Assessing Driver Behavior at Back of Queues: Implications for Queue Warning System in Work Zones

Final Report
Revised September 2020

SWZDI
Smart Work Zone Deployment Initiative

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Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

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16. Abstract

Rear-end crashes are one of the primary crash types in work zones and frequently occur at the back-of-queue (BOQ). Some agencies have utilized back-of-queue warning systems (QWSs), where real-time sensors are located upstream of stopped or slowed traffic, either to actually detect BOQs or monitor conditions to predict BOQ locations. QWSs then provide notifications of traffic conditions to drivers, which ideally lead to lower speeds and drivers being prepared to react to the BOQ, resulting in fewer crashes and conflicts. However, a driver needs to be properly monitoring the roadway environment to receive the warning and, then, needs to be prepared to take the appropriate actions when necessary. In many cases, drivers are distracted and fail to recognize warnings, or they receive the warning but fail to comply with appropriate speeds. As a result, one of the main needs to address BOQ situations is to understand what drivers are doing so that a QWS can get a driver's attention. Additionally, driver behavior may indicate that other countermeasures, such as speed management, may be as effective as formal QWSs. The research described in this report aims to address this knowledge gap through the following objectives:

- Identify common types of QWSs
- Summarize QWSs used in Smart Work Zone Deployment Initiative (SWZDI) states
- Identify driver behaviors in BOQ scenarios
- Make recommendations
- Summarize needs for connected vehicle applications

Safety critical events (SCEs) were evaluated for back-of-queue situations using two different datasets. The first was a set of BOQ SCEs that were reduced from camera image captures at BOQ locations in work zones in Iowa during the 2019 construction season. Analysis of these data indicated speeding, following too closely, and forced merges were the primary characteristics associated with BOQ. The second dataset was an analysis of BOQ events in the second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS). Analysis of these data indicated that following too closely and glances away from the roadway task of 1 or more seconds were statistically significant.

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The following sentence in the Overview and Executive Summary was corrected:

The main drawback for QWSs is that they may not be less effective for distracted or inattentive drivers who may not notice the queue warning system.

To read as follows:

The main drawback for QWSs is that they may be less effective for distracted or inattentive drivers who may not notice the queue warning system.

ASSESSING DRIVER BEHAVIOR AT BACK OF QUEUES: IMPLICATIONS FOR QUEUE WARNING SYSTEM FOR WORK ZONES

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OVERVIEW AND EXECUTIVE SUMMARY

In 2017, a total of 710 fatal work zone crashes occurred, and these crashes accounted for 1.7% of all roadway fatal crashes in the US (710 of 42,231). Additionally, 94,000 total crashes and 25,000 injury crashes occurred in work zones in 2017. Moreover, work zone fatalities on US roads increased by 3.2% from 2016 to 2017 (NWZSIC 2020). Work zone crashes are not only a problem for the traveling public, they are a serious concern for highway workers who are injured or killed by errant vehicles. A total of 132 work zone worker fatalities occurred in 2017 (NWZSIC 2020), and 60% of worker fatalities were a result of being struck by vehicles in the work zone (CDC 2020). Consequently, addressing work zone crashes is critical for both the traveling public and highway workers. Statistics are provided for 2017 since that is the most recent year for which all of the above reported statistics were consistently available.

Queue warning systems (QWSs) have been noted as effective, and the majority of QWSs provide a visual warning (e.g., message sign, flashing beacon) to drivers, which ideally helps them be prepared for congestion or queued traffic. However, a driver needs to be properly monitoring the roadway environment to receive the warning and, then, needs to be prepared to take the appropriate actions when necessary. This includes being alert and slowing to a manageable speed. In many cases, drivers are distracted and fail to recognize warnings. In other cases, drivers receive the warning but fail to comply with appropriate speeds. As a result, one of the main needs to address back-of-queue (BOQ) situations is to understand what drivers are doing so that QWSs can get a driver’s attention. Additionally, driver behavior may indicate that other countermeasures, such as speed management, may be as effective as formal QWSs.

The objectives of this research were as follows:

- Identify common types of QWSs
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- Make recommendations
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Contributing Factors to Rear-End Crashes from the Literature

Rear-end crashes are one of the predominant types of crashes in work zones with estimates ranging from 18% to 65%. A number of factors contributing to rear-end crashes have been noted. Location within the work zone was one factor. Weng and Meng (2011) found rear-end crashes were most likely to occur in the lane closest to the work area.

Other studies have noted that the majority of rear-end crashes are due to vehicles slowing or stopping due to the work zone activities or lane-changing behavior (Ullman et al. 2018) and congestion. One study noted a relationship between crashes and queues that were present for 5 minutes or longer (Mekker et al. 2020).

Mekker et al. (2020) also found 87% of fatal BOQ crashes occurred when congestion was present involved large trucks while they contributed to 39% of back-of-queue crashes during free flow conditions.

Aggressive behavior also has been linked to rear-end crash risk in work zones. One study showed tailgating (<2 second gap) accounted for 55% of rear-end crashes (Rakotonirainy et al. 2017). Another study indicated 24% of rear-end crashes in work zones were due to following too closely (Raub et al. 2001). Dissanayake and Akepati (2009) noted that 10% of all work zone crashes were due to following too closely. Forced merges were also noted as problematic (Ullman et al. 2001). Speeding was also noted as a factor in 52% of rear-end crashes by Raub et al. (2001). Dissanayake and Akepati (2009) reported 8% and Johnson (2015) reported 9% of all work zone crashes were due to speeding.

Raub et al. (2001) reported distractions accounted for 17% of rear-end work zone crashes and Johnson (2015) reported inattention/distraction was the main contributing factor for 13% of all severe work zone crashes.

Queue Warning Systems

In order to address BOQ crashes, many agencies have utilized QWSs. A QWS typically consists of sensors placed upstream of a work zone or other locations where queues are expected to form. Sensors are typically wirelessly linked to a central data processing unit along with one or more changeable message system (CMS) or portable message system (PMS). System logic assesses the status of the sensors and displays an appropriate queue warning message based on the distance of the sign to the nearest sensor that detects slowed or stopped traffic.

A number of commercial QWSs are available and are summarized in Chapter 2. QWSs used in the SWZDI states (Iowa, Wisconsin, Kansas, Illinois, and Nebraska) along with those used in several other states (Michigan, Texas, and Minnesota) are also summarized in Chapter 3.

Studies have indicated that QWSs are reasonably effective with a 22% to 66% reduction in crashes and up to a 66% reduction in incidents. QWSs have also been shown to be effective in reducing forced merges, erratic maneuvers, and speed variance.

The effectiveness of QWSs are summarized in Chapter 4. Queue warning systems vary but have generally been shown to be effective. A description of the studies on QWS effectiveness is summarized in Table 1.

Table 1. Summary of studies on the effectiveness of QWS

Study	Location	Configuration	Findings
Roelofs and Brookes 2014	San Diego, CA	Roadways surrounding shopping center	• Reduction in incidents of 66%
Hourdos et al. 2017	Minnesota	Interstate	• 22% decrease in crashes • 54% decrease in near-crashes
Pesti et al. 2008	Houston, TX	Interstate	• Decrease in speed variance • Sudden decrease in sudden braking • Forced lane changes decreased by 55% • Erratic maneuvers decreased by 2% to 3%
Ullman et al. 2018	Central Texas	Interstate	• Portable transverse rumble strips only • CMF = 0.89 for non-queuing scenarios • CMF = 0.34 (p = 0.23) for queues • QWS and PRS • CMF = 0.72 for non-queuing scenario • CMF = 0.47 for queues
WisDOT 2018	Manitowoc County, WI	Interstate	• 15% decrease in queue-related crashes • 63% decrease in injury crashes
Roelofs and Brookes 2014	Madison County, IL	Interstate	• 13.8% decrease in rear-end queueing type crashes

Analysis of Back-of-Queue Safety Critical Events

This current study analyzed BOQ safety critical events (SCEs) to further evaluate which driver behaviors contribute to back-of-queue incidents. Two different datasets were utilized.

The first was an observational study of back-of-queue behavior at work zones in Iowa during the 2019 construction season. Potential BOQs were monitored, and near-crashes or conflicts were manually coded. A total of 68 SCEs were recorded. Almost 40% of drivers who were engaged in a safety critical event (27 of 68 events) were traveling at a speed that was determined to be too fast for the conditions. Drivers involved in an SCE were more likely to be following closely (54%). Following closely was subjectively defined as less than 1 second between the subject vehicle and lead vehicle. Following was defined as approximately 2 seconds between vehicles and accounted for 36.8% of drivers involved in an SCE, and drivers who were not following made up 8.8% of SCEs. Additionally, in almost 9% of cases, a forced merge occurred, which contributed to the SCE. Similar to other studies, this analysis indicated speeding, following too closely, and forced merges were major contributors to safety critical events.

The second dataset was the Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS). The SHRP2 NDS collected vehicle (e.g., speed, acceleration, position), driver face, and over-the-shoulder video; a forward roadway video; and other data streams for naïve drivers in their own vehicles. A number of safety critical events (crashes, near-crashes, or conflicts) had been identified by Virginia Tech Transportation Institute (VTTI), and time series data and forward roadway videos were obtained. Additionally, the team had access to several thousand time series traces through work zones collected for a related project. BOQ events were also identified, and several additional conflicts were obtained through a review of that data. This resulted in 46 safety critical events and 283 normal events, which are used as controls. VTTI reduced glance location, distraction, and cell phone use for 6 seconds prior to and 6 seconds after the subject vehicle encountered a stopped or slowed lead vehicle. Type of work zone (i.e., lane closure), roadway type, and type of barrier present were reduced from the forward roadway video. Vehicle speeds (average, maximum, and standard deviation of speed) were extracted from the time series data for the 10 seconds prior to when the subject vehicle encountered a slowed or stopped lead vehicle. Following behavior in the queue was also noted.

