes with at fault drivers (defined as the striking vehicle in a rear end crash) are filtered and are used for comparison with at fault driver non-work zone crashes. The purpose of these analyses is to identify factors that characterize freeway work zone crashes as compared to freeway nonwork zone crashes and use that information to propose most relevant and effective countermeasures in later chapters.

The third part of the chapter deals with analyzing speed related behavior of the drivers in work zone and non-work zone passes using naturalistic driving data. Both speed and speed variability are analyzed for work zone vs non-work zone passes as well as for different conditions within the work zones. The work zones are selected based on a list of active work zones between 2015-2016 provided by MDOT which was then location matched using driving trajectory data from Safety Pilot dataset (http://safetypilot.umtri.umich.edu/) Work zones that have passes of instrumented vehicles from safety pilot project are retained and used for this part of the analysis.

3.1 Work zone and Nonwork zone Crash Characteristics

3.1.1 Methodology

Five years (2012-2016) of Michigan crash data were analyzed for the purpose and the results are presented in following sections. The flag of ‘worker present’ has been added in Michigan crash reports since 2015, so that variable is only available for the 2016 data. To utilize the explanatory power of entire five years of data, ‘worker present’ is not considered for statistical models. However, work zone worker safety is also one of the concerns of this project, therefore, we also present a comparison of work zone crashes with worker present versus work zone crashes without worker present using the 2016 crash data only. Crashes are compared on crash types, weather and light conditions, time of day, day of week, number of lanes and speed limit and the results are presented in appropriate sections

3.1.2 Findings

Work zone Crashes by Count, Types and Events

Figure 1 shows the count of work zone crashes in Michigan between 2012 and 2016. The work zone crashes are identified by the variable *cnst_type_cd* in Michigan crash data which flags construction, maintenance and utility related work. For the purpose of this analysis, all three categories are treated as work zone.

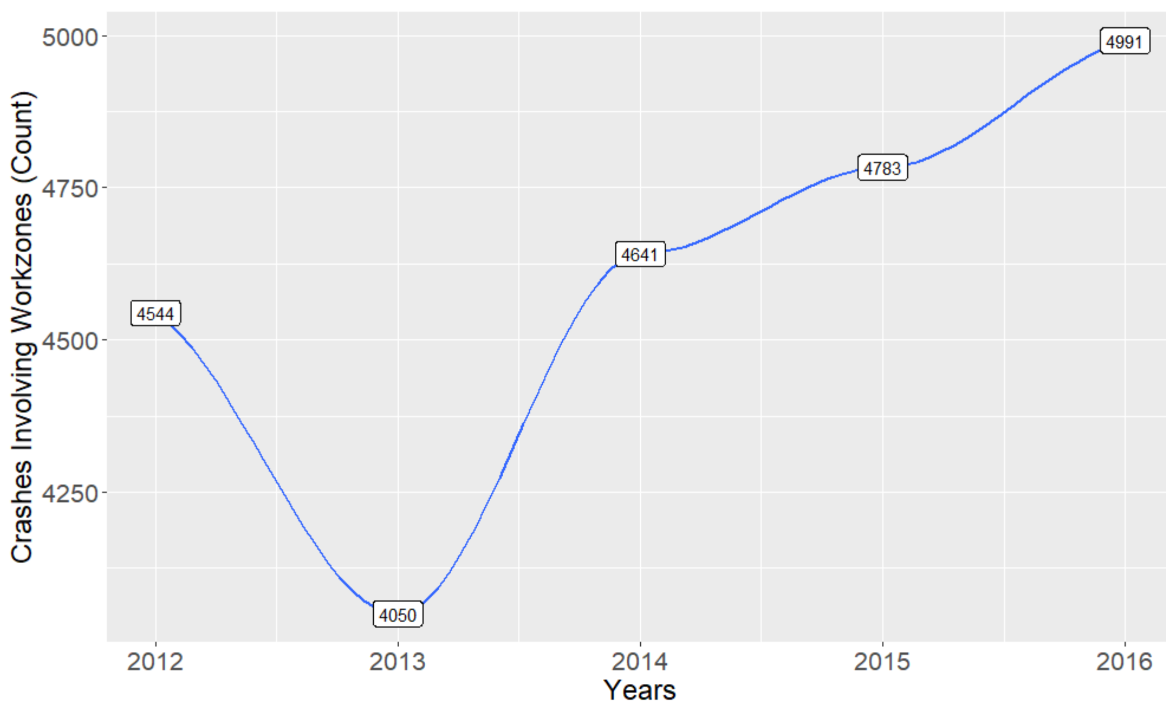


Figure 1. Count of Work zone Crashes in Michigan, 2012-2016

As is seen in Figure 1 and as mentioned before, the count of work zone crashes in Michigan increased from 2013 with the highest percentage increase happening between 2013 and 2014 (14.5%). The increase between 2014 and 2015 is ~3% and between 2015 and 2016 is ~4%. The trend in Michigan is similar to the national trend and it is unclear at this stage if that is caused by an increasing VMT over the years and/or an increasing number of work zones for maintenance activities in an aging infrastructure system.

Figure 2 shows the distribution of the different types of work zone and non-work zone crashes. Work zone crashes are more likely to be rear end crashes (~40%), followed by angle and sideswipe same direction crashes. Rear end crash, the predominant type, can result from delayed reaction to work zone signs, particularly in congested areas and in queues while angle and same direction sideswipe can result from distracted merging/overtaking or lane changing. At work zones, distracted driving can lead to overlooking of advance notices of the closure as well as a reduced sight distance. In addition, for work zones where the closure point is not distinctly marked or the taper merge region is short and ill defined, distracted drivers are more likely to get involved in sideswipe and angle crashes as they are paying less attention to the surrounding environment. Figure 3 shows the distribution of crash types for work zone with workers present and work zones without workers present and there is no significant difference in the distribution of type of crashes between worker present and worker not present on types of crashes except for single vehicle crashes and same direction sideswipe are. These two types of crashes are less likely to happen in work zones where workers are present as compared to work zones where workers are not present.

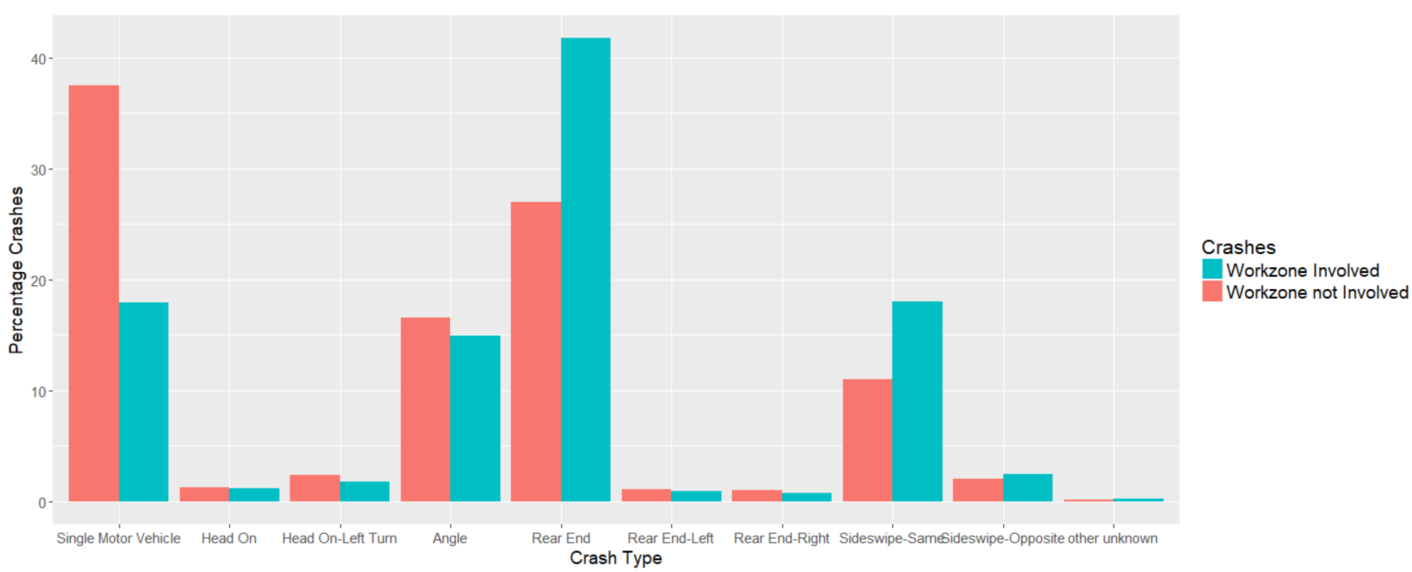


Figure 2. Percentage Distribution of Types of Crashes in Work zones vs Non-work zones (2015-2016)

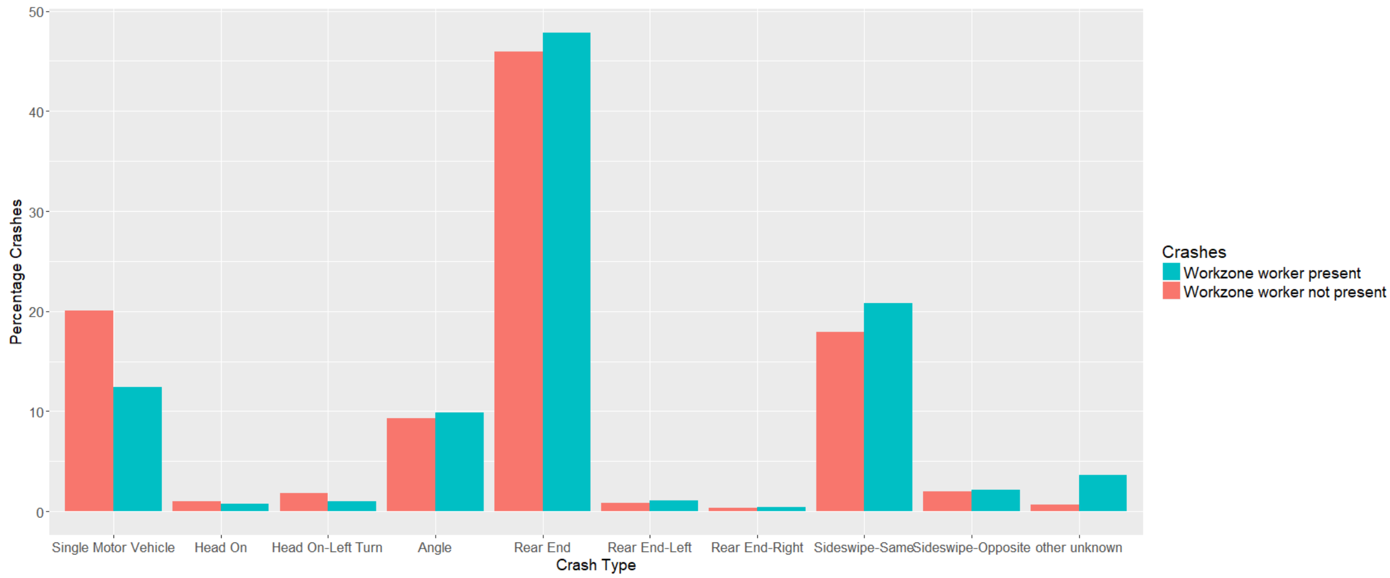


Figure 3. Percentage Distribution of Types of Crashes in Work zones with Workers vs Work zones with No Worker (2015-2016)

Another way of looking at the work zone crashes, along with the type of crashes, is through the most harmful event in a crash, which gives an idea of how the crash may have happened. Table 1 shows the most harmful events for single vehicle crashes in work zones vs non-work zonenon-work zones. As is evident from Table 1, the single vehicle work zones crashes have a higher proportion of run-off-road crashes, collision with fixed and non-fixed objects, and collision with pedestrians compared to non-work zonenon-work zone crashes.

Table 1. Most Harmful Events for Single Vehicle Work zone Vs Non-work zoneNon-work zone Crashes

Most Harmful Event	Non-Workzone		Workzone		Total
	Count	Percent	Count	Percent	Count
Uncoded & errors	715	0.33%	44	1.78%	759
Noncollision Event - Loss of control	2760	1.27%	74	2.99%	2834
Noncollision Event - Ran off roadway left	1311	0.61%	34	1.37%	1345
Noncollision Event - Ran off roadway right	2129	0.98%	49	1.98%	2178
Noncollision Event - Overturn	13861	6.40%	124	5.01%	13985
Collision With Nonfixed Objects - Pedestrian	2820	1.30%	67	2.71%	2887
Collision With Nonfixed Objects - Bicyclist (pedalcycle)	2411	1.11%	27	1.09%	2438
Collision With Nonfixed Objects - Motor vehicle in transport*	7326	3.38%	129	5.21%	7455
Collision With Nonfixed Objects - Animal	92956	42.93%	294	11.88%	93250
Collision With Nonfixed Objects - Other nonfixed object	8827	4.08%	517	20.90%	9344
Collision With Fixed Object - Guardrail face	12019	5.55%	107	4.32%	12126
Collision With Fixed Object - Median barrier	18710	8.64%	238	9.62%	18948
Collision With Fixed Object - Highway traffic sign post	5838	2.70%	110	4.45%	5948
Collision With Fixed Object - Luminaire / light support	2317	1.07%	25	1.01%	2342
Collision With Fixed Object - Other pole	1790	0.83%	30	1.21%	1820
Collision With Fixed Object - Curb	2336	1.08%	45	1.82%	2381
Collision With Fixed Object - Ditch	9716	4.49%	119	4.81%	9835
Collision With Fixed Object - Embankment	2801	1.29%	26	1.05%	2827
Collision With Fixed Object - Tree	7765	3.59%	23	0.93%	7788
Collision With Fixed Object - Other fixed object	4003	1.85%	200	8.08%	4203
Other	14110	6.52%	192	7.76%	14302
Total	216521	100.00%	2474	100.00%	218995

Work zone Crashes and Light Conditions

Work zone crashes are most likely to happen in daylight followed by dark lighted and dark unlighted conditions .Non-work zone crashes are significantly more likely to be during dark unlighted conditions than work zone crashes whereas work zone crashes are significantly higher in daylight conditions than non-work zone crashes. Work zone crashes where workers are present are also more likely to be daylight crashes and less likely to be dark lighted or dark unlighted conditions which may be a reflection of the work hours of the work zone workers.