A mixed-effect logistic regression model was developed with probability of a near-crash as the response variable. The best-fit model included glance behavior, following behavior, and average speed. The odds of being involved in a BOQ SCE is 3.8 times more likely if the driver was engaged in a glance away from the roadway task of 1 or more seconds ($p = 0.0147$). When a driver is following closely (<2 seconds), they are 2.91 times more likely to be involved in an SCE ($p = 0.0568$) than when not following. Drivers following another vehicle (within 2 to 3 seconds) are less likely to be involved in an SCE, but the result was not statistically significant ($p = 0.6003$). This value was provided since it was evaluated with the other conditions for following. The average speed of the subject driver was also significant. Drivers are more likely to be involved in an SCE at lower speeds than higher speeds. This is counterintuitive since in most cases, it is expected that higher speeds are related to BOQ crashes. In most cases, BOQ events occur under congested conditions when speeds are lower. Additionally, only the actual speed of subject vehicle could be determined. In most cases, work zone speed limit could not be determined. Consequently, whether the vehicle was speeding could not be determined. Additionally, the speed of prevailing vehicles could not be determined, so the condition of traveling at a speed too fast for the conditions similarly could not be identified. As a result, while speed was included in the model, speeding could not be determined.

Recommendations

QWSs have been demonstrated to be a reasonably effective monitor for speed. Studies have indicated QWSs reduce crashes from 22% to 66% and up to 66% for incidents. QWSs also have been shown to be effective in reducing forced merges, erratic maneuvers, and speed variance. They are also likely to be effective for tailgating if drivers have heightened awareness of the potential for BOQ situations.

The main drawback for QWSs is that they may be less effective for distracted or inattentive drivers who may not notice the queue warning system. This research evaluated factors associated with BOQ safety critical events in general. As noted, those factors included speeding, glances away from the roadway, following too closely, and forced merges.

QWSs are likely to be effective for speeding. Other countermeasures may also be effective when combined with QWSs. For instance, multiple studies have indicated dynamic speed feedback signs (DSFSs) are effective in reducing speeds.

QWSs are less likely to be effective for distracted drivers who may not be paying attention to work zone traffic control. One strategy to address both speeding and distracted drivers is the use of portable rumble strips, which have been shown to be effective in conjunction with QWSs. Portable rumble strips provide a tactile warning to drivers, which may be effective for distracted drivers. The drawback to portable rumble strips is that it may be difficult to pinpoint a distinct back-of-queue point to place the devices. Additionally, portable rumble strips may not be appropriate for all roadway types.

The models used to assess the SHRP2 data were not able to find a statistically significant relationship between cell phone use and safety critical events. However, a simplistic analysis of the data indicated drivers who were involved in SCEs were twice as likely to be engaged in some cell phone task. Additionally, glances away from the driving task of 1 or more seconds was found to be statistically significant. This included glances related to cell phone tasks (i.e., texting) as well as other distractions. As a result, the study found evidence to reinforce laws prohibiting cell phones in work zones.

Wayfinding applications (apps) may also provide another tool to address back-of-queue incidents. Several wayfinding apps have the potential to provide in-vehicle messaging to drivers, which could assist in alerting drivers about the upcoming presence of BOQs. Audible messages are available in these apps and may be particularly helpful for distracted and inattentive drivers who may not notice on-road messaging.

Recommendations for future research include the following:

- Further evaluate the effectiveness of DSFSs in conjunction with QWSs
- Identify other audible attenuator countermeasures that may target distracted drivers
- Develop Iowa-specific crash modification factors for QWSs

CHAPTER 1. BACKGROUND

Introduction

In 2017, a total of 710 fatal work zone crashes occurred, and these crashes accounted for 1.7% of all roadway fatal crashes in the US (710 of 42,231). Additionally, 94,000 total crashes and 25,000 injury crashes occurred in work zones in 2017. Moreover, work zone fatalities on US roads increased by 3.2% from 2016 to 2017 (NWZSIC 2019). Work zone crashes are not only a problem for the traveling public; they are a serious concern for highway workers who are injured or killed by errant vehicles. A total of 132 work zone worker fatalities occurred in 2017 (NWZSIC 2019), and 60% of worker fatalities were a result of being struck by vehicles in the work zone (CDC 2020). Consequently, addressing work zone crashes is critical for both the traveling public and highway workers. Statistics are provided for 2017 since that was the most recent year for which all of the above reported statistics were consistently available.

Types of Work Zone Crashes

Rear-end crashes have been noted as one of the predominant types of crashes in work zones. Nemeth and Migletz (1978) analyzed 151 construction-related incidents identified from crash reports and construction diaries for rural interstates in Ohio. Results showed that the most frequently occurring crashes were rear-end, single-vehicle, and fixed-object. A study by Garber and Zhao (2002) found that rear-end crashes were the predominant type of crash. Sisiopiku et al. (2015) conducted a simplistic analysis of work zone crashes in Alabama from 2008 to 2018. They found rear-end collisions accounted for 32% of work zone crashes followed by single-vehicle crashes, which made up 15%. Sideswipe crashes accounted for 8% of work zone crashes.

The Minnesota Department of Transportation (MnDOT) noted 29% of severe work zone and 51% of all work zone crashes were rear-end, followed by 21% of severe work zone crashes being right angle (Johnson 2015).

Li and Bai (2008) modeled work zone crash severity outcomes. They found head-on collisions were the main type of fatal crash type and rear-end collisions were the dominant injury accident type. Ullman et al. (2018) analyzed the National Motor Vehicle Crash Causation Survey (NMVCCS) and found 45.5% of freeway and interstate crashes were rear-end. They estimated 65% of freeway/intestate crashes were rear-end crashes, and the majority of those occurred at or near the back of queue (BOQ). In the same study, Ullman et al. (2018) conducted an in-depth evaluation of work zone crash narratives from the Virginia DOT crash database. They found 18.1% were rear-end, 15.1% were angle crashes, 18.8% were sideswipe same direction, and 66.2% were fixed-object run-off-road (ROR) crashes.

Dissanayake and Akepati (2009) evaluated characteristics of work zone crashes in Smart Work Zone Deployment Initiative (SWZDI) states (Iowa, Kansas, Missouri, Nebraska, and Wisconsin). A cross-classification method to find relationships between variables was used and indicated the following:

- 47.6% of crashes occurred within or adjacent to the work zone activity
- 5.5% occurred before work zone warning signs
- 14.9% occurred between advance warning sign and work area
- 17.4% occurred within the transition area for lane shifts
- 14.6% occurred in other areas

They also found 41.7% were read end, 15.0% were angle-side impact, and 10.8% were sideswipe same direction.

Contributing Factors for Rear-End Crashes

Several researchers have noted contributing factors to rear-end crashes. In many cases, they are a result of BOQ. Congestion was also noted as a primary cause along with forced merges, truck volumes, following too closely, and speeding.

Weng and Meng (2011) developed rear-end crash risk models to examine the relationship between rear-end crash risk in the activity area and its contributing factors. Model results indicated that rear-end crash risk at work zone activity areas increase with heavy vehicle percentage and lane traffic flow rate. They also found the lane closest to the work area was prone to higher rear-end crash risk. Additionally, they noted the expressway work zone activity area had much larger crash risk than arterial work zone activity area. Ullman et al. (2018) conducted an in-depth evaluation of work zone crash narratives from the Virginia DOT crash database. Almost 65% of rear-end crashes in work zones were due to slowing/stopping due to work zone presence; 12% were due to slowing/stopping for flagger, police office, or work zone traffic control; and almost 9% were due to changing lanes in work zone. The researchers also estimated that around 24% of all work zone crash types was due to stopping/slowing due to congestion.

Mekker et al. (2020) evaluated three years of crash and crowd-sourced probe vehicle data to assess the impact of queuing versus free flow conditions. They focused on BOQ crashes rather than just rear-end. They found commercial vehicles were involved in more than 87% of BOQ fatal crashes compared to 39% of all fatal crashes during free flow. They also found the congested crash rate was 24 times higher than the uncongested crash rate. Additionally, they reported that 90% of congestion-related crashes were for situations where queues were present for 5 minutes or longer.

A study by Rakotonirainy et al. (2017) investigated the relationship between rear-end crashes and unsafe following behavior in Queensland, Australia. They evaluated rear-end crashes in general rather than just work zone related. The researchers identified 10 rear-end crash hotspots using safety performance functions and the observed behaviors in those locations. They found tailgating (<2 second gap) occurred in 55.4% of observations.

Ullman et al. (2001) conducted an observational study of erratic maneuvers in six work zone locations in Texas where queueing was expected to be present. They reported around 2% of observed vehicles engaged in a forced merge and around 1% had a hard braking at one site. Hard braking and forced merge events occurred at other sites, but volumes were not reported so information could not be compared across sites.

Raub et al. (2001) analyzed patterns for 110 work zone crashes in Illinois. They reported rear-end collisions accounted for 56% of crashes in work zones, and within the work zone area they accounted for 64% of crashes. Officers were asked to comment on factors leading to the crash. Stopping or suddenly slowing was noted for 37% of work zone crashes. Following too closely was the second most cited factor (24%). Distractions in the work zone were noted for 17% of crashes. Drivers were cited with speed too fast for the conditions in 52% of the crashes.

Dissanayake and Akepati (2009) evaluated characteristics of work zone crashes in SWZDI states using a cross-classification method. They reported 1.2% exceeded the posted speed limit, 6.7% were driving too fast for the conditions, and 9.7% were following too closely (all crashes not just rear-end).

The MnDOT reported that the main contributing factors for severe work zone crashes were inattention/distraction (13%), failure to yield (13%), and illegal/unsafe speed (9%) (Johnson 2015).

Problem Statement and Objectives

Rear-end crashes are one of the primary crash types in work zones and frequently occur at the BOQ. In advance of the work zone, drivers are frequently traveling at high speeds, and when they unexpectantly encounter a queue, they have little time for evasive actions, which can lead to a rear-end or run-off-road crash. In other cases, stop-and-go congestion coupled with lack of attention can also result in drivers failing to account for a BOQ. Although rear-end crashes are usually lower severity crashes in other contexts, within a work zone, higher speeds frequently lead to more severe outcomes.

Some agencies have utilized back-of-queue warning systems (QWSs), where real-time sensors are located upstream of stopped or slowed traffic, either to actually detect BOQs or monitor conditions to predict BOQ locations. QWSs then provide notifications of traffic conditions to drivers, which ideally lead to lower speeds and drivers being prepared to react to the BOQ, resulting in fewer crashes and conflicts.

The majority of QWSs provide a visual warning (e.g., message sign, flashing beacon) to drivers, which ideally helps them be prepared for congestion or queued traffic. However, a driver needs to be properly monitoring the roadway environment in to receive the warning and, then, needs to be prepared to take the appropriate actions when necessary. This includes being alert and slowing to a manageable speed. In many cases, drivers are distracted and fail to recognize warnings. In other cases, drivers receive the warning but fail to comply with appropriate speeds. As a result, one of the main needs to address BOQ situations is to understand what drivers are doing so that a QWS can get a driver’s attention. Additionally, driver behavior may indicate that other countermeasures, such as speed management, may be as effective as formal QWSs.

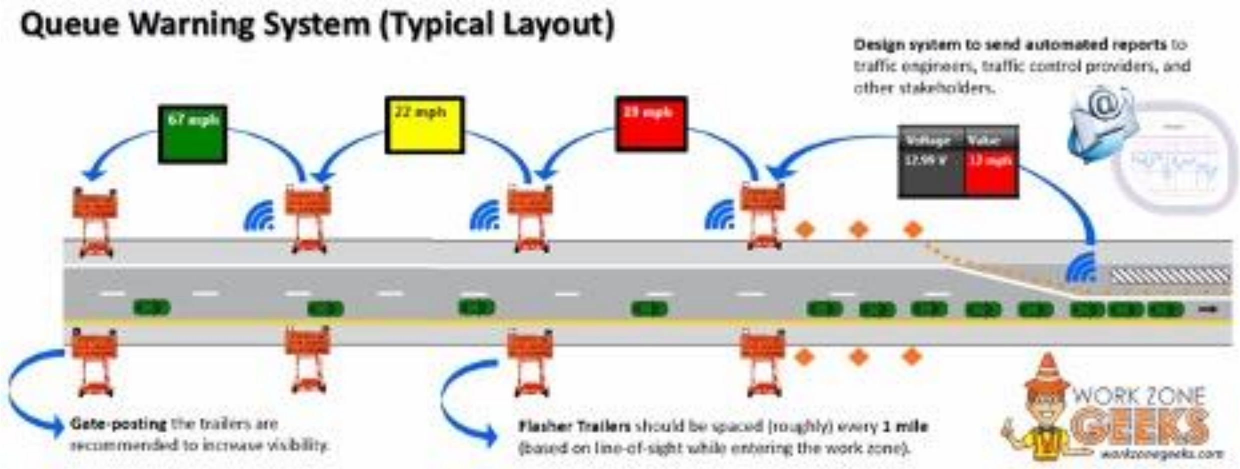
The research described in this report aims to address this knowledge gap through the following objectives:

- Identify common types of QWSs
- Summarize QWSs used in SWZDI states
- Identify driver behaviors in BOQ scenarios
- Make recommendations
- Summarize needs for connected vehicle applications

CHAPTER 2. QUEUE WARNING SYSTEMS

Description

QWSs are frequently used to address back-of-queue crashes. A QWS typically consists of sensors placed upstream of a work zone or other locations where queues are expected to form. Sensors are linked to a central data processing unit along with one or more changeable message system (CMS) or portable message system (PMS). System logic assesses the status of the sensors and displays an appropriate queue warning message based on the distance of the sign to the nearest sensor, which detects slowed or stopped traffic, typically based on speed. An example of a QWS is shown in Figure 1.



https://www.streetsmartrental.com/smart-work-zones/queue-warning-system/
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Figure 1. Typical QWS configuration

When more sensors are deployed, the system provides faster notification of changes to conditions and increases the accuracy of the data. More sensors also increase resources needed. Typically, sensors are spaced every half-mile in urban areas.

In some work zones, where queue lengths are known or predictable, static signs with flashing beacons also have been used.

Commercially Available QWSs

Several commercially available QWSs are available. The following sections offer a brief summary of each.

Site-Safe

Site-Safe has developed a Mobile Queue Warning Alert System (MQWAS) to help reduce the number and severity of secondary roadway crashes. The MQWAS provides notifications of major highway incidents and stopped or slowed traffic upstream of a work zone. The information can be provided to officials as well as the motoring public.

The system uses iCone radar technology to collect and monitor speed data. The information is transmitted to a network, and queues are determined using algorithms. Next, the network sends information to connected traffic control devices (TCDs) such as a portable changeable message sign (PCMS) or vehicle-mounted message board. The TCD relays credible messages, such as “Stopped Traffic” or “Slowed Traffic.” Alerts can also be sent via text or email (Site-Safe 2019).

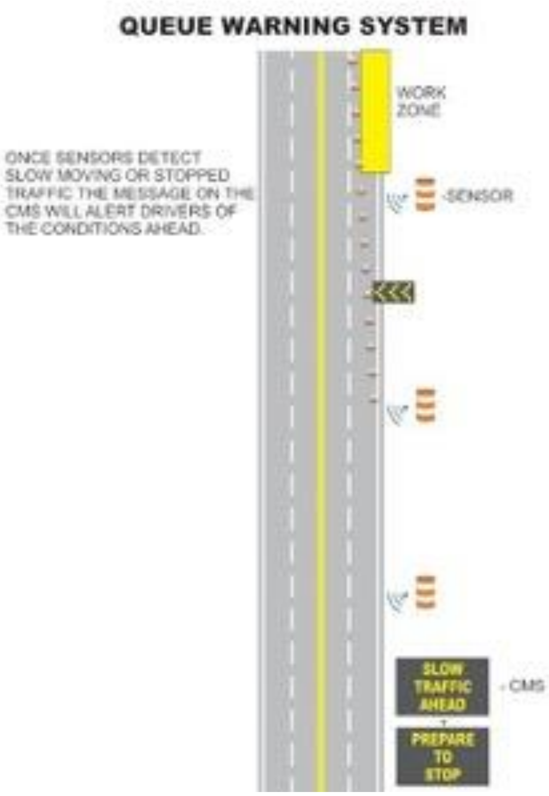
iCone

The iCone is a traffic monitoring system integrated into a conventional construction barrel. The system contains speed detectors, communication equipment, and a solar panel. The iCone is simple, portable, and work-ready. The system has Global Positioning System (GPS) tracking, speed monitoring, and web connectivity. When speeds drop below a defined threshold, the iCone can send an alert to construction personnel and traffic management centers (TMCs), which allows workers to identify and respond to crashes and incidents. Additionally, the system can communicate with variable message boards to remotely notify drivers of incidents with warning signs such as “Stopped Traffic Ahead.”

iCone provides web tools that allow traffic managers and other stakeholders to easily obtain real time and historical data. If desired by the agency, the iCone data also can be made available to the public, which could help in integration with existing traveler information tools. iCone has shown its ability to integrate with the navigation app Waze. Waze has designed a free, two-way data share of publicly available traffic information through the Connected Citizens Program, which promotes greater safety, efficiency, and deeper insights for travelers (iCone 2019).

Road-Tech Safety Services, Inc.

Road-Tech Safety Services has a QWS that uses sensors placed at specific intervals within the work zone. The system detects slow moving or stopped traffic and sends a message to a CMS. The systems reacts when traffic speeds drop below a user-defined level, and then the software triggers messages on PCMSs upstream, which gives drivers time to prepare. Road-Tech sensors are equipped with both cellular and satellite modems. The Road-Tech QWS includes real-time monitoring, customized reports, plan designs, and fine tuning the system in real-time. Road-Tech has the ability to immediately look up traffic conditions at a certain time, date, and GPS location. The Road-Tech system is shown in Figure 2.



https://www.road-tech.com/workzone-its

Figure 2. Road-Tech QWS

INRIX

Real-time INRIX XD speed data helps detect BOQ locations. The application is being used by the Indiana DOT’s operations center and Indiana State Police patrol cars to address queues. INRIX XD Monitoring provides real-time insights into traffic speeds, travel times, and the location of back-ups for every major road type and class from highways, ramps, and interchanges to arterials, city streets, and other secondary roads.

INRIX seems to offer speed data that can be used to analyze and identify time, location, and length of queues among traffic, although not necessarily QWS equipment placed within or around a work zone compared to other companies (INRIX 2019).

Street Smart

The Street Smart QWS uses traffic detection sensors to send an advanced warning to motorists by activating CMSs or flasher trailers. The Street Smart system monitors and reports queue warning information in real-time using automation software. Data is archived by the minute, allowing a user to analyze traffic impacts a specific work zone has and its effect on the driving public. Email and text alerts can also be sent based on traffic queuing conditions as well as other system issues (Street Smart 2019).

Street Smart’s QWS (Stopped Traffic Advisory System) informs drivers of the presence of downstream stop-and-go traffic (based on real-time traffic detection) using warning signs and flashing lights. Given the various types of sensors used, Street Smart can also determine different vehicle characteristics, including speed, volume, classification, gap, occupancy, and headway. CMSs show a symbol or word when stop-and-go traffic is near. The Street Smart system was shown previously in Figure 1.

Wavetronix

Wavetronix’s SmartSensor Advance has a large toolbox of channel, alert, and zone controls available to accommodate a wide variety of traffic control methodologies, which include queue length estimation, queue reduction, and queue calling. The system utilizes SmartSensor HD devices mounted on portable trailers in advance of work zone lane closures. Speed and volume data are analyzed, and if the data meet certain thresholds, it activates a PCMS located a few miles upstream of the work zone. The message notifies drivers that traffic ahead has slowed or is at a standstill. This allows drivers to make informed decisions and gives them more time to prepare to slow down (Wavetronix 2020).

The Wavetronix system is portable and easy to set up. The SmartSensor not only has a long-range detection capability, which makes it uniquely cost-effective for many queue detection applications, but it is classified as a continuous tracking advance detector (CTAD), which means that it continuously tracks the speed, position, and estimated time of arrival (ETA) of approaching vehicles.

Wanco

Wanco has a queue detection and warning system (QDWS), where real-time traffic sensors placed upstream of locations where stopped or slow traffic is expected. The system uses onboard GPS for tracking equipment, sensors, and an onboard processing system that can communicate real-time data. The system is configured to display on variable message signs (VMS) that are continuously available. The system also has a web-based platform. The system uses technology such as radar, Bluetooth, video cameras, and computer systems to monitor and communicate hazardous or unexpected driving conditions to roadway motorists (Wanco 2019).