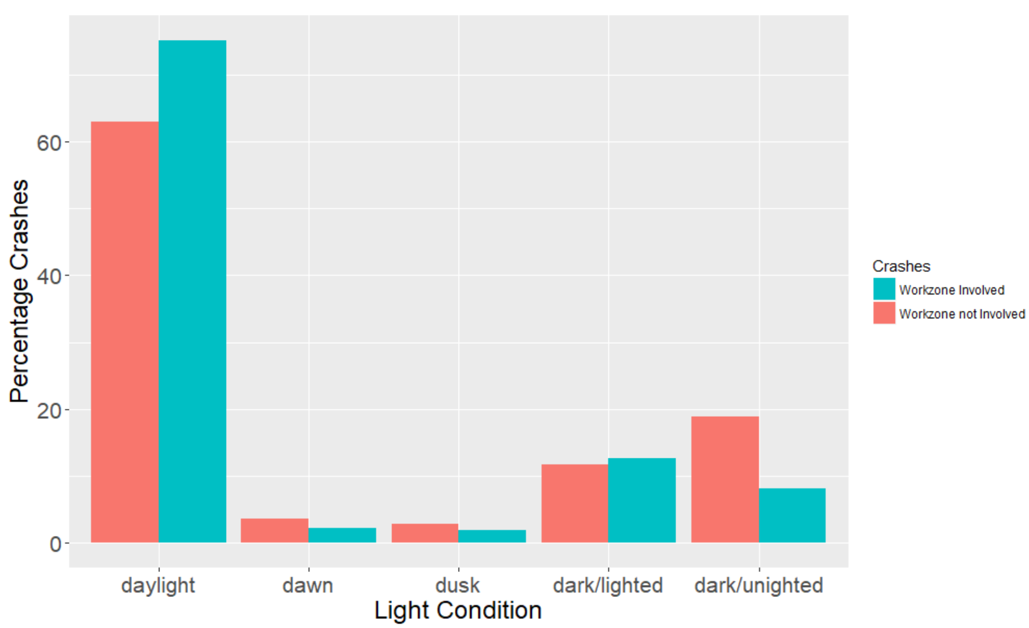


Figure 4. Percentage Distribution across Light Conditions for Work zones and Non-work zoneNon-work zones Crashes (2015-2016)

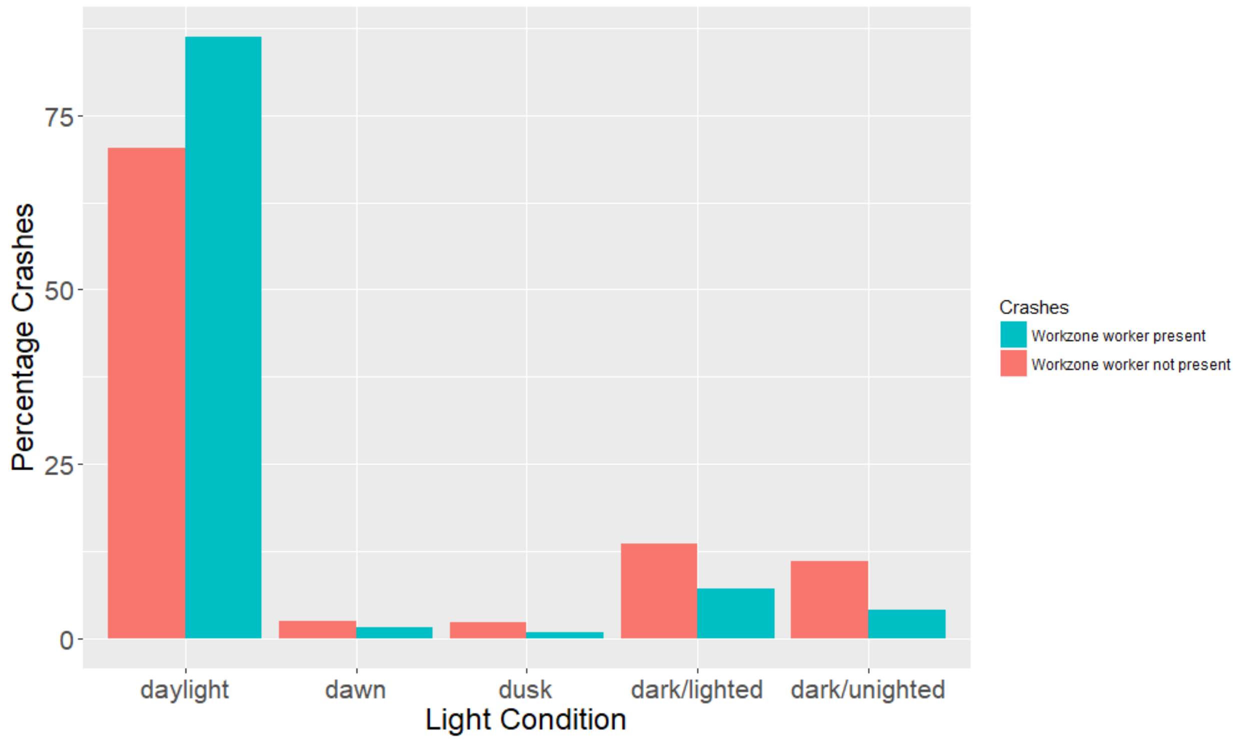


Figure 5. Percentage Distribution Across Light Conditions for Crashes in Work zones with and without Workers Present (2015-2016)

Work zone Crashes, Day of Week and Time of Day

Figure 6 and Figure 7 present the percentage distribution of crashes across days of the week for work zone vs non-work zonenon-work zone and for work zone with worker present vs work zone without worker respectively. Work zone crashes are slightly more likely to happen during Tuesday, Wednesday and Saturday while within work zone crashes, the crashes in worker present work zones are significantly higher than those in no worker present work zones during weekdays as compared to weekends. This again, may be a reflection that majority of the workers are present in work zones during the weekdays rather than the weekends.

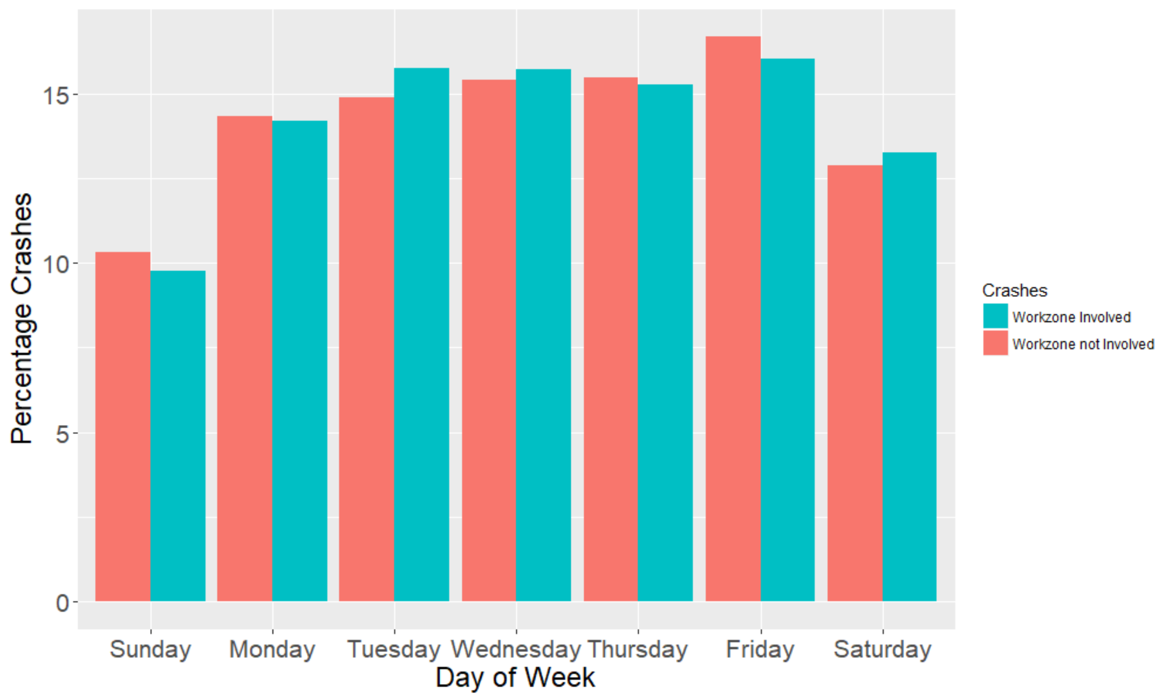


Figure 6. Percentage Distribution across Days of the Week for Work zone and Non-work zone Crashes (2015-2016)

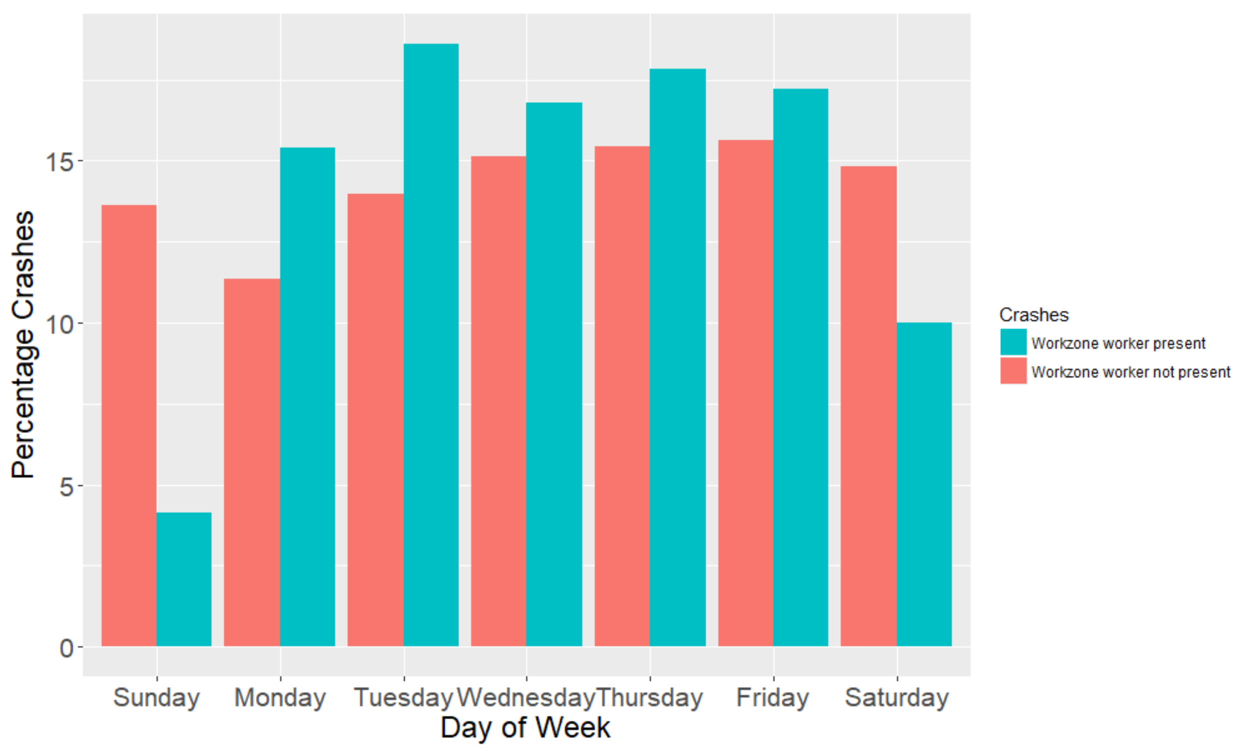


Figure 7. Percentage Distribution Across Days of the Week for Crashes in Work zones with and without Workers Present (2015-2016)

Figure 8 and Figure 9 show the percentage distribution of crashes during the different hours of the day for work zone vs non-work zonenon-work zone and within work zones, for work zones with workers present and with workers not present. In general, work zone crashes are during the day, with peaks almost matching traffic volume peak hours, but they are also more likely to happen late at night as compared to other crash types. Construction worker present crashes are much more likely during the day and less likely during late at night. However, this has not been measured against the proportion (or number) of construction workers actually working during these times (exposure).

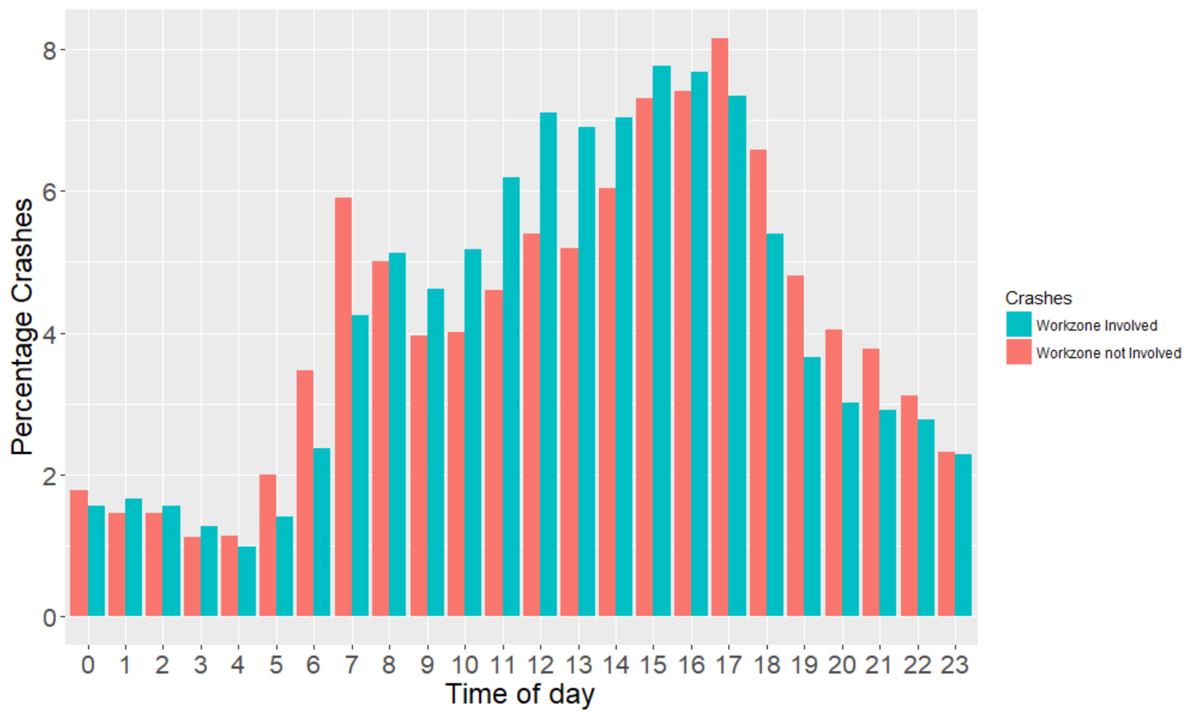


Figure 8. Percentage Distribution across Hours of the Day for Work zones and Non-work zoneNon-work zones Crashes (2015-2016)