Ver-Mac

Ver-Mac’s JamLogic software analyzes traffic data and provides real-time information. Ver-Mac’s JamLogic (queue detection system) collects data wirelessly via cameras, Doppler-based speed sensors, weather stations, Bluetooth, microwave volume sensors, and third-party data (such as Here and TomTom). The JamLogic software gathers data through a high-speed modem and then uses algorithms to analyze the data. Logic and messaging is determined by the agency. Once thresholds are met, the system provides real-time information to devices such as CMSs, public websites, or email/text alerts (Ver-Mac 2019).

Ver-Mac provides smart work zone technology and equipment of various features, one being automated queue warning (AQW). The AQW application is based on real-time traffic data that automatically informs travelers of the presence of downstream stop-and-go traffic with the use of message signs positioned upstream.

Ver-Mac also provides a portable QWS for quick daily lane closures or nighttime asphalt paving applications. The portable AQW uses a preprogrammed algorithm that instantly begins automating queue warning messages to PCMSs upstream. One advantage is that drivers are informed of non-recurring congestion, and the result is reduced rear-end collisions.

CHAPTER 3. QUEUE WARNING SYSTEMS IN SWZDI AND OTHER STATES

This chapter summarizes QWSs in the SWZDI states. Descriptions were found for a few other states in the Midwest, and those are included as well.

Iowa

Iowa uses two types of alerts to warn drivers. One is a QWS that posts messages to dynamic message signs (DMSs) for traffic approaching the work zone, and the other is a text alerting system that provides information to motorists about the time of congestion and duration of the event.

For the QWS, the Iowa DOT uses an alert processing system (APS) within the TransSuite Advanced Transportation Management System (ATMS). The system has been refined over the last couple years by the Iowa DOT for work zone queue alerts. If speeds drop below free flow traffic speed conditions, the upstream DMS will read "Slow Traffic Ahead," and if speeds drop even lower than the specified threshold, the message "Stopped Traffic Ahead" is displayed. Once speeds have recovered, "Traffic Delays Possible for up to 5 minutes" is displayed. This message can be slightly different depending on the situation. In addition to the threshold-driven automated DMS messages, a machine learning algorithm is used to send an alert to the traffic management center (Knickerbocker et al. 2019). After receiving an automatic alert, the operator can decide whether a message needs to be posted on the DMS or whether the current alert can be ignored.

The machine learning-driven dynamic alerts use vehicle speed and occupancy data streaming from multiple work zone sensors at a 20 second frequency. The raw data (Extensible Markup Language [XML] format) from Wavetronix sensors are first parsed (converted to comma-separated values [CSV] format), and then traffic, speed, and occupancy data are extracted. A wavelet filter is applied to de-noise the sensor data. The Iowa DOT decided to use four advisory speed classes to implement advised speed limits of 70 mph (no message), 55 mph, 45 mph, and 35 mph. Following this policy, the k-means clustering algorithm was applied to identify distinct groups in the data. Based on the preprocessed data with labels, a supervised learning algorithm decision tree was trained to find the underlying function (experts' engineering judgment) that mapped the new incoming sensor data (speed and occupancy) to a desired advised speed limit. Sensor readings always have inherent noise and a wavelet filter was applied to smooth the sensor data. Wavelet transform is based on the mother wavelet that enables changes in the property of data over time (Sifuzzaman et al. 2009). For the application of the dynamic alerts, real-time noise filtering is performed. Therefore, the data are treated as though they have been received in a streaming manner. The DMS employed a sliding window approach for data smoothing, where the sliding window applied a small subset of recent historical data (previous 20 minutes).

After smoothing the data, a clustering analysis is applied to assist in the development of the new DMS alert logic. Clustering analyses deal with unlabeled data, whereas supervised learning algorithms need labeled data, and it is expensive to obtain a labeled dataset. One approach to labeling data is to apply a clustering method to find reasonable clusters, assign labels based on the number of clusters, and then use these labeled data for subsequent supervised classification.

Similar to this concept, for this new DMS alert logic system, k-means clustering was applied to cluster unlabeled data into several groups, which could then be used to aid traffic engineers in assigning a specific DMS alert to each cluster. Based on the preprocessed dataset, a decision tree was used to replicate the engineering judgment, such that as sensor data streamed in, the improved DMS alert logic system automatically mapped the new data to a proper message and replicated the decision-making of a traffic engineer. The logic was based on different traffic conditions with four types of variable speed limits generated: Normal condition without display (70 mph), 55 mph advised, 45 mph advised, and 35 mph advised.

Wisconsin

The Wisconsin DOT's (WisDOT's) QWS efforts began in 2017 with its I-17 project. The selection criteria for QWS implementation included speed sensors and PCMS, lane closures, roadway location experiences frequent queues, and 1+ mile traffic backup.

WisDOT worked with the University of Wisconsin-Madison (UWM) on a QWS online tool that the UWM's Traffic Operations and Safety Laboratory created. This tool helps select where a QWS should be implemented by assessing the roadway geometry and crash history in the specified roadway area where the project is occurring. In tandem, WisDOT also utilizes the smart work zone manual.

WisDOT has worked with traffic control companies that provide equipment and devices to install a commercial QWS such as Ver-Mac, Street Smart, and Slander. These companies work with WisDOT based on the contract bid selection process.

Some advantages WisDOT noted after implementation were dynamic late merge features, drivers' satisfaction with travel time alerts from QWS, and the spacing distribution of devices within the work zone. Some disadvantages noticed after implementation were the site locations selected to implement the QWS and the type of projects limited the possibility of incorporating a QWS. WisDOT staff thinks it could be potentially helpful to explore research to convey information about construction activity concerning truck speed and occupancy vehicle threshold (Schoon 2019)

Kansas

Two examples of QWSs in Kansas were recorded. The first was in Wichita, during the first phase of the I-235/US 54 interchange improvements. During the three years of construction, a smart work zone was used to alert drivers to traffic incidents and other problems leading to congestion in the work zone. From K-42 to Central Avenue on I-235 and from Maize Road to downtown Wichita on US 54, multiple monitoring devices were positioned throughout the project area to communicate real-time travel conditions and then automatically post travel times to common destinations in the city.

Fifteen portable message signs were used and placed on arterial streets to complement the large roadside message boards. Messages with estimated drive times through the construction zone allowed drivers to make informed decisions about their route. According to data collected during construction, as much as 50% of the traffic was diverted once delays of 7 minutes or more were reported on the message signs. "The design of the smart work zone kept traffic moving safely, both through the construction site and along the alternative routes" (Olson 2019).

The second example was a temporary traffic system through the I-35 corridor from K-33 to US 56 in southern Johnson County, known as the I-35 Smart Work Zone Traffic System, which was launched by the Kansas DOT (KDOT). The Smart Work Zone Traffic System included PCMSs, cameras, speed sensors, and variable speed limit signs on the I-35 mainline lanes to help monitor traffic flow and advise drivers to potential delays via slow traffic, traffic incidents, etc. Drivers were able to view the roadways and obtain real-time traffic information through the smart work zone system online hosted on JamLogic's platform (Qualls 2013).

Illinois

The Illinois DOT's (IDOT's) Back of Queue Warning System (BOQWS) began in the early 2000s due to a severe crash that occurred on I-57 in District 8. IDOT uses two different BOQ implementation approaches: project-specific and on-call. The initial BOQWS initiative was project-specific at first. This included queue analysis estimation, location of BOQ, and distance a QWS needs to be from taper. The second approach is an on-call smart work zone (SWZ) system (projects two weeks or less)—referred to as SWZ light, which is known to be low-cost and last a shorter duration.

Funds used for QWSs are parsed into two categories: on-call funds versus long-term project funds. The devices deployed for a typical IDOT smart work zone configuration include sensors, communication to the TMC, and then PCMSs, which provide feedback to motorists. IDOT does not specifically partner with certain traffic control companies directly for work zone QWS equipment but rather it is chosen by the company that wins the bid process. IDOT is currently working on developing policy shaped around criteria and standards of QWS deployment concerning safety and mobility.

Currently, selection criteria for QWSs include significant routes where expected queues and delays occur recurrently (e.g., interstates and highways), situations that will cause 5+ minutes of delay and 1+ mile backup. They also consider the traffic patterns of the area with respect to the time of day and day of the week (e.g., every Friday afternoon). The Bureau of Safety leaves the decision-making to the design and traffic operation engineers at the district level when deciding on QWS implementation. QWS styles in Illinois include PCMSs and static signs with flashing lights. Illinois also implements dynamic merge systems, travel delay systems, and alternative route systems in urban areas.

In 2011, when IDOT implemented a SWZ QWS, there was an acknowledged decrease in property-damage-only (PDO) and injury crashes but no change in crash fatalities. This represented an approximately 14% decrease in total queueing crashes. Although, there has been a noticeable decrease in crashes and queue length, it still has been hard to quantify what percent decrease can be attributed to the SWZ QWS.

The public's perception and understanding of SWZ QWSs has not been considered. There have been no major efforts in marketing, educational training, or information dispersed to the public. It has been noticed that travel time systems are helpful in urban areas, while BOQ systems are usually implemented in rural areas.

In 2016, IDOT was a part of a study conducted by the University of Illinois that evaluated ways to improve SWZ technology through optimal spacing of sensors.

Some benefits of implementing a SWZ QWSs are the connectivity with motorists, whether it be the PCMS or temporary rumble strips. The SWZ QWS has shown not only to be interactive but also express real-time activity and information for roadway users—not just relying on static messaging that drivers sometimes get inundated with. Some setbacks of implementing QWSs have been that they are cost prohibitive and low reliability of information being projected. This low reliability in data relayed is commonly due to data drops in the communication system, where there is an error in the traffic conditions data being transmitted. These data drops can occur either at low traffic volumes or high traffic volumes when traffic is at a standstill—gridlock. This then sends the wrong message of "free flow/no traffic" to the communication system when in fact there is indeed traffic (Pava 2019).

Nebraska

No information was found about use of work zone QWS in Nebraska. Advance Warning System (AWS) have been developed by the Nebraska DOT (NDOT) for use at isolated signalized intersections for normal traffic operations (NDOT 2019).

Missouri

The Missouri DOT (MoDOT) uses portable intelligent transportation system (ITS) technologies such as DMSs, highway advisory radio, and queue length detectors to monitor traffic conditions and provide messages to motorists. These work zone ITSs collect data such as traffic speeds and lane occupancy. This information is sent to a computer, and the computer processes the data and determines messages to display on the DMS. This technology can be used to provide information that can be used to keep motorists advised of conditions ahead, support smooth traffic flow, and provide warnings of incidents or detours (Clark et al. 2017).

MoDOT's rural Queue and Delay Warning system builds on these tools. The system is built on TransCore TransSuite Event Management System software and leverages real time HERE probe segment speeds. The system monitors speeds for slowed or stopped traffic. Once a certain threshold has been met, the system displays a message about stopped traffic.

Michigan

The Michigan DOT's (MDOT's) QWS study began in 2012 and became a part of their standardized implementation between 2014 and 2015 and continued to 2019 with a desire to increase coverage across the state of Michigan. MDOT has a defined selection criterion for when a QWS will be put into effect. The design engineers decide where a QWS is necessary given the roadway characteristics (e.g., high impact route, lane closure during peak hours, construction causes 1+ mile backup). MDOT uses at least two specifications that have been implemented in several projects that have incorporated QWSs: dynamic stopped traffic advisory system and speed-based detection. Past projects have shown that if a project is over-budget, then a smart work zone QWS is given lowest priority. MDOT subcontracts to the following companies that provide devices that contribute to its QWS configuration: iCone, Street Smart, Capital Barricades, and Slander.

MDOT has noticed the impact QWSs have made with an overall reduction of total rear-end crashes from 60% to 40% (undetermined what percent of those crashes are work zone crashes). Some areas of improvement are reliability or trustworthiness of the data used to convey accurate smart messaging and arrow boards. Along with increasing motorists' awareness of the difference between a smart work zone and a static work zone, the QWS drives the public's reaction behavior to traffic downstream. MDOT staff desires to conduct in-depth studies that could help measure the safety effectiveness and long-term plans for a project. Some future efforts include a standardized method of defining smart versus static work zones (i.e., disable static signs with alerts unless live conditions are valid) and consistency across all states. Another effort is adaptive cruise control through vehicle dashboards that communicate traffic downstream to the driver, as well as a semi-truck alert system, where truckers communicate traffic conditions over radio waves that are relayed to TMCs and update QWS messaging in real-time (Brookes 2019).

Texas

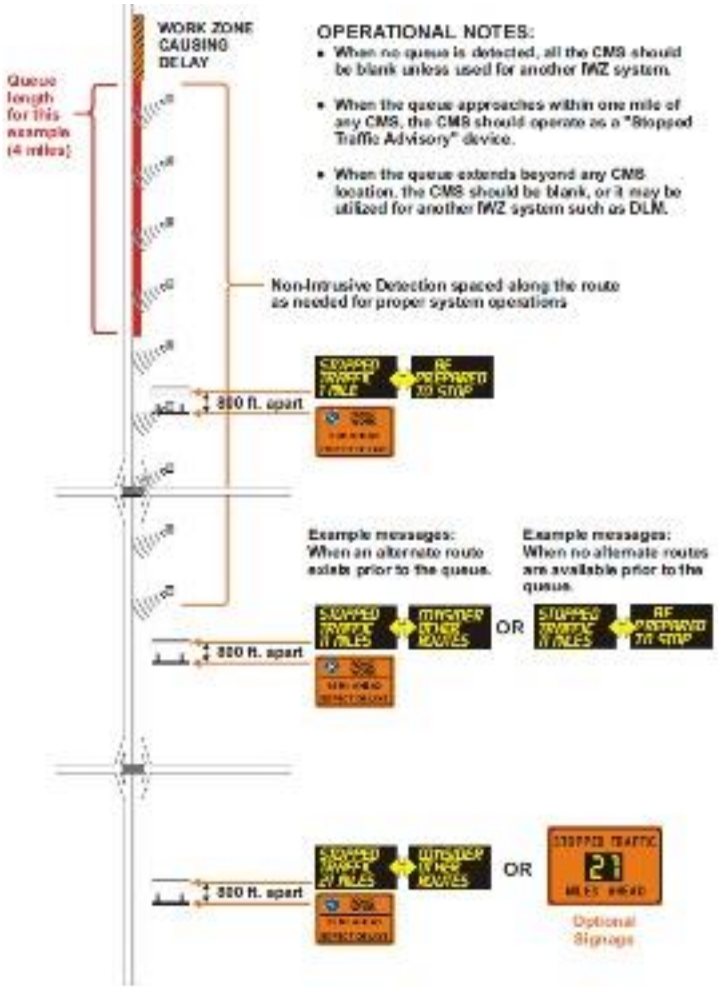
The most notable example for QWSs in Texas is their I-35 deployment (2013–2018). The Texas Transportation Institute (TTI) developed an integrated system that provides the Texas DOT with work zone monitoring and traveler information dissemination capabilities. The main goal of this system was to detect and predict the formation of queues and warn motorists of slow and stopped traffic ahead. The system configuration consisted of 17 remote traffic microwave sensors (RTMSs) for measuring the traffic speed, volume, and vehicle classification; 40 pairs of Bluetooth sensors for detecting the travel time; 6 closed-circuit television (CCTV) cameras for traffic surveillance; and 10 PCMSs for disseminating traffic information.

The system collected and integrated planned lane closure schedules from the multiple contractors working on the I-35 corridor, from Austin to Waco, automatically assessing the traffic queuing and delay potential associated with those planned closures, and disseminated advance notification of the closures and potential impacts to potential users of the corridor through multiple outreach mechanisms, including social media.

The system was designed to assist the Texas DOT and contractors with deployment decisions of portable end-of-queue warning systems and integrate inputs from those systems with various other traffic monitoring technologies in the corridor to develop accurate delay forecasts. The TTI system worked in conjunction with the Texas DOT Lonestar system for posting messages to corridor signage. Much of the deployed equipment (CCTV, Wavetronix, Bluetooth) concurrently reported data to TTI as well as the Texas DOT. Prior to any deployment, a complete concept of operations; a system architecture; and identified user needs through stakeholder meetings, public surveys, and a comprehensive system of engineering processes were conducted (Petter and Poe 2013, Habermann 2015).

Minnesota

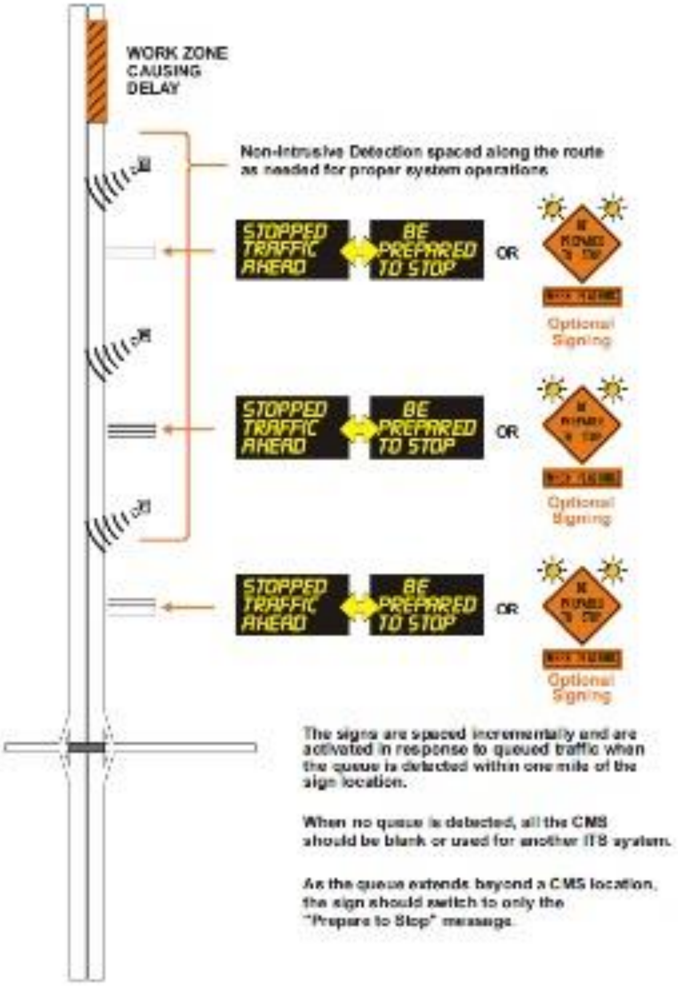
Minnesota developed an Intelligent Work Zone System Toolbox (MnDOT 2008), which lays out the basics for various ITSs. One of the described systems is a QWS that provides notifications for congestion. The system provides an alert to drivers of an upcoming traffic slow-down or stopped traffic. This provides time for drivers to select an alternate route or to be prepared for stops. The system suggests queue detection be placed within 1 mile of the advisory sign, since it was felt that signs placed more than a mile ahead are typically forgotten by the motorist. The system has non-intrusive detection spaced along the route as needed for proper system operations. CMS are incrementally spaced and activated when the queue is detected within 1 mile of the sign location. As the queue extends beyond a CMS location, the sign switches to a “Prepare to Stop” message. When no queue is detected, the CMS is blank or used for another ITS. An example is shown in Figure 3.



MnDOT 2008

Figure 3. Minnesota QWS for congestion

The Intelligent Work Zone System Toolbox also has a stopped traffic advisory system as shown in Figure 4.



The signs are spaced incrementally and are activated in response to queued traffic when the queue is detected within one mile of the sign location.

When no queue is detected, all the CMS should be blank or used for another ITS system.

As the queue extends beyond a CMS location, the sign should switch to only the "Prepare to Stop" message.

MnDOT 2008

Figure 4. Minnesota stopped traffic advisory

Work Zone Intelligent Transportation Systems

Minnesota developed several work zone intelligent transportation systems (WZITS) as a safety countermeasure to warn drivers of dangerous traffic conditions. They noted the effectiveness of WZTIS can be diminished if the actual traffic flow conditions do not correspond with the sensor information leading to false warnings, which confuses drivers and reduces the credibility of the system.

As a result, a low-cost rapidly deployable and portable queue detection WZITS warning system was proposed and a queue detection algorithm was designed and tested using widely available, field-proven, and machine vision hardware, along with video data collected in the field from the portable device. The warning trigger generated by the algorithm is then transmitted to a remote upstream location for triggering roadside emergency warning devices (VMS, flashers, etc.).

The purpose of the algorithm is to detect queue tails as they propagate upstream into oncoming traffic, and output a warning alarm trigger that can be used by roadside warning devices placed upstream of the sensor to warn drivers of the impending queue. In order to achieve this, an algorithm that utilizes trip-wire presence detection was developed. The algorithm produced three outputs: (1) a detection event of a stopped vehicle, or the start of a queue, (2) an alarm trigger that can be transmitted to an upstream roadside warning device, and (3) a real-time estimate of queue length, which can be used to estimate the queue tail location within the detection area.