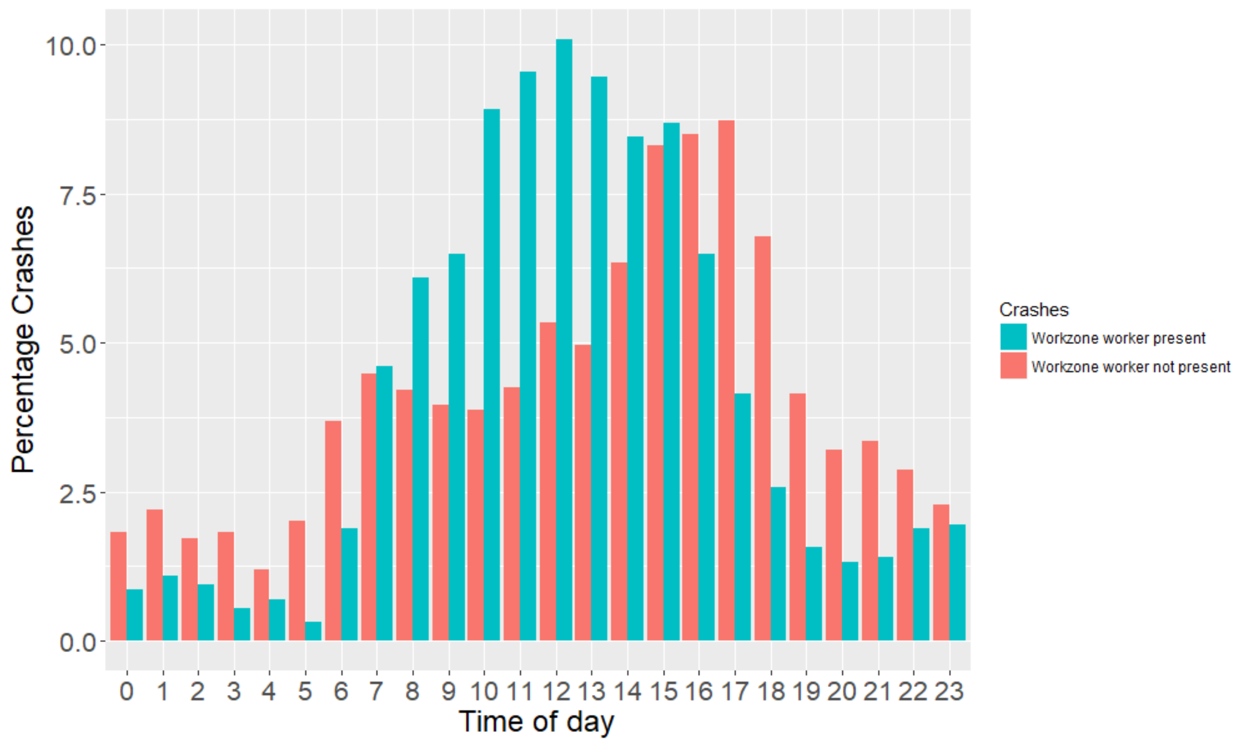


Figure 9. Percentage Distribution Across Hours of the Day for Crashes in Work zones with and without Workers Present (2015-2016)

Crashes, Number of Lanes and Speed Limits

Figure 10 and Figure 11 present the percentage distribution of crashes across number of lanes for work zone vs non-work zone crashes and within work zones, worker present vs worker not present work zones. Work zone crashes are more likely to be on 1, 3 or 4 lanes as compared to non-work zone crashes. However, within work zone crashes, worker present crashes are more likely to be on 2 and 3 lane roads. It should be noted that this analysis does not make any distinction between roadway functional classes (for example, freeway vs arterial) because the data do not provide relevant information for such analysis. The researchers do acknowledge that effect of road type confound the effect of number of lanes on work zone related crashes and should be considered in conjunction. A step in this direction may be analyzing crash narratives from crash data which may provide more information on crash environment.

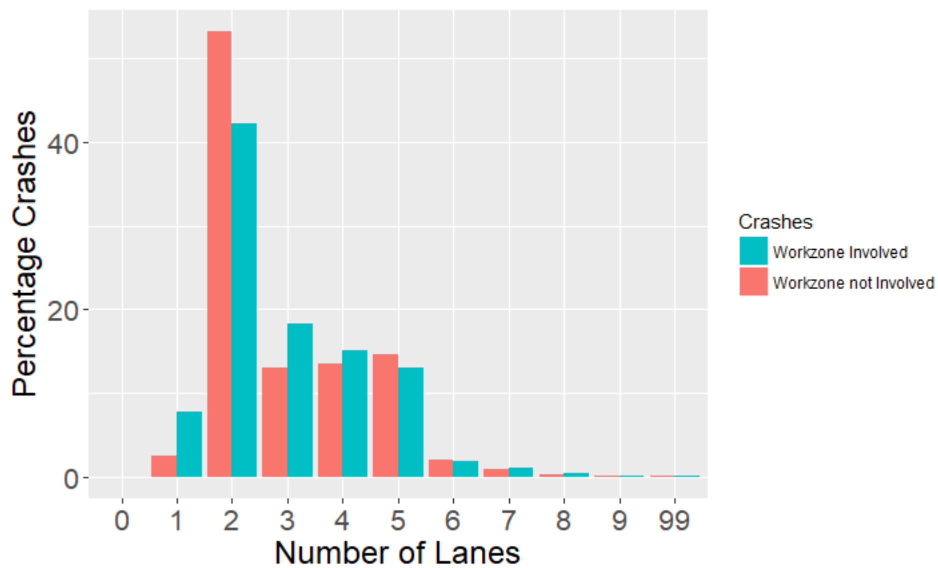


Figure 10. Percentage Distribution across Number of Lanes for Work zone and Non-work zone Crashes (2015-2016)

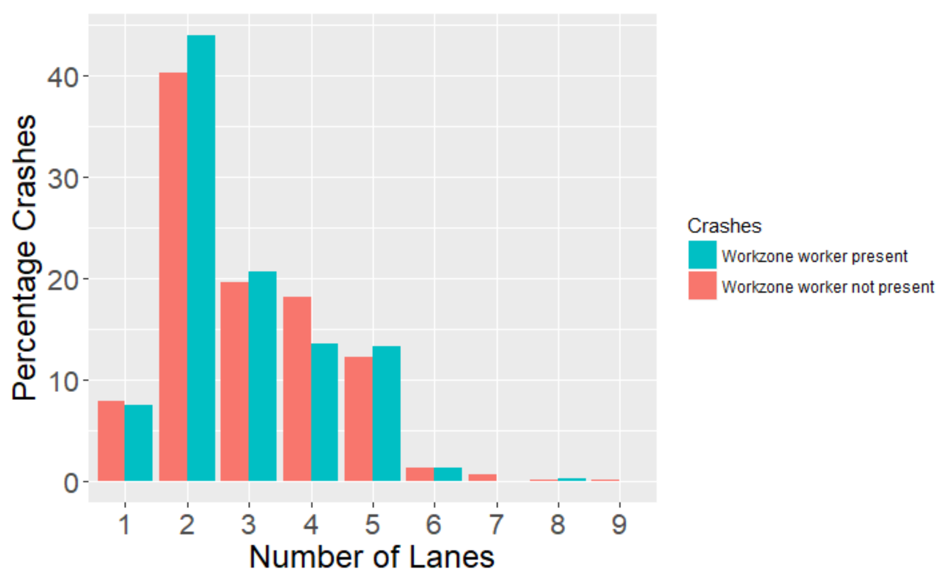


Figure 11. Percentage Distribution Across Number of Lanes for Crashes in Work zones with and without Workers Present (2015-2016)

Figure 11 and Figure 12 show the percentage distribution of crashes across posted speed limits for work zone and non-work zone crashes and within work zones, worker present vs worker not present scenarios. Work zone crashes are more likely on low –medium speed roads and on roads with speed limit 60 mph whereas work zone crashes with worker present are more likely at low speeds and most likely at 45 mph speed limit roads. It should be noted that the speed limit used in this analysis is the speed limit noted in the crash report ,which is likely the normal speed limit for that road segment and not the work zone speed limit. The data also do not provide information on speed differentials – the difference between normal speed limit and the reduced work zone speed limit, hence even though the researchers acknowledge that speed differentials are likely more significant predictors of work zone crashes than speed limits, this dataset does not lend itself to that particular analysis. However, effect of speed differentials are considered later in the chapter where naturalistic driving data have been used to understand work zone driving behavior.

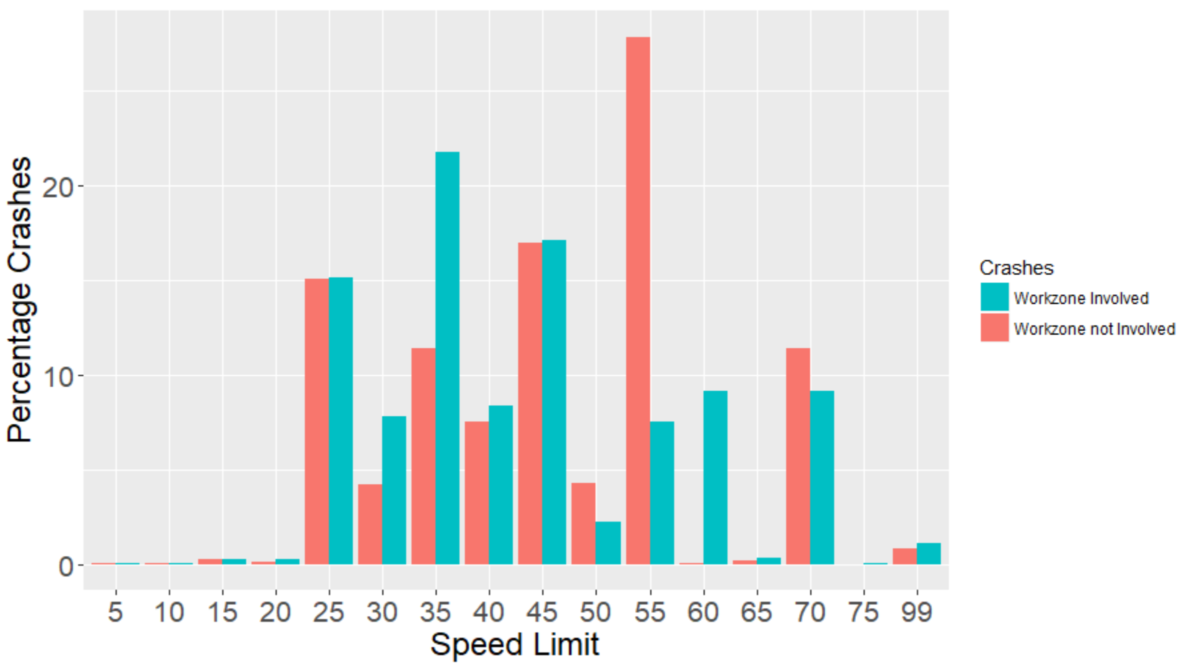


Figure 12. Percentage Distribution across Speed Limits for Work zone and Non-work zone Crashes (2015-2016)

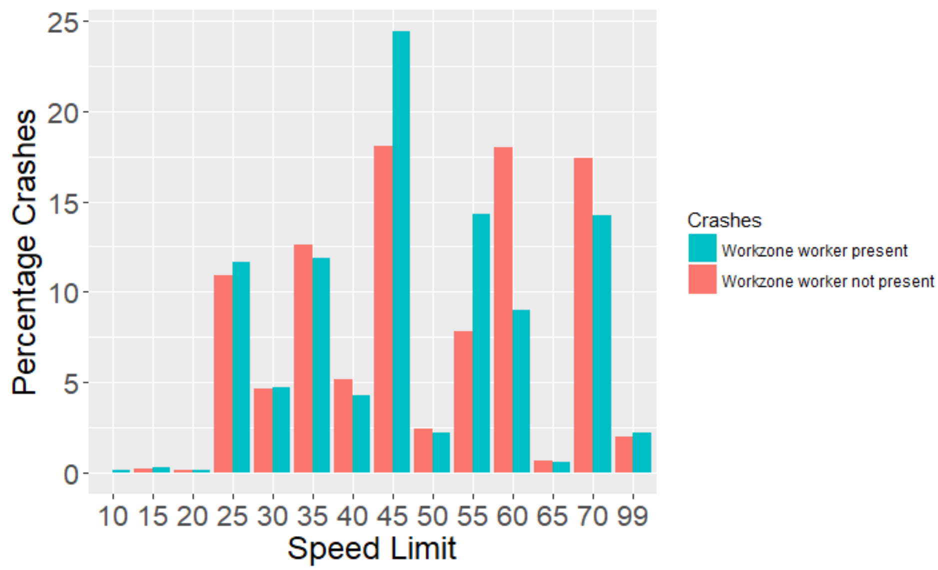


Figure 13. Percentage Distribution Across Speed Limits for Crashes in Work zones with and without Workers Present (2015-2016)

Work zone Crashes and Senior and Young Drivers

Figure 14 and Figure 15 show the percentage distribution of crashes for work zones and non-work zone non-work zones with senior driver (age 65 and above) and young driver (age 15-21) involvement respectively. While young drivers are slightly less likely to be involved in work zone crashes, senior drivers are slightly more likely to be involved in work zone crashes.