Two intersection sites located along a high-speed, high-volume suburban arterial that carries traffic into (eastbound) and out of (westbound) the core city of Minneapolis were used to collect queue data. The results of queue detection for the intersection sites for all queue onset detections were within ±5 seconds from the observed ground truth time. The overall results indicated a true-positive queue detection rate of 84%, with the highest rate occurring at the Glenwood Avenue site (96.7%) and lowest rate occurring during the midday test for the Rhode Island Avenue site (74%). The false-positive alarm rate was very low, averaging 0.143 false detections per hour. The false positive queue warning alarm trigger-on rate was equivalent to the true positive queue detection rate (Morris et al. 2011).

I-35 Corridor

A QWS was deployed at another location in Minnesota. The I-35 corridor in Duluth, Minnesota included many old bridges that were in desperate need of major reconstruction. The vital link between Minneapolis and Duluth and tourist destinations to the north had to be kept open to traffic during the reconstruction. Traffic was restricted to an 11 ft lane in each direction and significant delays were anticipated during April 2010 and October 2011. The goal of the ITS project was to provide an automated system that would convey travel times as far as 30–90 miles in advance to allow drivers to pick alternative routes. In addition, the area south of the work zone, where traffic backed up, was often prone to fog and bad visibility due to high speeds and limited vertical sight distance. Equipment used on the project included 3 PCMS/3 travel time signs, 4 Prepare to Stop flashers, 16 traffic sensors, and 1 camera trailer. It is important to note that the prime contractor was not allowed to start construction until the intelligent work zone (IWZ) system was up and operational (FHWA 2014).

CHAPTER 4. EFFECTIVENESS OF BACK-OF-QUEUE WARNING SYSTEMS

Queue warning systems vary but generally have been shown to be effective. A description of the studies on QWS effectiveness is provided below and summarized in Table 2.

Table 2. Summary of studies on the effectiveness of QWS

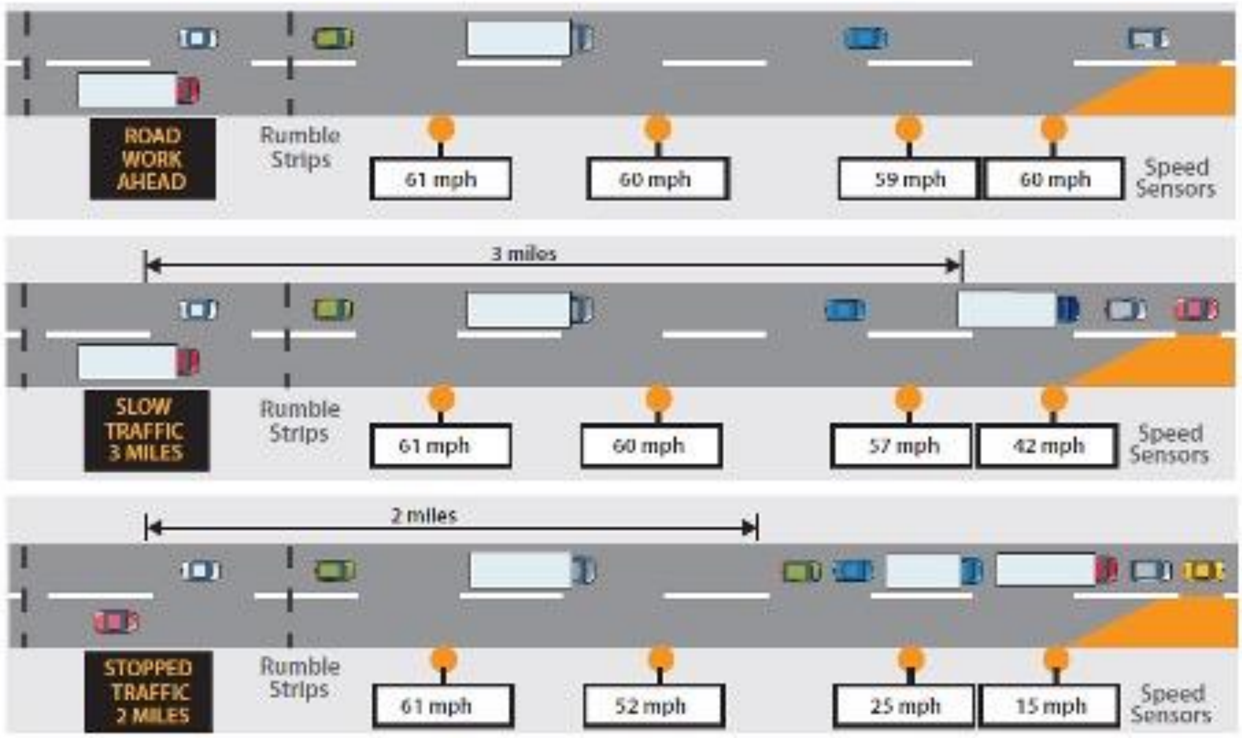
Study	Location	Configuration	Findings
FHWA 2014	San Diego, CA	Roadways surrounding shopping center	• Reduction in incidents of 66%
Hourdos et al. 2017	Minnesota	Interstate	• 22% decrease in crashes • 54% decrease in near-crashes
Pesti et al. 2008	Houston, TX	Interstate	• Decrease in speed variance • Sudden decrease in sudden braking • Forced lane changes decreased by 55% • Erratic maneuvers decreased by 2% to 3%
Ullman et al. 2018	Central Texas	Interstate	• Portable transverse rumble strips only • CMF = 0.89 for non-queuing scenarios • CMF = 0.34 (p = 0.23) for queues • QWS and PRS • CMF = 0.72 for non-queuing scenario • CMF = 0.47 for queues
WisDOT 2018	Manitowoc County, WI	Interstate	• 15% decrease in queue-related crashes • 63% decrease in injury crashes
Roelofs and Brookes 2014	Madison County, IL	Interstate	• 13.8% decrease in rear-end queueing type crashes

The Federal Highway Administration (FHWA) Enterprise Pooled Fund study (FHWA 2104) summarized examples of QWS deployments. They reported that incidents were reduced by 66% for a QWS deployed at a mall in San Diego, California (2013) where steep hills and blind corners contribute to high traffic volumes.

Hourdos et al. (2017) developed a queue warning system at I-94 and I-35W in Minnesota using the infrastructure for their Active Traffic Management system. The intelligent lane control signals were placed at every half-mile to identify queueing conditions on the freeway. The system was tested at I-94 and I-35W. The result showed that after the implementation of the queue warning system, there was a 22% decrease in crashes and a 54% decrease in near-crashes at I-94. Similarly, the result at I-35W showed a reduction in speed variance near the queue locations.

Pesti et al. (2008) evaluated the effectiveness of an end-of-queue warning system (EOQWS). The warning system was deployed at IH 610 and US 59 in Houston, Texas. Both the sites were associated with significant congestion and long queues. QWSs were used to warn drivers of the approaching queue. Speeds were collected for a week before and after the installation of the system using Wavetronix. Average speeds were within 1 mph from the before to after period. However, speed variance at both the sites was significantly reduced. Erratic maneuvers were also evaluated. They reported sudden braking was reduced by 7%, forced lane changes were reduced by 55%, and other erratic maneuvers were reduced by 3% at the IH 610 site. They found reductions of 2% to 3% in erratic maneuvers at the US 59 site.

Ullman et al. 2018, evaluated EOQWS and portable rumble strips (PRS) at a 7 year project in central Texas on the I-35 corridor. The EOQWS used radar speed sensors, which were linked wirelessly to a central data processing unit along with one or more PCMSs. The system logic assessed sensor status and automatically displayed an appropriate queue warning message based on the distance from the sign to the location of the closest sensor. They also used black portable transverse rumble strips. An example of a similar deployment in Texas is shown in Figure 5.



ARTBA 2015

Figure 5. Example of QWS used in Texas

The researchers compared crashes against work zones in 2012 where no countermeasures were deployed. They conducted a simplistic analysis and developed the following crash modification factors (CMFs) (Ullman et al. 2018):

- Portable transverse rumble strips only

    - CMF = 0.89 (p = 0.77) for non-queuing scenarios
    - CMF = 0.34 (p = 0.23) for queues
- EOQWS and PRS
    - CMF = 0.72 (p = 0.42) for non-queuing scenarios
    - CMF = 0.47 (p = 0.08) for queues

In 2015, Wisconsin recorded 2,404 work zone crashes that resulted in 945 injuries and 12 fatalities. To enhance the safety of highway workers and motorists, WisDOT completed a study to evaluate the effectiveness of a QWS in advance of lane closures to reduce speeds and improve safety. The study evaluated the QWS implemented with the improvement project along I-43 in Manitowoc County, Wisconsin. The objective of the QWS study was to collect individual vehicle speed data at multiple locations to determine if motorists were slowing down or reacting to the PCMS messages. A crash analysis was completed to compare crashes from a similar I-43 project in the same vicinity during a 2016–2017 project to determine if there was a reduction in the frequency and severity of crashes. The crash analysis compared queue-related crashes that occurred without a QWS (2016) to with a QWS (2017). The number of crashes from 2016 to 2017 decreased by 15%, from 13 crashes down to 11 crashes. The number of injury crashes decreased by 63% from 2016 to 2017. A cost/benefit analysis found that the QWS reduced queue-related work zone crash costs by 13% (WisDOT 2018).

The Illinois DOT deployed a “Real Time Monitoring System” to cover three construction projects on I-55 (I-70 to IL 140) in Madison County, Illinois from November 2010 to June 2012. The objective was to reduce the number of rear-end accidents with a secondary function to alert traffic to delay times and suggest alternate routes when delay times warranted such.

Equipment used on the project was stationed 6 miles in advance and included 73 PCMS and 56 Doppler sensors. Queue detection PCMSs were spaced 1 mile apart along the route to warn motorists about stopped traffic, travel times, delay times, and to provide a dynamic detour. When queues were detected, the system alerted motorists 1–2 miles in advance of the condition. When speed sensors detected traffic slowed (below 40 mph), the software would trigger STOPPED TRAFFIC AHEAD and BE PREAPRED TO STOP messages for the two boards approaching where the slowed traffic was detected. An analysis was conducted of rear-end queuing type crashes for the I-55 project and was compared with a similar project on I-55 without the QWS in place. They reported a 13.8 % reduction in rear-end queuing crashes during 2011 (Roelofs and Brookes 2014).