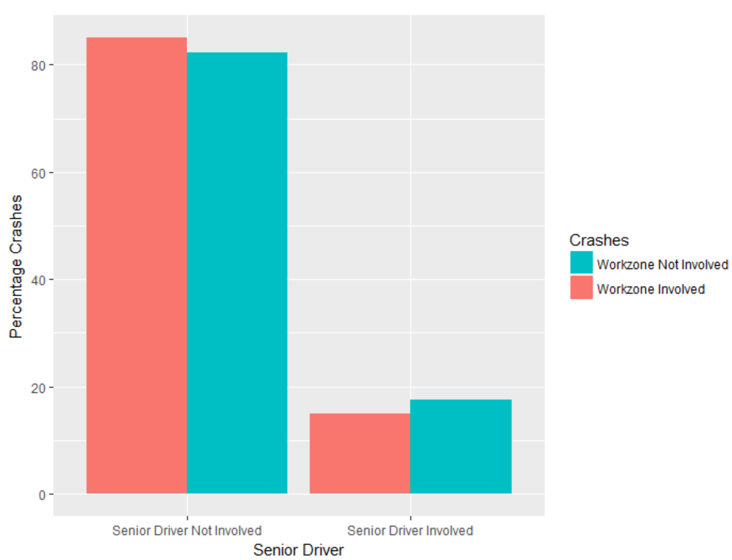


Figure 14. Percentage Distribution across Senior Driver Involvement for Work zone and Non-work zone Crashes (2015-2016)

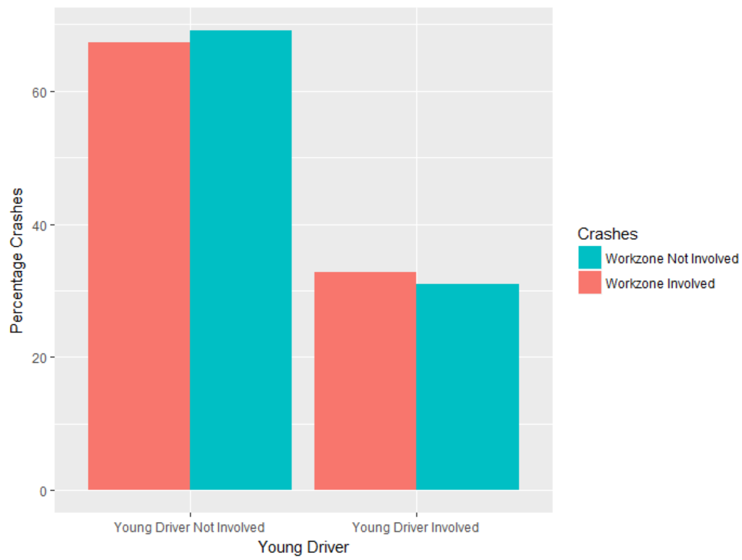


Figure 15. Percentage Distribution across Young Driver Involvement for Work zone and Non-work zone Crashes (2015-2016)

Work zone Crashes and Driver Attributes

Table 2A-2D show the distribution of work zone vs non-work zonenon-work zone crashes for different driver attributes. While there are no significant differences between age groups and gender, work zone crashes with driver drinking and work zone crashes with driver distracted are twice in proportion as compared to non-work zone crashes.

Table 2A. Percentage Distribution of Work zone vs Non-work zone Crashes Across Age

		Non Workzone	Workzone	Total
Age	<25	25.38%	24.16%	25.36%
	26-35	19.62%	19.80%	19.62%
	36-45	16.39%	16.32%	16.39%
	46-55	17.38%	16.90%	17.38%
	56-65	13.23%	13.93%	13.24%
	66-75	5.82%	6.38%	5.83%
	75+	2.18%	2.52%	2.18%
	Total	100.00%	100.00%	100.00%

Table 2B. Percentage Distribution of Work zone vs Non-work zone Crashes Across Sex

		Non Workzone	Workzone	Total
Sex	Female	39.96%	37.59%	39.93%
	Male	60.04%	62.41%	60.07%
	Total	100.00%	100.00%	100.00%

Table 2C. Percentage Distribution of Work zone vs Non-work zone Crashes Across Driver Drinking

		Non Workzone	Workzone	Total
Drinking	Not Drinking	96.44%	92.62%	96.39%
	Drinking	3.56%	7.38%	3.61%
	Total	100.00%	100.00%	100.00%

Table 2D. Percentage Distribution of Work zone vs Non-work zone Crashes Across Driver Distraction

		Non Workzone	Workzone	Total
Distracted	Not Distracted	99.01%	98.04%	99.00%
	Distracted	0.99%	1.96%	1.00%
	Total	100.00%	100.00%	100.00%

Work zone Crashes and Vehicle Type

Table 3 shows the distribution of work zone vs non-work zonenon-work zone crashes across different vehicle types. As is indicated in literature, truck involved crashes are over represented in work zone crashes as compared to non-work zonenon-work zone crashes. A significant number of work zone crashes happen related to work zone machinery (Kivi and Olidis 2015), which may also be a reason for this over representation.

Table 3. Percentage Distribution of Work zone vs Non-work zoneNon-work zone Crashes Across Vehicle Type

		Non Workzone	Workzone	Total
Vehicle Type	Passenger Car/Pickup	91.14%	86.05%	91.09%
	Truck/Heavy Truck	3.92%	7.31%	3.96%
	Other	4.93%	6.63%	4.95%
	Total	100.00%	100.00%	100.00%

3.1.3 Discussion

Work zone crashes are distinct from nonwork zone crashes in their significant overrepresentation of rear end, angle and sideswipe crashes, their prevalence in daylight conditions and in low to medium speed limit roads. The crash environment in cases where workers are present does not significantly differ from that of where workers are not present except for day of week and time of day which most likely reflect the effect of actual work hours and times when workers are present in the work zone. No significant difference is noted for weather conditions – work zone crashes follow the same pattern as non-work zonenon-work zone crashes. Distraction is significantly under reported in Michigan crash reports with no data for 2015 and the reporting variable changing in 2016, so any result involving distraction should be treated with caution. However, even with underreporting, the proportion of work zone crashes involving distracted drivers is twice as high as non-work zonenon-work zone crashes involving distracted drivers. Similar ratios are observed for work zone crashes involving driver drinking as compared to nonwork zone crashes involving driver drinking.

3.2 Multivariate Models for Work zone Crashes vs Nonwork zone Crashes

In this part of the chapter we try to make causal inferences for work zone crashes, i.e., we explore factors that may contribute to crashes being in work zones. The first step is to set up an experimental design that can help us determine the relationship between crashes and its causal factor, which we set as presence of work zone. However, it should be noted that since this a natural experiment and a retrospective study, we cannot directly control for other confounding factors which may bias the estimated effect of work zone on crashes – for example, speed limit may have influence on crash risk in general and if not controlled, will inflate the effect of work zones on high speed limit roads and deflate the same for low speed limit roads. Multivariate analysis enables us to capture the relation between such different variables simultaneously in a retrospective study. Multivariate analysis is used both for multiple outcome (or event of interest) experiments as well as for cases where there are multiple factors that are hypothesized to have simultaneously influenced the outcome or event of interest. In this study, our event of interest or outcome is traffic crashes while presence of work zone is the exposure that might have caused the crash. However, roadway environment, driver attribute and other external factors are also hypothesized to influence that outcome. Multivariate analysis is particularly useful in cases like this when randomized experiments cannot be conducted in a controlled laboratory environment to control for factors other than exposure. Multivariate analysis provides an ability to control for the effects of different variables and isolate the causal effect of any one of them. However, that still does not address the issue where such confounding factors may be associated with the exposure itself i.e., when presence of work zone is associated with high speed limits. To address that, we use a matched case control analysis which is explained in detail in the methodology section below.

It should, however, be noted that causal inference is highly debated for retrospective studies – retrospective case control studies can only infer about cause-effect association and not about cause-effect relationship i.e., from this analysis, we can only infer that some factors are associated with higher risk of crashes in work zones but we cannot infer that some factor causes work zone crash.

3.2.1 Methodology

The crash analysis method used here is similar to that of Harb et al. (2008) which is again from that used by Abdel-Aty et al. (2004). We use a retrospective matched case-control approach in the analysis which means we compare work zone crashes (cases) with non-work zone crashes (controls) based on data from crashes that have already happened (retrospective). The matching helps in controlling for confounding factors – for example, if we hypothesize that there is an association between number of lanes and presence of work zone and/or between number of lanes and crash propensity, then cases (work zone crashes) are matched with controls (non-work zone crashes) with respect to that factor (number of lanes) and comparisons between case and control are done within groups. Matching can be either on factors hypothesized to influence outcome only (Mantel and Haenzel, 1960), on factors that can possibly influence both outcome and exposure (Miettinen 1960) and sometimes on factors that can influence only exposure.
When cases and controls are matched, analysis must be done using conditional logistic regression, rather than standard logistic regression. The analysis "conditions on," or accounts for the fact that specific work zone and non-work zone crashes are grouped together (matched) in the same stratum. The intercept in the model accounts for the number of crashes in the different strata, and the analysis is essentially asking the question "how do these variables distinguish work zone from non-work zone crashes that are in the same stratum"? Variables that increase the probability that a crash is a work zone crash are thus related to *increased* risk of crashing in a work zone compared to other situations. The analysis addresses these risk factors across strata, so the results are general. We separate the crashes by single vehicle and two vehicle crashes and for two vehicle crashes, we use only the at-fault drivers defined by citation in a rear end crash. Crashes are stratified by speed limit and number of lanes with each stratum being a combination of speed limit and number of lanes value (e.g., 40mph speed limit and 3 lane road stratum). Within any particular combination of speed limit- number of lanes stratum, the crash risk for that combination of speed limit and number of lanes is same both work zone and non-work zone crashes.

3.2.2 Findings

Table 4 presents the parameter estimates for the conditional logistic model for single vehicle crashes and Table 5 presents the point estimates for the same model. Table 6 presents the parameter estimates for the two-vehicle model and Table 7 presents the point estimates for that model.

Table 4. Model 1: Conditional Logistic Regression Model for Single Vehicle Crashes

Variables	Estimate	Standard Error	Wald Chi-square	Pr > ChiSq
Dawn/Dusk	-0.3985	0.1164	11.7196	0.0006
Dark Lighted	-0.1807	0.086	4.4148	0.0356
Dark Unlighted	-0.4959	0.0662	56.1914	<.0001
Cloudy	-0.412	0.0689	35.7942	<.0001
Other	-0.8597	0.0731	138.1238	<.0001
Drinking	0.4876	0.1127	18.709	<.0001
Distracted	0.3343	0.1885	3.1444	0.0762
65+	0.0777	0.0976	0.6346	0.4257
<25	-0.1166	0.0641	3.313	0.0687
Trucks	0.435	0.1046	17.308	<.0001

Table 5. Point Estimates for Model 1

Effect	Point Estimate	95% Wald Confidence Limits	
Dawn/Dusk vs. Daylight	0.671	0.534	0.843
Dark Lighted vs. Daylight	0.835	0.705	0.988
Dark Unlighted vs. Daylight	0.609	0.535	0.693
Cloudy vs. Clear	0.662	0.579	0.758
Other vs. Clear	0.423	0.367	0.489
Drinking vs. Not	1.628	1.306	2.031
Distracted vs. Not	1.397	0.965	2.022
65+ vs. 26-64	1.081	0.893	1.309
<25 vs. 26-64	0.89	0.785	1.009
Trucks vs. Passenger Car	1.545	1.259	1.896

Table 6. Model 2: Conditional Logistic Regression Model for Two Vehicle Crashes

Variables	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Dawn/Dusk	1	-0.3376	0.1227	7.5754	0.0059
Dark Lighted	1	-0.2847	0.0779	13.3701	0.0003
Dark Unlighted	1	-0.0529	0.0962	0.3028	0.5821
Cloudy	1	-0.2504	0.0515	23.6141	<.0001
Other	1	-0.7656	0.0739	107.2802	<.0001
Drinking	1	0.3608	0.1414	6.5149	0.0107
Distracted	1	0.3729	0.0863	18.6904	<.0001
65+	1	0.2301	0.0735	9.813	0.0017
<25	1	-0.0516	0.0475	1.1808	0.2772
Trucks	1	0.3572	0.0964	13.7297	0.0002

Table 7. Point Estimates for Model 1

Effect	Point Estimate	95% Wald Confidence Limits	
Dawn/Dusk vs. Daylight	0.713	0.561	0.907
Dark Lighted vs. Daylight	0.752	0.646	0.876
Dark Unlighted vs. Daylight	0.948	0.786	1.145
Cloudy vs. Clear	0.778	0.704	0.861
Other vs. Clear	0.465	0.402	0.538
Drinking vs. Not	1.434	1.087	1.892
Distracted vs. Not	1.452	1.226	1.719
65+ vs. 26-64	1.259	1.09	1.454
<25 vs. 26-64	0.95	0.865	1.042
Trucks vs. Passenger Car	1.429	1.183	1.727

3.2.3 Discussion

The variables considered in the models are light conditions (daylight, dawn/dusk, dark lighted and dark lighted), weather conditions (clear, cloudy, other), driver drinking (no, yes), driver distracted (no, yes), age (<25, 25-64, 65+), vehicle type (passenger car and truck). For the light conditions, daylight is the base category and a negative co-efficient for other categories indicate that as compared to daylight, the risk of a work zone crash is less in those light conditions. From model 1, for single vehicle crashes, all light conditions are significant at 0.05 level and daylight has the highest risk of a crash being a work zone crash as compared to other light conditions. However, when stratification on speed limits is removed, on roads with speed limit between 25 mph and 40 mph, dark lighted conditions are found to have positive co-efficients indicating higher risk of a crash being a work zone crash than daylight. The higher risk of work zone crashes during daylight may be explained by drivers being more attentive and cautious in work zones during poor light conditions. The higher risk for dark lighted condition for speed limits 25-40mph likely indicate urban arterial situations and possible congestion/merging related crashes.

Similar to light conditions, weather conditions also indicate that the risk of work zone crashes are more in clear weather than cloudy or any other weather type and that weather is a significant factor for work zone crash risk. This result agrees with literature and the commonly inferred reason is drivers being more cautious during bad weathers and also less prevalence of work zones during snow and/or heavy rain seasons.

Driver drinking is also found to be a significant factor for work zone crash risk with driver drinking having much more risk of a crash being a work zone crash as compared to driver not drinking cases. It may reflect drunk drivers' reduced ability to handle complexity in driving or anything unexpected (e.g., slowed traffic ahead). Distraction and age is not significant but is kept in the model for understanding their effects on work zone crash risk based on literature. Distraction shows a higher crash risk as compared to non-distracted drivers while drivers in the age group of 65+ are also at higher risk of work zone crashes than drivers in other age groups. Drivers in the age group of <25 are however, at less risk of work zone crashes.