CHAPTER 5. DRIVER BEHAVIOR IN ENCOUNTERING BACK OF QUEUE USING IOWA DATA

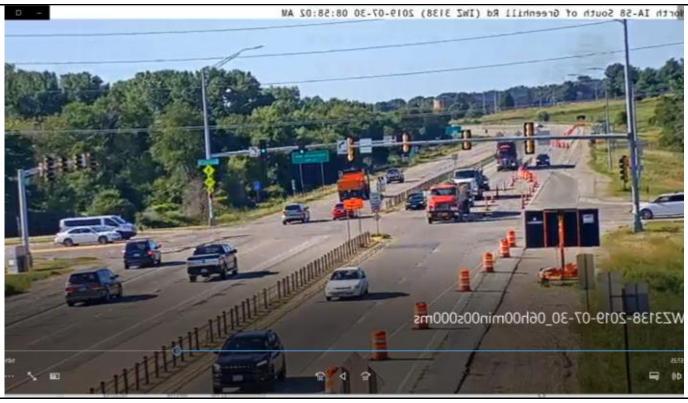
The majority of QWSs provide a visual warning (e.g., message sign, flashing beacon) to drivers, which ideally helps them be prepared for congestion or queued traffic. However, a driver needs to be properly monitoring the roadway environment to receive the warning and, then, be prepared to take the appropriate actions when necessary. This includes being alert and slowing to a manageable speed. In many cases, drivers are distracted and fail to recognize warnings. In other cases, drivers receive the warning but fail to comply with appropriate speeds. As a result, one of the main needs to address BOQ situations is to understand what drivers are doing so that QWSs can get a driver’s attention. Additionally, an understanding of driver behavior may suggest other countermeasures, such as speed management, may be effective.

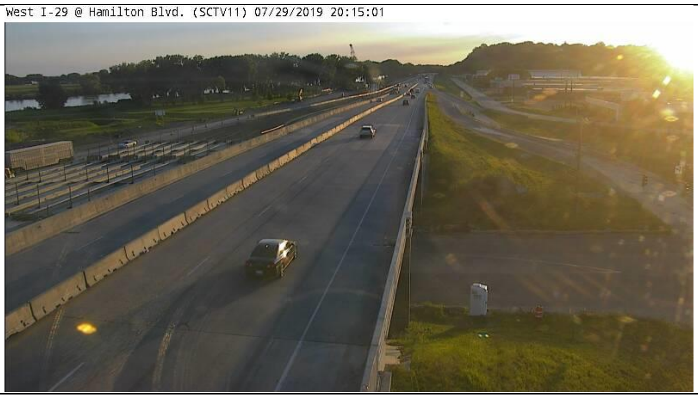
This knowledge gap in understanding driver behavior was addressed by evaluating work zone BOQ events using two different datasets. The first dataset was developed by coding BOQ events in Iowa work zones for the 2019 construction season. The second was evaluating BOQ safety critical events (SCEs) in the Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS).

Iowa Data

The team worked with the project technical advisory committee to identify potential work zones for the 2019 construction season. Nineteen work zones were identified on state roads that had a lane closure. The locations of cameras for each work zone were identified from a database maintained by the Iowa DOT. The Real-Time Analytics of Transportation Data (REACTOR) Laboratory at the Institute for Transportation (InTrans) has video feeds from work zone cameras deployed by the Iowa DOT. Camera locations at work zones where queues were likely to form were identified resulting in seven locations as noted in Table 3.

Table 3. Location of work zones in Iowa where queue was expected

• Work zone 2P • IA-58 southwest of Waterloo • 4-lane (far approach reduced to 1 lane) • Ultimately, queues due to work zone could not be distinguished from intersection queues	

• Work zone 5V • I-35 south of Decatur City • 4-lane divided to 2-way head-to-head • No significant queues formed	
• Work zone 1BM • IA 415 South of Ankeny • Several crashes occurred within the activity area, and queues formed on many occasions	
• Work zone 2Q • US 20 south of Waterloo • 4-lane divided to 2-lane head-to-head during work zone • Multiple queues were noted	
• Work zone 3B • I-29 in Sioux City • 6 lanes reduced to 2/2 • Queues resulted, but due to the camera configuration they were difficult to see	

• I-29 in Sioux City (second location) • 6 lanes reduced to 2/2 • Queues but no conflicts	
• Work zone 3S • I-29 north of Modale • 4-lanes, SB reduced to 1 lane • No queues noted	

Videos from each camera were downloaded daily from July 29, 2019 to October 15, 2019. The team wrote code to identify queuing at the seven locations identified. Since the code could only identify potential queues, video segments where a queue was noted had to be manually reviewed. As noted in Table 3, work zone 2P, had a lane closure but was near an intersection and ultimately queues from the work zone could not be distinguished from queues due to intersection operations. Additionally, no queues were recorded for work zones 5V and 3S.

Performance Metrics for Iowa Data

Crashes are the best indicator of safety. However, the number of crashes at any given BOQ location were expected to be low. In fact, while several crashes were noted at various work zone locations, no crashes were identified in any of the locations where BOQ events were being monitored. As a result, SCEs were selected as the performance metric of interest. This included near-crashes defined as an interaction between a subject vehicle and one or more other road users that requires a rapid, evasive maneuver by one or more of the road users to avoid a crash, and conflicts defined as an interaction between a subject vehicle and one or more other road users that entails a risk of collision if actions are not taken.

In NDSs, near-crashes and conflicts can be defined by metrics such as acceleration (forward or lateral), changes in speed, or changes in steering actions of a certain magnitude, or specific driver actions, since these variables are collected through an in-vehicle instrumentation system. However, speed and acceleration could not be accurately extracted from the video and other metrics (steering and driver reaction) could not be assessed at all. As a result, a set of criteria was used to subjectively determine near-crashes and conflicts (called safety critical events) as defined above. Potential SCEs were identified by the several coders used to manually reduce the video. Each SCE was flagged, and a single coder reviewed each event to determine whether they should be included as a safety critical event. A single coder was used to ensure consistency.

In the context of a BOQ scenario, a near-crash may have included actions such as a driver braking hard and steering left or right to avoid a collision. A few examples are shown in Table 3. A conflict would include hard braking, changing lanes, or engaging in some noticeable action to avoid a crash but not at the level of a near-crash.

A total of 68 SCEs were recorded. Thirty four were classified as conflicts and 34 were classified as near-crashes. Driver behavior only could be observed through the video. Due to camera angle and volumes, it was not possible to measure actual speed. As a result, speed was coded as traveling:

- Below speed of prevailing vehicles
- At speed of prevailing vehicles
- Faster than speed of prevailing vehicles (speed too fast for the conditions)

Following behavior was also coded as:

- Not following (gap >2 seconds)
- Following (gap approximately 1 to 2 seconds)
- Following closely (gap <1 seconds, obviously tailgating)

Merges were also noted as:

- Normal merge
- Forced merge (which entailed a vehicle creating a gap)

Other maneuvers such as hard braking, steering left or right to avoid the lead vehicle, leaving the lane, etc. were also coded.

It was not feasible to reduce a large dataset of non-safety critical events as a comparison. As a result, only a simple comparative analysis of the data was possible. As shown in Figure 6, almost 40% of drivers who were engaged in an SCE (27 of 68 events) were traveling at a speed that was determined to be too fast for the conditions.

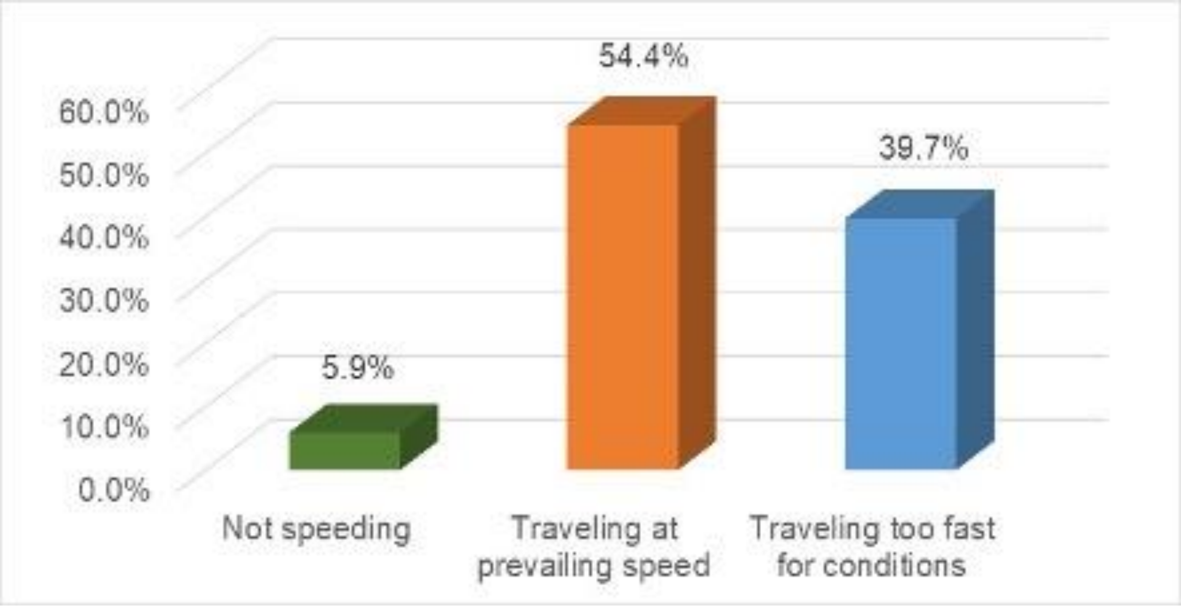


Figure 6. Speed status for SCEs

Figure 7 shows following behavior for safety critical events.