Model results from two vehicle crashes follow the same pattern as the single vehicle crashes, except for driver drinking and distraction variables. Driver drinking loses its significance in the two-vehicle model while distraction becomes significant, both still being at higher probability of work zone crashes.

From the point estimates (Table 5 and Table 7), for single vehicles, driver drinking increases the probability of being a work zone crash by 60% and driver distracted increases the probability by 30% while for two-vehicle crashes, driver distracted and driver drinking both increase the probability of being in a work zone crash by 45%. Being in the age group of above 65 years also increases the probability of wokrzone crashes – by 8% for single vehicle crashes and by 25% for two-vehicle crashes. Trucks are also more likely to be involved in work zone crashes as compared to passenger cars – by about 54% for single vehicle crashes and by about 42% for two-vehicle crashes.

It should be noted that there will be other situations under which work zone crashes are more likely that will not show up as factors in this analysis - the stratification eliminates those effects. Also, any variable that changes overall risk but does so in the same way for work zone and non-work zone will not be identified as a factor here, even though it can have a big effect on risk for work zone crashes, per se.

3.3 Work zones and Driver Speeding Behavior

As mentioned before, in this part, we look at the speed related behavior of drivers in work zones and compare that with non-work zone passes. We also compare speed and speed variability for different work zone conditions to understand any influence of such conditions on driver behavior. Although the initial plan was to identify work zone crash and near crash events from naturalistic driving data, work zones identified from in-house Safety Pilot Data and matched with MDOT list of active work zones did not show any crash or near crash events and were mostly under freeflow conditions. Therefore, the only analysis option was to look at general characteristics of work zone and non-work zone driving. In particular, we looked at mean speed and speed variability for different work zone conditions as well as for work zone and nonwork zone passes from the same road segments.

3.3.1 Methodology

The datasets available to UMTRI contain large samples of naturalistic driving data from a sample of over 3000 vehicles that have been driving in the Ann Arbor area for over two years (Safety Pilot Model Deployment, or SPMD). A subset of that data involving 120 drivers contains trip video data, which provides the opportunity to identify work zone environments in addition the trajectory data already available for all vehicles part of Safety Pilot Deployment Project. Initially, a list of active work zones during 2015-2016 has been obtained from MDOT. First, a buffer is created around each work zone location from that list and any Safety Pilot trips that have trajectory points within any of the work zone buffer areas and have timestamps within the work zone active period, are selected. Because of possible geocoding errors and also because of the unreliability of work zone active time data, only 78 matches are found. Of these 78 matches only 38 has video data and hence are useful for this part of the analysis.

At the second stage, trips through the work zone location when the work zone is not active are identified. For that, the SPMD database is queried for all trips that pass through the buffer zone and are within a month of the time of the work zone trip. On selected trips, a more precise matching is done by matching them with the work zone trip road segment-wise for a 1 mile stretch before the work zone start point and after the work zone end point. Special considerations are given to maintain sufficient variation in the matched trips with respect to different conditions of interest, like day and night trips through the same location etc.

The analysis is done in two parts: (i) we compare the speed and speed variability of work zone trips and non-work zone trips under different conditions. For example, to understand if work zone passes are different than non-work zone trips during night, we compare the speed and speed variability of each pass through the work zone during night time to the average speed and speed variability of non-work zone passes (baseline) during night and present the mean, max, median and minimum of all such calculated ratios. The higher or lower the ratio is than 1, the more different is the speeding behavior between work zone and non-work zone trips under similar external conditions. A higher value than 1 for speed ratios indicate that the speed of the work zone pass is higher than that of non-work zone passes through the same road segment. Likewise, speed ratios lower than 1 indicate average work zone speed to be lower than the corresponding non-work zone passes through the same road segment. A greater than 1 speed variability ratio indicate a greater variability in speeds through the work zones, indicating traffic situations that require the driver to accelerate or decelerate frequently while a less than 1 speed variability ratio indicate smooth flow of traffic through the work zones. The analysis is carried out for seven conditions: day, night, worker present and worker not present, traffic and freeflow conditions, and for different work zone treatment types; (ii) we also compare speed profiles of work zone passes before and after the work zone signage is visible (to the coder, which is estimated to be about the same time the driver sees the sign). For this analysis, speed profiles are plotted and time stamps marked on the profiles with dotted lines which indicate the point where the signage is seen and the work zone start and end points so that any changes in speed profiles can be detected visually.

3.3.2 Findings

Table 8A-8D and Figure 16A-16D show the ratio of work zone speed to the mean non-work zone speeds and the ratio of speed variability for work zones to mean speed variability for non-work zones, for traffic and free flow conditions, day and night passes, worker present and not present conditions and for different work zone treatments respectively. The first column of the tables shows the distribution of work zone passes in each category, the second column gives the ratio of speed for work zone pass to mean of non-work zone passes for each category and the third column gives the speed variance ratio for each category. For example, in Table 8A, 36 of the 38 work zone passes are in no traffic or free flow condition (note: no traffic is coded as where the vehicle under consideration did not have to decelerate or stop because of the preceding vehicle), 2 of the passes are through traffic conditions. The ratio of work zone pass speed for no traffic condition to mean non-work zone pass speeds for no traffic condition is given under Mean Ratio – we provide the mean, median, max and min for the 36 ratios thus calculated.

Since there are very few work zone passes through congestion, in night and with worker present, the variability ratio is often high in such cases, but the mean ratio is close to 1 for all mean of the speed ratios, indicating that there is no significant difference in driving behavior between work zone and non-work zones.

Figure 17 shows sample trajectories of the work zone pass and the trajectories of the matched non-work zone passes, as well as the speed profiles of the work zone pass in red and the speed profiles of the non-work zone passes in black. The blue line indicates the speed profile of the mean of the speeds of non-work zone passes.

Figure 18 shows sample (refer to Appendix B for other profiles) speed profile of work zone passes a mile before and a mile after the work zone start and end points. The start and end of work zones are marked with black dotted lines while the time point where roadside signages for work zones are noted in a dotted blue line. The speed traces are used to identify drivers' reaction to work zone signages and no significant differences are found.

Table 8A. Comparison of Work zone Speeds and Speed Variability to Mean Non-work zone Speeds and Speed Variability for Freeflow and With Traffic Condition

		Mean Ratio				Variance Ratio			
Traffic	Frequency	Avg.	Median	Min	Max	Avg.	Median	Min	Max
No	36	0.969	1.000	0.689	1.132	1.432	1.058	0.149	8.767
Yes	2	1.044	1.044	0.884	1.204	1.137	1.137	0.974	1.300

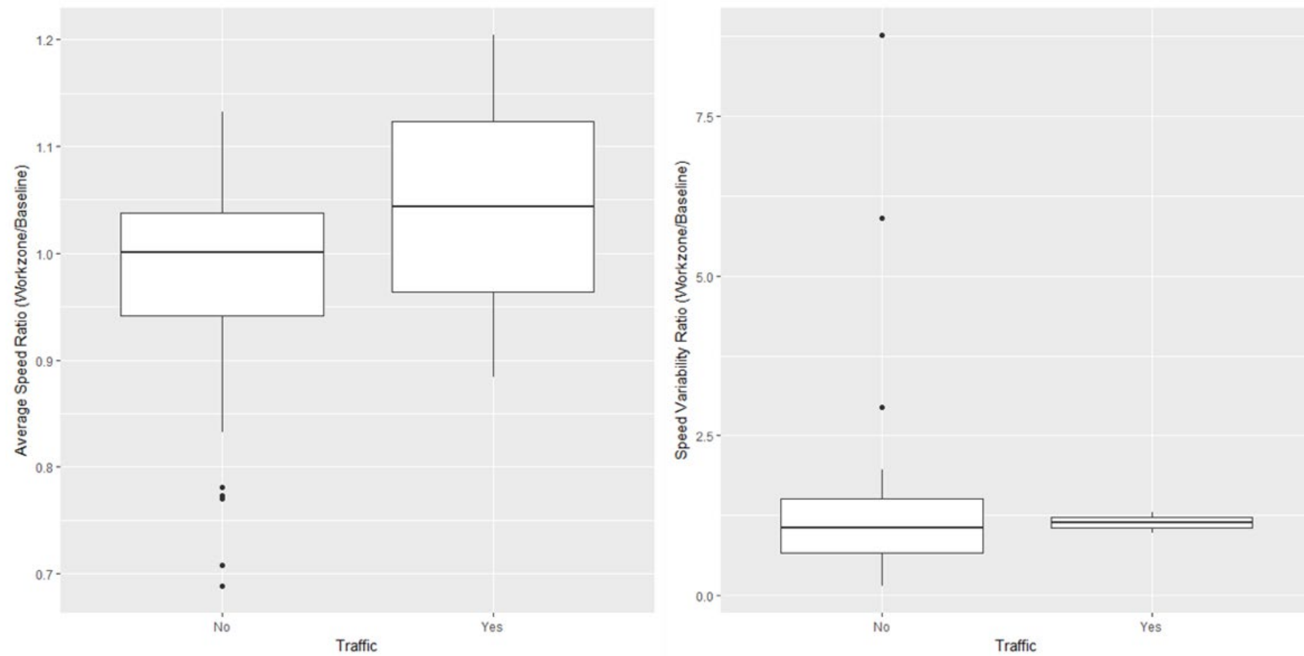


Figure 16A. Average Speed and Speed Variability Ratio for With and Without Traffic Passes through Work zones

Table 8B. Comparison of Work zone Speeds and Speed Variability to Mean Non-work zone Speeds and Speed Variability for Day and Night Condition

		Mean Ratio				Variance Ratio			
Time	Frequency	Avg.	Median	Min	Max	Avg.	Median	Min	Max
Day	34	0.975	1.000	0.689	1.204	1.515	1.080	0.294	8.767
Night	4	0.949	0.981	0.781	1.055	0.578	0.457	0.149	1.249

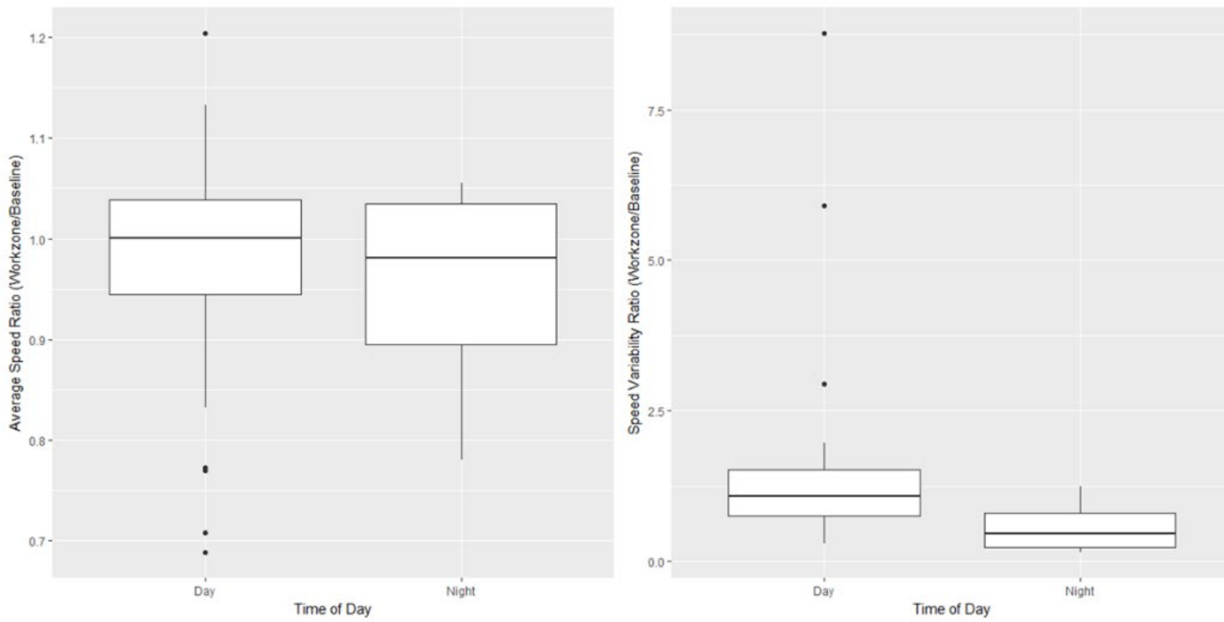


Figure 16B. Average Speed and Speed Variability Ratio for Day and Night Passes through Work zones

Table 8C. Comparison of Work zone Speeds and Speed Variability to Mean Non-work zone Speeds and Speed Variability for Worker Present and Not Present Condition

Worker		Mean Ratio				Variance Ratio			
Present	Frequency	Avg.	Median	Min	Max	Avg.	Median	Min	Max
No	36	0.983	1.001	0.708	1.204	1.224	1.058	0.149	5.906
Yes	2	0.786	0.786	0.689	0.884	4.871	4.871	0.974	8.767

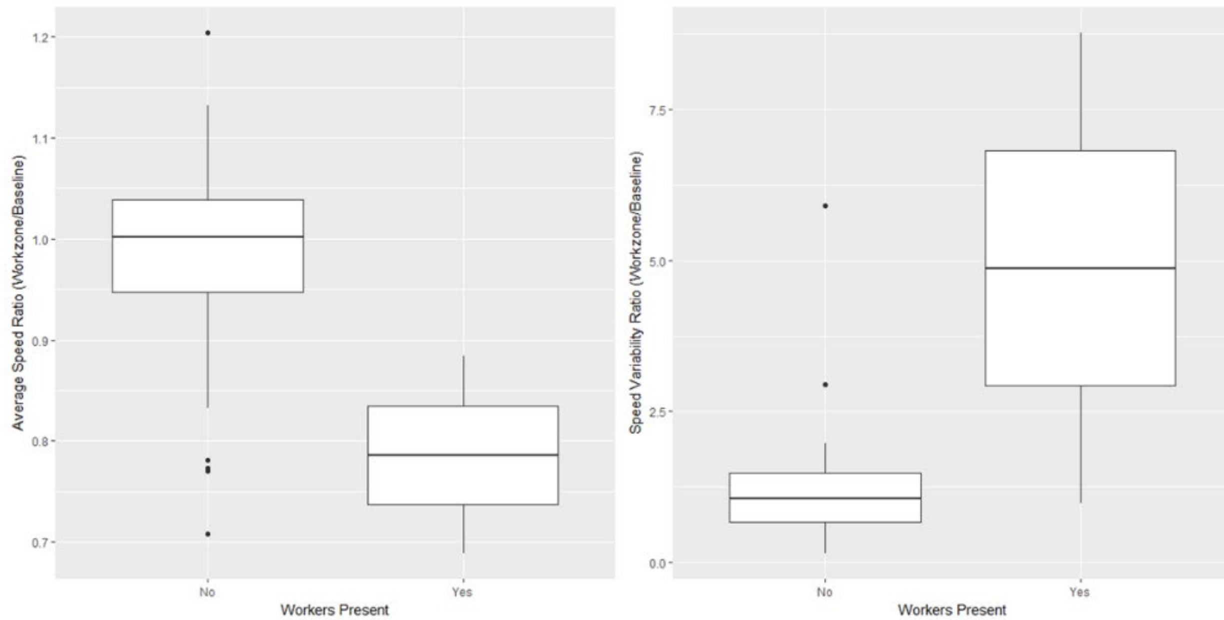


Figure 16C. Average Speed and Speed Variability Ratio for Worker Present and Worker Not Present Passes through Work zones

Table 8D. Comparison of Work zone Speeds and Speed Variability to Mean Non-work zone Speeds and Speed Variability for Different Work zone Treatments

		Mean Ratio				Variance Ratio			
Treatment	Frequency	Avg.	Median	Min	Max	Avg.	Median	Min	Max
Unknown	30	0.973	0.999	0.708	1.204	1.247	1.008	0.267	5.906
Barrels, Message board	1	1.055	1.055	1.055	1.055	0.149	0.149	0.149	0.149
Cones	3	0.979	0.999	0.901	1.037	1.147	1.075	0.588	1.778
Cones, Message board	2	0.851	0.851	0.689	1.013	4.888	4.888	1.009	8.767
Drums	1	1.076	1.076	1.076	1.076	1.409	1.409	1.409	1.409
Message board, Cones	1	1.002	1.002	1.002	1.002	1.647	1.647	1.647	1.647

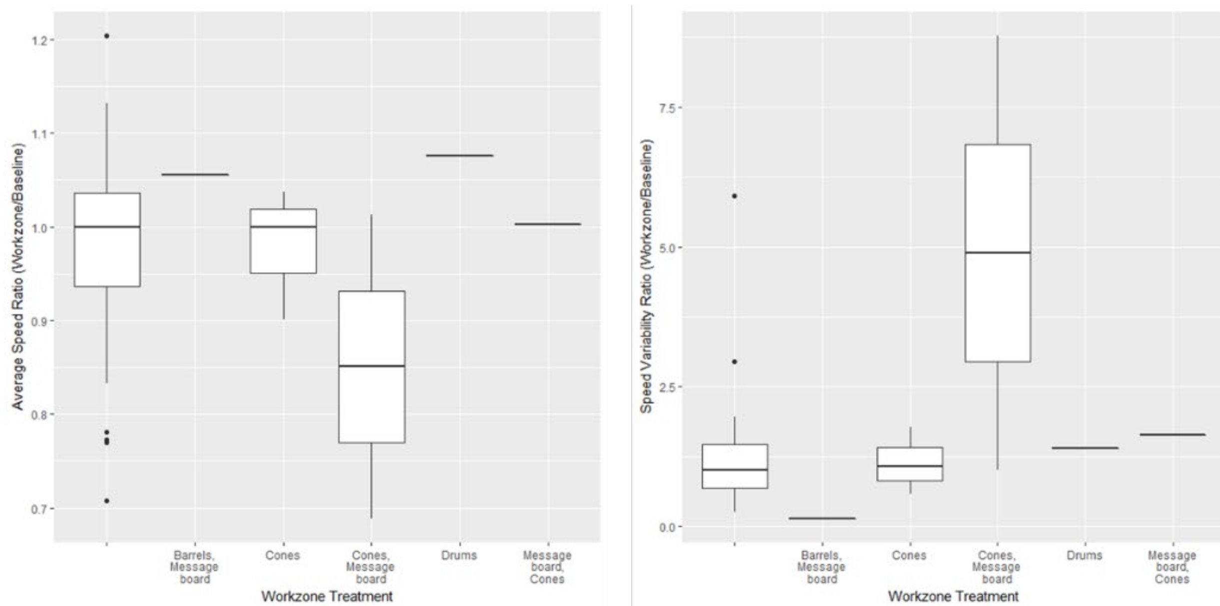
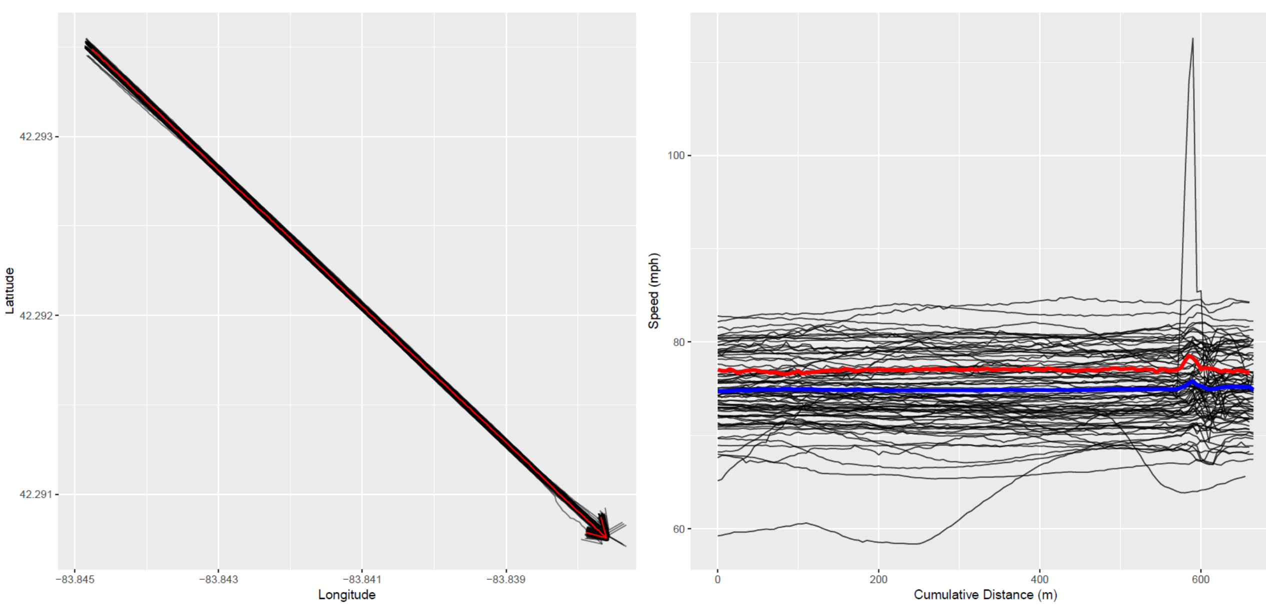


Figure 16D. Average Speed and Speed Variability Ratio for Different Work zone Treatments



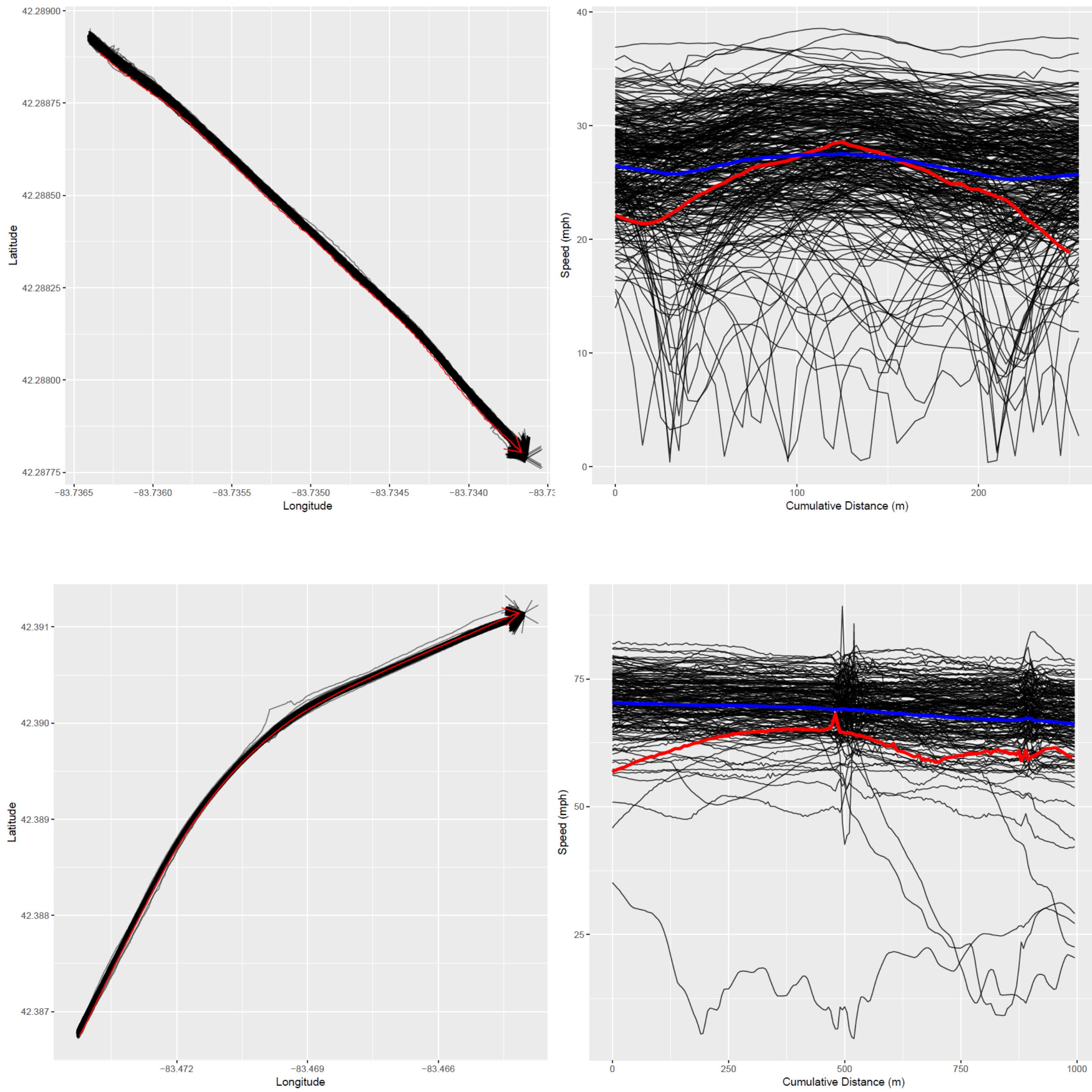
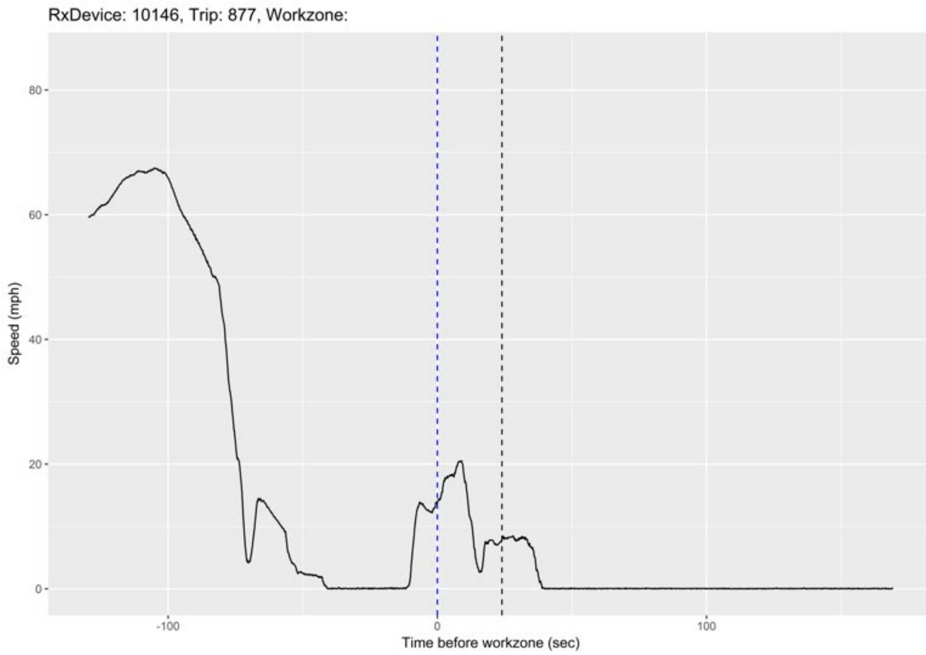
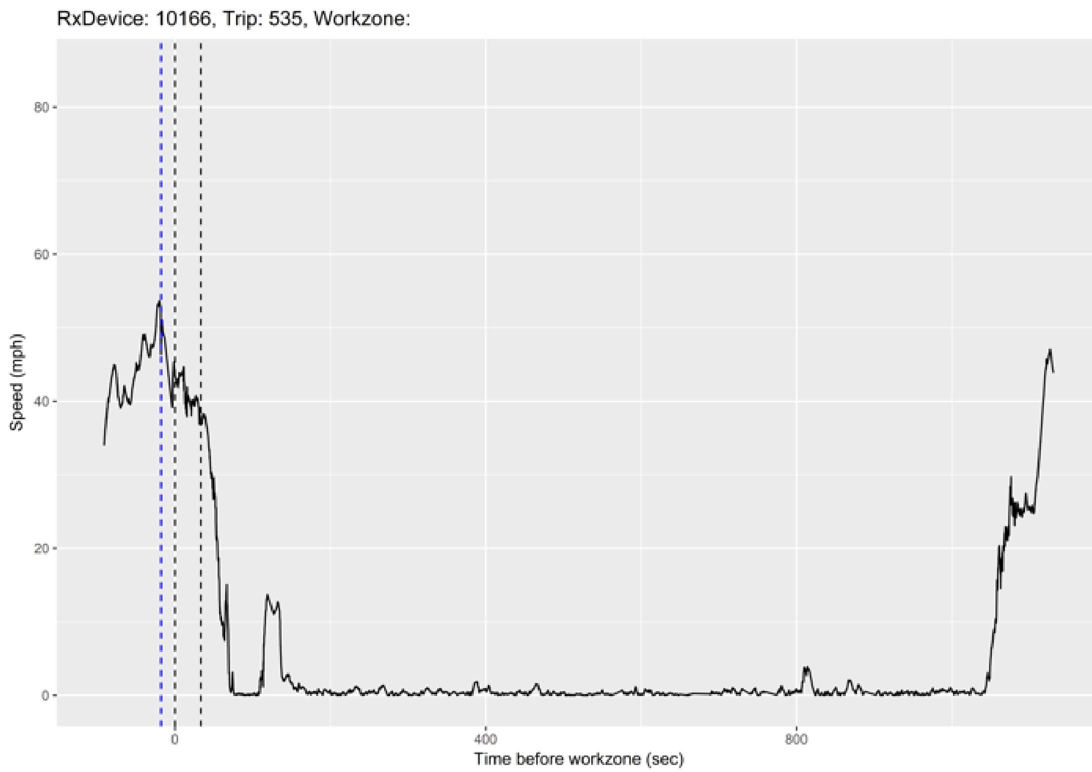


Figure 17. Sample Trajectory and Speed Traces of Work zone Passes and Non-work zone Passes through Same Road Segments


RxDevice: 10146, Trip: 877, Workzone:
Speed (mph)
Time before workzone (sec)
80
60
40
20
0
-100
0
100


RxDevice: 10166, Trip: 535, Workzone:
Speed (mph)
Time before workzone (sec)
80
60
40
20
0
0
400
800

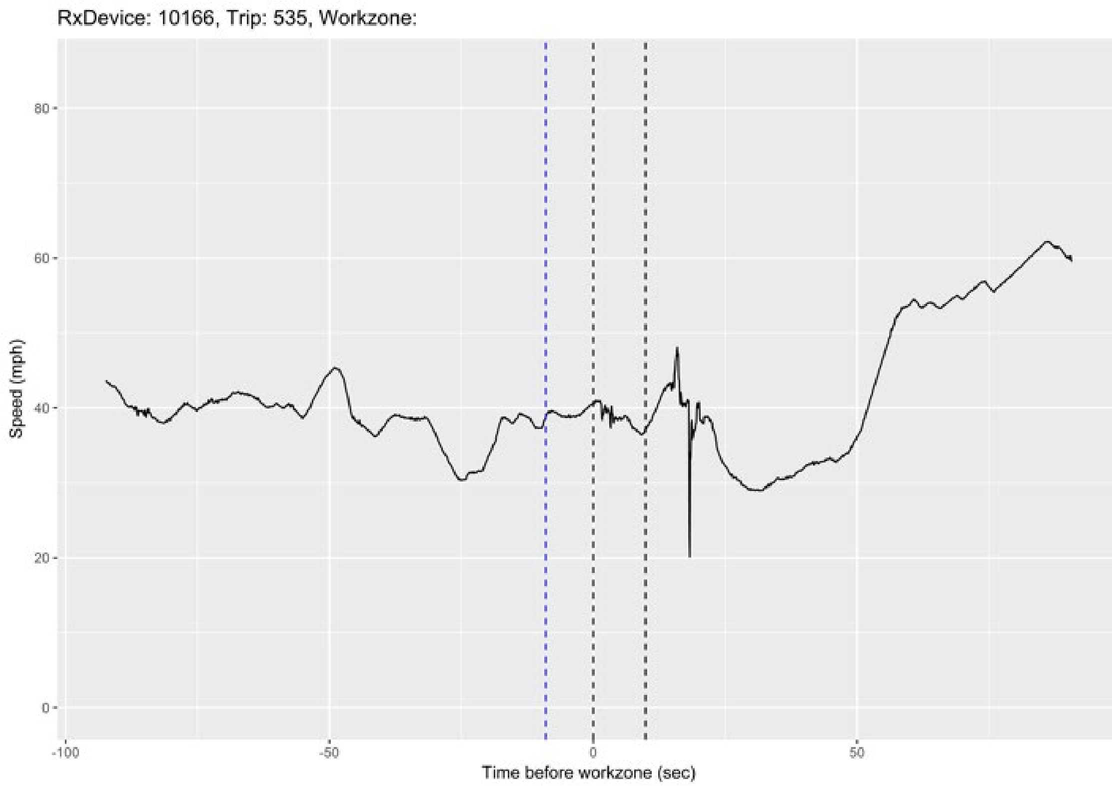


Figure 18. Sample Speed Profiles of Work zone Passes Before and After Signage

3.3.3 Discussion

There is no significant difference in the speed traces through the work zone vs the mean speed trace from passes through the same area with no work zone. Similarly, no significant difference is seen in driver behavior before and after work zone sign. Any changes, however small, are only recorded after the drivers are physically within the work zone or when they see workers present in the work zone. It should be noted though that none of our passes are through congestion or involve merging in traffic and are mostly represent free flow conditions in the freeway. Therefore, we cannot make conclusions about the behavior of the drivers under such situations. From our analysis of the available data, it appears that drivers do not react or slow down on seeing work zone signs, neither are their behaviors different than non-work zonenon-work zone conditions when there is a free flow situation. Combined with our previous crash analysis that points to driver distraction and drunk driving as over represented in work zone crashes and at higher risk of work zone crashes as well as drivers in general not reacting to work zone signage, it seems logical that in-vehicle alert systems should be more effective than roadside signages or messages in warning drivers of upcoming work zones and queue lengths .In the next chapter we discuss the benefits of different technologies related to providing in-vehicle messages.

CHAPTER 4. WORK ZONE AND CONNECTED VEHICLE TECHNOLOGY

4.1 Background

Based on the crash and naturalistic driving data analysis done in previous chapters, and from our literature review, we note that there is no evidence in our data that drivers respond to work zone signs or message boards, as measured by their speed variation, nor is there any conclusive evidence on the effectiveness of such measures for work zone speed management and control. On the other hand, distraction and drunk driving are found to be over represented in work zone related crashes, as are rear end and sideswipe crashes which can result from improper car following distance and merging. Therefore, any effective countermeasure should have the ability to (i) manage speeding by alerting a driver of an upcoming work zone, (ii) avoid rear end crashes by preemptively alerting the striking vehicle and (iii) avoid merging related crashes by alerting drivers of surrounding environment. In-vehicle warning/messaging systems can help the drivers by alerting them to upcoming work zones, surrounding traffic and to back of queues.

The recent advances in in-vehicle advanced safety systems (Forward Collision Warning, Lane Departure Warning, Blind Spot Warning etc.) address the surrounding traffic environment condition and provide in-vehicle alerts to the drivers but are not customized for work zone situations like merging or temporary traffic barriers. In addition, advanced safety systems are not mandatory in vehicles yet and often come at a higher price. An alternative and complementary system can be effected via vehicle connectivity – vehicle to vehicle (V2V) and/or vehicle to infrastructure (V2I) connectivity.

4.2 Methodology

Connected vehicle technology can be thought of as an assembly of three components – (i) sensing and communicating the vehicle's own location and position, (ii) sensing the position/location of other vehicles or objects and communicating/sharing that information with the environment and (iii) real-time in-vehicle alert/messaging. Of these, sensing of a vehicle's own location can be achieved by in-vehicle means (e.g., integrated sensors, smartphones or aftermarket devices) or by a roadside infrastructure equipped with sensing technology. However, sensing the location of other vehicles and objects requires either in-vehicle sensors or an infrastructure that can either sense vehicles within a buffer zone or receive such information from other vehicles and retransmit that information to vehicles that do not have sensing capability. Sharing the location information with the environment in both cases can only be done when there is connectivity either between vehicles or between vehicle and infrastructure that can then retransmit the information to other vehicles. In-vehicle messaging can be effected via basic safety messages (BSM), which requires vehicles to be able to receive such messages. Therefore, the scenarios under which the connected vehicle technology for in-vehicle alert systems might be implemented are:

1) All interacting vehicles are equipped with sensors and communication technology, and thus can communicate directly with each other.

2) Roadway infrastructure is equipped with communication and sensing technology and at least some interacting vehicles can receive and interpret (e.g., via an app) messages from the infrastructure.

4.3 Findings

If we consider only the contributions to effectiveness that are platform-independent, the effectiveness of countermeasures under the two alternative conditions becomes a function of the availability of relevant technologies and their adoption rates. For the first scenario, vehicle to vehicle communication (V2V), any two-vehicle interaction dependent on communication for safety countermeasures (as opposed to in-vehicle sensing per se) requires that both vehicles have the capability to send and receive relevant messages from each other. Thus, the probability that two vehicles in a situation will be equipped increases with the square of the market penetration. Early in the adoption phase, this probability, which determines the maximum *potential* effectiveness of a countermeasure, increases slowly. Thus, effectiveness will be initially slow to grow but will pick up over time.

On the other hand, scenario 2 depends on the ability to receive and interpret messages at the vehicle end while relying on sensing at the infrastructure end. In this scenario, the infrastructure-based sensing does not itself rely on the market penetration of applications in vehicles. The effectiveness of infrastructure-based messaging in the single-vehicle situation increases linearly with the market penetration of applications able to receive and interpret the messages. In two-vehicle conflicts, if either vehicle can address the conflict, then effectiveness will increase with the probability that *either* vehicle is equipped, which is initially faster than the rate of market penetration. For situations where only one vehicle can address the conflict, effectiveness will increase linearly with market penetration. These market-penetration-based effectiveness of these alternatives are illustrated in Figure 19.

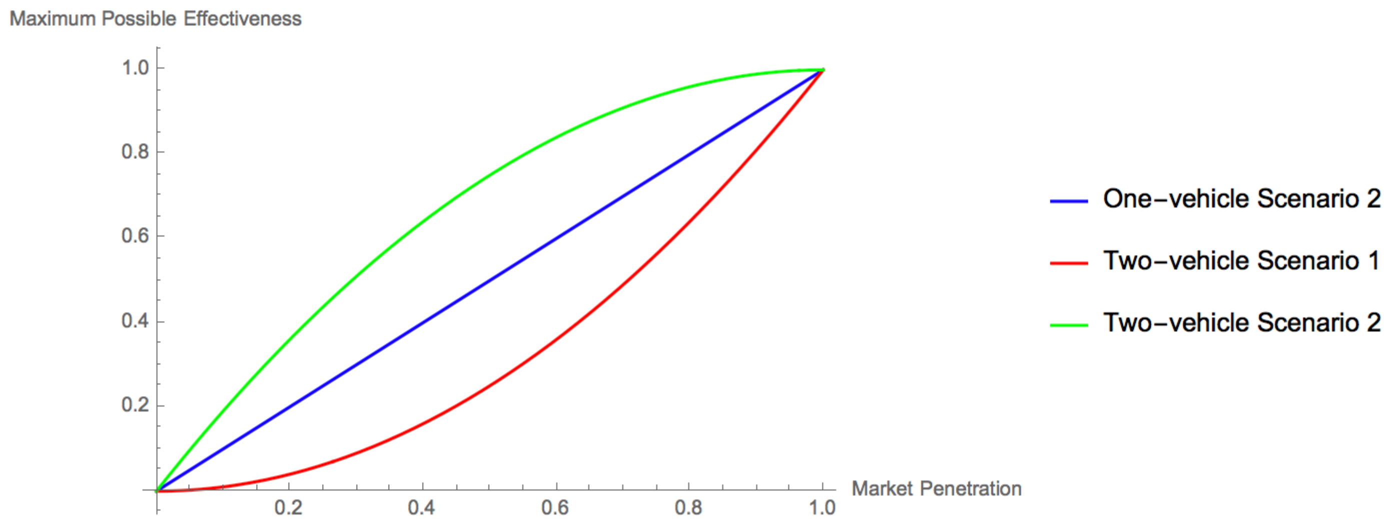


Figure 19. Maximum effectiveness as a function of market penetration for three crash type/technology scenarios. See text for details.

Another way of looking at the effectiveness of these alternatives is to assess the crashes they can help mitigate. Table 9 shows the work zone related conflicts and the applicability of the specific technologies in mitigating the conflicts. Crashes related to merging that can be avoided if either of the two vehicles in conflict has relevant information, can be addressed by having an infrastructure-based solution (Two-vehicle Scenario 2 in Figure 19). On the other hand, for crashes where either the lead or the following vehicle has to have the information in order to avoid conflict, the infrastructure-based solution can only be effective if that particular vehicle is able to receive and interpret messages (One-vehicle Scenario 2 in Figure 19). Vehicle-to-vehicle communications can only address conflicts when both the vehicles are equipped and connected, which reduces its effectiveness when fleet penetration is low (Two-vehicle Scenario 1 in Figure 19).

4.4 Discussion

Based on our analysis, a two-stage solution is suggested where at the first stage existing roadside infrastructure may be retrofitted with instruments to receive and transmit messages to vehicles with communication capability. At the second stage, applications may be developed and deployed that can communicate with the infrastructure. Infrastructure-based messaging system will help MDOT to tailor it according to their needs. In addition, receiving roadway information from vehicles in real time can prove useful for future planning and traffic management for MDOT.

Table 9. Effectiveness of Technologies in Avoiding Work zone Relevant Crashes

Vehicle 1 (striking)	Vehicle 2 (struck)	Scenario	Infrastructure	Smartphone Application	Avoid?
DSRC	DSRC	Rear-end	No	No	Yes
DSRC	No	Rear-end	No	No	No
No	DSRC	Rear-end	No	No	No
No	No	Rear-end	No	No	No
DSRC	DSRC	Rear-end	Yes	No	Yes
DSRC	No	Rear-end	Yes	No	Yes
No	DSRC	Rear-end	Yes	No	No
No	No	Rear-end	Yes	No	No
DSRC	DSRC	Rear-end	Yes	Yes	Yes
DSRC	No	Rear-end	Yes	Yes	Yes
No DSRC, But smartphone app	DSRC	Rear-end	Yes	Yes	Yes
No DSRC, But smartphone app	No DSRC, But smartphone app	Rear-end	Yes	Yes	Yes
No	No DSRC, But smartphone app	Rear-end	Yes	Yes	No
No	No	Rear-end	Yes	Yes	No
DSRC	DSRC	Merging	No	No	Yes
DSRC	No	Merging	No	No	No
No	DSRC	Merging	No	No	No
No	No	Merging	No	No	No
DSRC	DSRC	Merging	Yes	No	Yes
DSRC	No	Merging	Yes	No	Yes
No	DSRC	Merging	Yes	No	Yes
No	No	Merging	Yes	No	Yes
DSRC	DSRC	Merging	Yes	Yes	Yes
DSRC	No	Merging	Yes	Yes	Yes
No DSRC, But smartphone app	DSRC	Merging	Yes	Yes	Yes
No DSRC, But smartphone app	No DSRC, But smartphone app	Merging	Yes	Yes	Yes
No	No DSRC, But smartphone app	Merging	Yes	Yes	Yes
No	No	Merging	Yes	Yes	Yes

CHAPTER 5. CONCLUSIONS

As our infrastructure ages, work zones will become more frequent occurrences. At the same time, work zones provide a disruption to regular routine traffic conditions and flows, requiring real-time adjustment and adaptation from drivers of all ages and capabilities. Work zones are also conflict areas between work zone workers and vehicles passing through the work zones. Therefore, proper safety treatments are needed at work zones to avoid conflicts and crashes while minimizing the traffic disruption. An extensive literature review revealed a major focus in that direction to be speed control and speed management through variable and dynamic messaging and through enforcement. However, there is no consensus on the effectiveness of these measures.

This study aimed at identifying work zone countermeasures for Michigan crashes. We started with analysis of crash data and crash context information to better inform countermeasure selection process. Analysis of crash data revealed overrepresentation of rear end crashes, drunk and distracted driving being at higher work zone crash risk and a non-response of drivers to work zone signage. Based on the analysis results, in-vehicle information/alert/warning systems were identified as most likely to be effective and a potential-benefits analysis was done comparing infrastructure-based vs. vehicle-based communication for the purpose. Based on the findings, the study team recommends that MDOT consider an infrastructure-based communication system that can communicate with vehicles based on accepted technology platforms and communication protocols. This will allow MDOT to customize messages instead of standard BSMs.

Finally, the study suffered from a lack of sufficient work zone related naturalistic driving data such that work zone crashes and near crash events could not be identified or simulated. The study team plans to learn from another related federal highway project using SHRP2 data the relevant kinematic signals or models that can be used to flag work zones near crashes in the naturalistic driving dataset and apply that in future work zone related projects.

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Appendix A: Conditional Logit Formulation

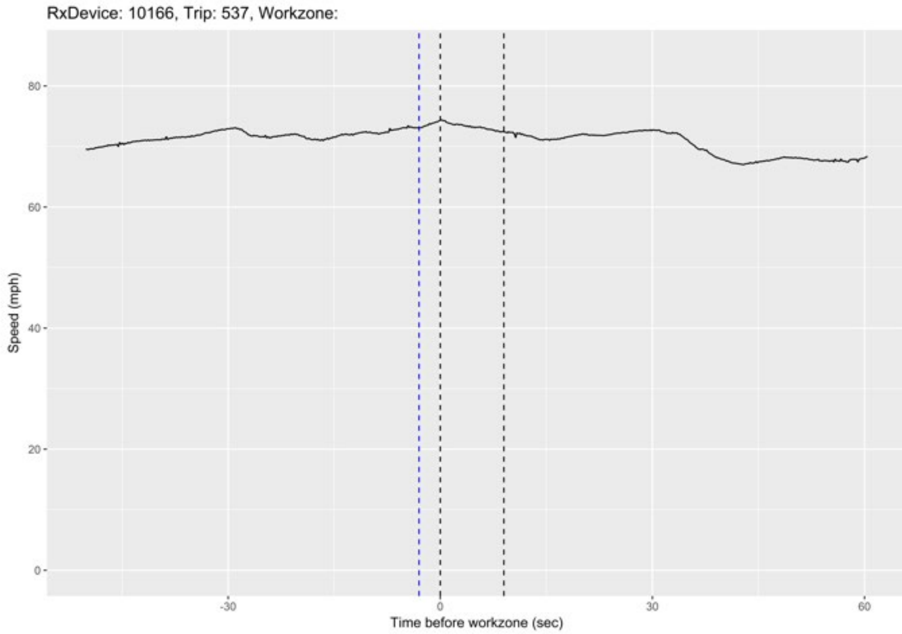
Mathematically, after Abdel-Aty et al. (2004) as found in Harb et al. (2006), assume there are N strata with n work zone crashes and m nonwork zone crashes in stratum $j, j = 1,2, \ldots., N$. Denoting the probability that the i^{th} observation in the j^{th} stratum is a crash is $p_j(x_{ij})$ where $x_{ij} = (x_{1ij}, x_{2ij}, \ldots x_{kij})$ is the vector of k causal factors, $i = 1,2, \ldots m + n - 1,\ j = 1, 2, \ldots N$. The probability of a crash being work zone crash as compared to being a non-work zone crash $p_j(x_{ij})$ can then be modeled using a linear logistic model as:

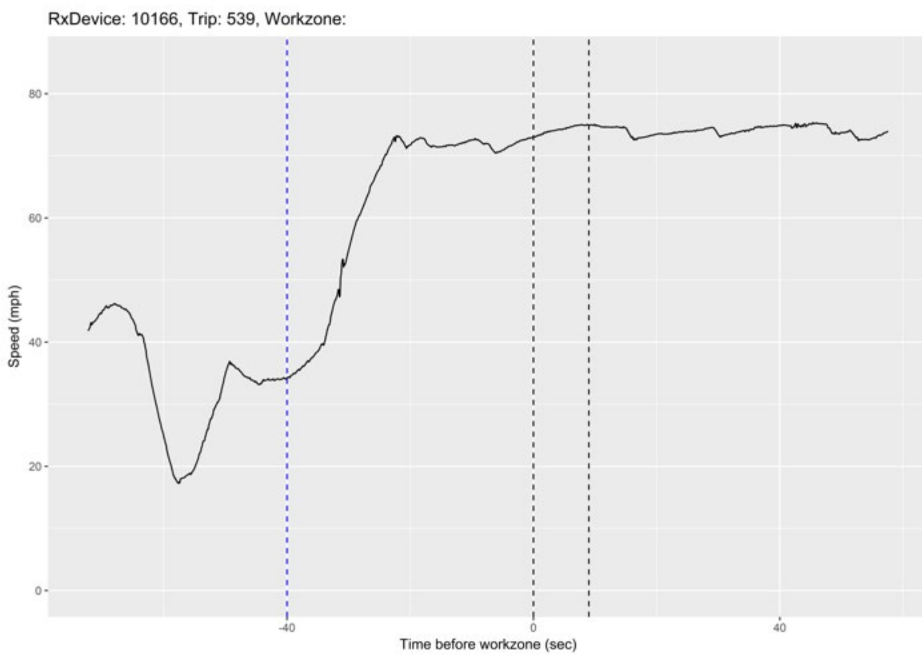
$$logit(p_j(x_{ij})) = \alpha_j + \beta_1 x_{1ij} + \beta_2 x_{2ij} + \cdots + \beta_k x_{kij}$$

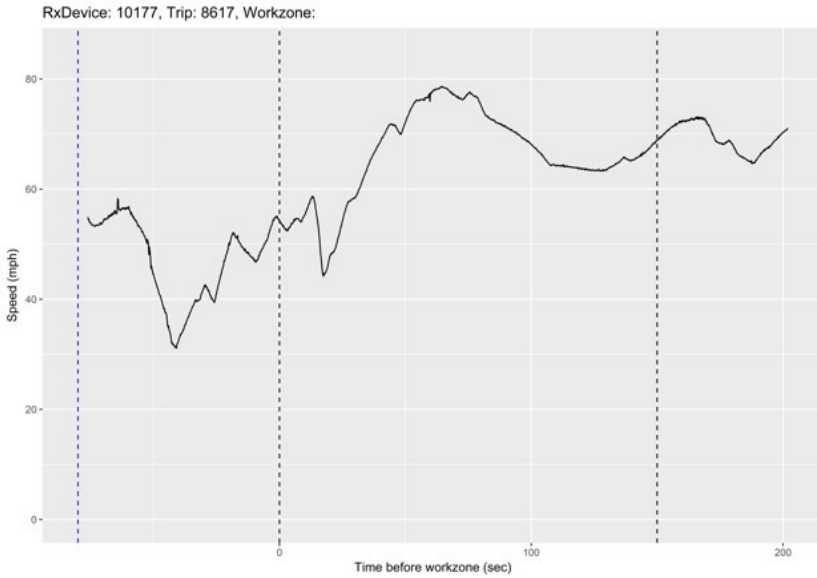
The intercept accounts for the effect of the matching variables on the crash probability and is hence different for different strata. The conditional likelihood function is given by:

$$L(\beta) = \prod_{j=1}^{N} \left[1 + \sum_{i=1}^{m} exp \left\{ \sum_{u=1}^{k} \beta_u \left(x_{uij} - x_{u0j} \right) \right\} \right]^{-1}$$

Appendix B: Speed Profiles of Work zone Passes Before and After Signage



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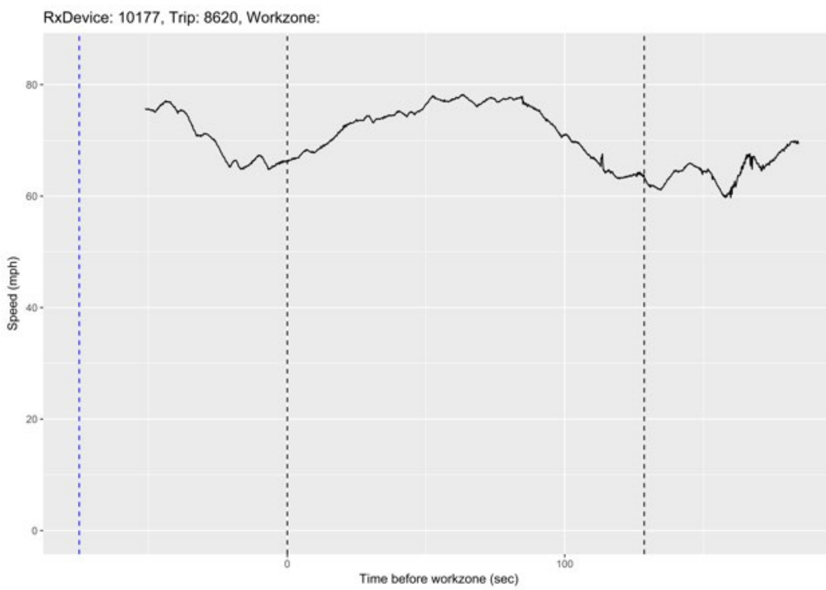
Speed (mph)
80
60
40
20
0
0
100
200
Time before workzone (sec)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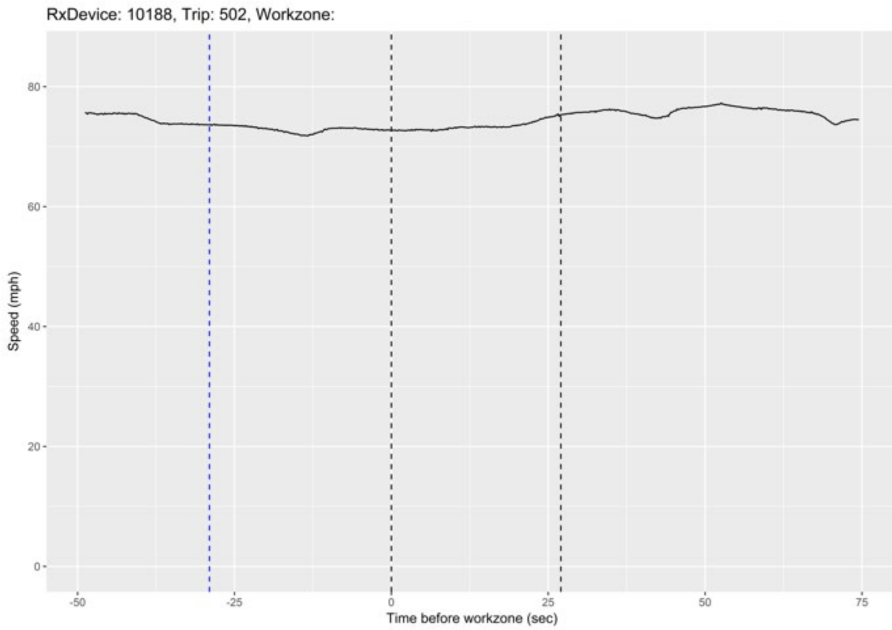
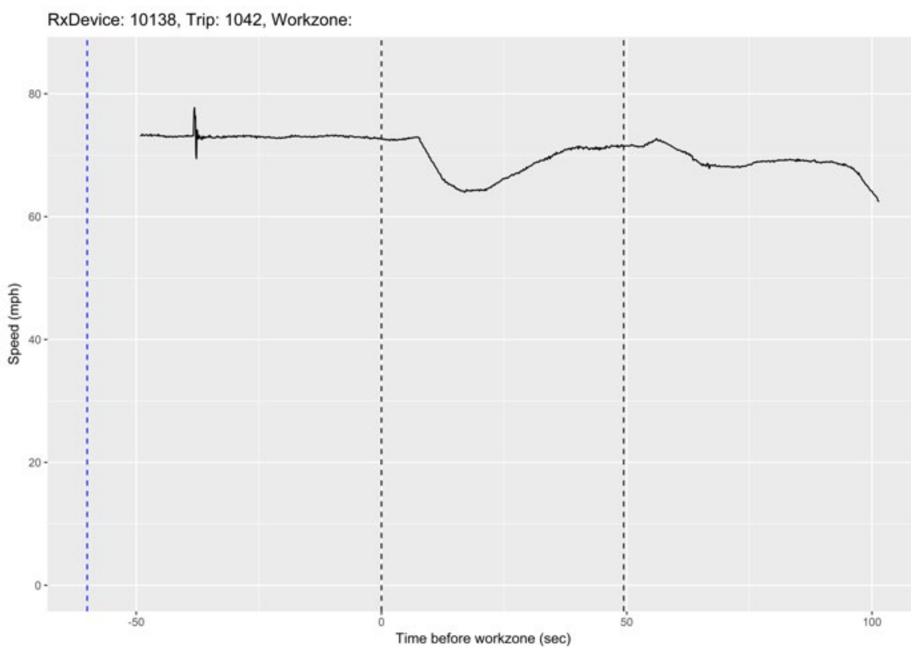
40
20
0
0
100
Time before workzone (sec)


RxDevice: 10188, Trip: 502, Workzone:
Speed (mph)
Time before workzone (sec)
80
60
40
20
0
-50
-25
0
25
50
75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Speed (mph)
Time before workzone (sec)
80
60
40
20
0
-50
0
50
100