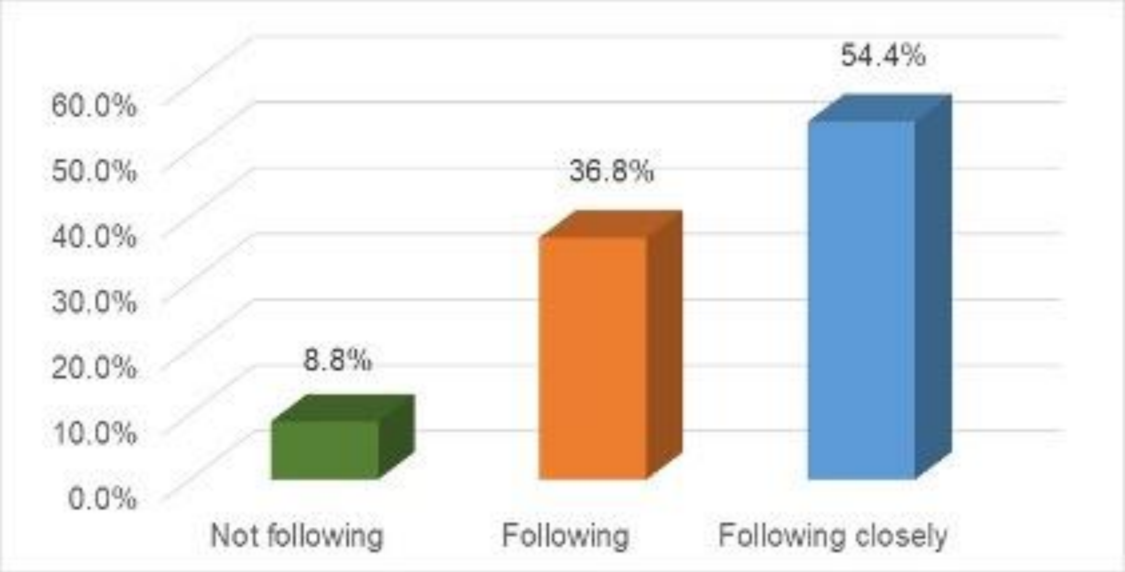


Figure 7. Following status for SCEs

As noted, drivers involved in an SCE were more likely to be following closely (54%). Following closely was subjectively defined as less than 1 second between the subject vehicle and lead vehicle. Following was defined as approximately 2 seconds between vehicles and accounted for 36.8% of drivers involved in a safety critical event and drivers who were not following made up 8.8% of SCEs.

As noted in the above, the majority of vehicles engaged in an SCE at the back-of-queue were traveling too fast for the conditions and traveling too closely. Additionally, in almost 9% of cases, a forced merge occurred, which contributed to the SCE.

Driver Behavior in Encountering Back-of-Queue Using the SHRP2 NDS

BOQ events were also evaluated using the SHRP2 NDS data. A related project conducted by the team used these data to evaluate naïve drivers within actual work zones to assess how they react to different work zone traffic control. A number of BOQ events were identified in the course of that project and utilized to evaluate driver behavior.

SHRP2 Datasets

The SHRP2 NDS data is the largest dataset of its kind. The project included the collection of information on speed, acceleration, GPS data, and radar from naïve drivers using a data acquisition system (DAS). Four cameras collected videos from forward, rear, driver's face, and over-the-shoulder views. Over the three years of the study, approximately 3,400 participants drove over 30 million data miles during 5 million trips in six US states. The participating states were Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington.

The SHRP2 Roadway Information Database (RID) was collected simultaneously with the SHRP2 NDS study. Mobile data collection was conducted on over 12,500 center-line miles across the six NDS states. Existing roadway and supplemental data acquired from public and private sources were also included in the RID. These data came from several sources including the NDS states' DOTs and the Highway Performance Monitoring System (HPMS), covering most roadways for each study state. In addition, supplemental data such as 511 data, construction projects data, and traffic volume were also collected to further strengthen the database.

Primarily, 511 data served as the main source of data to identify construction events for this study. The 511 system is a resource for national travelers, and it is set up and run by the U.S. DOT and FHWA. Currently, 35 states participate in the 511 system. The system allows drivers to dial 511 on their phones and receive real-time traffic information on road closures, accidents, route detours, weather alerts, etc. These data were archived and included in the RID.

The RID supplemental data that contains 511 information was queried for each of the three years the NDS was active (2011 to 2013). The resulting data included around 2 million records. The 511 files contained information about any traffic event occurring within the study state, including construction. Potential work zones were identified using an attribute query in ArcGIS using key words such as "construction," "lane closure," "road work," or "maintenance." Some information about the duration of the event was usually available, and potential work zones in place for more than three days were identified. Three days was used as a threshold because it was unlikely that a sufficient number of NDS time series traces would be available for short-duration work zones. Ultimately, 9,290 potential work zones were identified.

The next step linked the identified 511 events to the RID data. Locations for the 9,290 potential work zones were sent to VTTI, and the number of time series traces and drivers' age/gender information for the links of interest were requested. Potential work zone trips were determined by identifying the trips falling within the dates indicated in the 511 data.

Forward videos associated with time series traces were requested for each work zone. The forward video was reviewed to determine whether a work zone was actually present. The beginning and end points of each work zone, initially identified, were adjusted based on a review of the forward video and corresponding spatial location from the time series data. Once again, the dynamic segmentation method was used to find link IDs, 1 mile upstream and downstream of each work zone.

The final and the most reliable step toward finding work zones of interest was manually going over NDS forward videos. A large amount of useful information was manually coded from the forward view video that identified the active work zones with different configurations. Once a number of work zones and their extents were confirmed, around 10,000 traces were received, which were needed for the objectives of a related project. A trace indicated one trip through one work zone by one driver. The received data included time series data for each trace (i.e., speed, acceleration, brake position) at 0.1 second intervals. GPS position was also available, which allowed the traces to be linked to corresponding roadways segments.

In the process of reviewing work zone traces, a number of events were identified where the subject driver encountered a back of queue. Each BOQ event was flagged and additional data were reduced. The forward roadway was used to extract information about work zone characteristics such as traffic control, type of barrier, lane merge, etc.

Driver characteristics (e.g., age, gender, years driving, number of violations) were provided for each driver by the VTTI. Driver behaviors included the following: hands on wheel, impairments (e.g., drowsy, intoxicated), seat belt use, driving action (e.g., failure to yield), and speeding (e.g., exceeded speed limit, too fast for the conditions). VTTI coded distraction for the set of identified normal BOQ driving events. This included identifying glances away from the driving task. Distraction was coded in the form of secondary tasks. As a result, distractions were recorded when they involved a glance away from the forward roadway. Additionally, cell phone use was identified when possible and noted. Unlike distraction, cell phone use did not need to be associated with a glance away from the driving task. Distraction, glance data, and cell phone were joined to the corresponding time series trace using time stamps.

Safety Critical Events in the SHRP2 Data

VTTI, which houses the SHRP2 NDS data, identified a set of crashes and near-crashes, which are available through a secure data server. Crashes and near-crashes at BOQs in work zones were identified through a review of that data. Near-crash events are typically classified by VTTI when a deceleration of 0.5 g or higher occurs and/or when there is an evasive maneuver. A few additional near-crashes were identified through the review of normal driving traces. This resulted in 46 safety critical events and 283 normal, events which were used as controls. Figure 8 illustrates examples of BOQ events.

VTTI

Figure 8. Drivers encountering back of queue from the SHRP2 NDS data

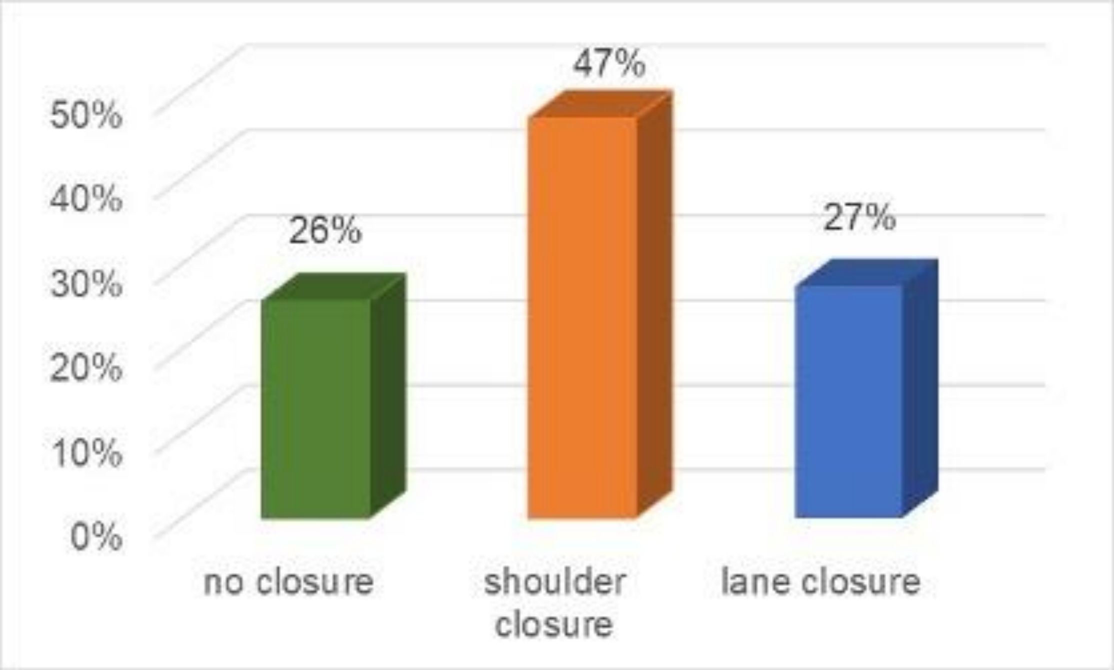
Several variables were recorded for each BOQ event including the following:

- **Reaction time:** time stamp where the lead vehicle begins braking or slowing, which suggests a need for the following (subject SHRP2 NDS driver) to also react
- **Incident time:** time stamp when the following subject vehicle takes action in response to the lead vehicle
- **Average speed:** average speed for subject vehicle 10 seconds prior to reaction time
- **Maximum speed:** maximum speed for subject vehicle 10 seconds prior to reaction time
- **STD:** standard deviation of speed for subject vehicle 10 seconds prior to reaction time
- **Max acceleration:** the maximum absolute value of acceleration (recorded in g) for subject vehicle 10 seconds prior to reaction time
- **Following:** a subjective measure of following behavior for subject vehicle
    - Following closely (<2 seconds)
    - Following (i.e., 2 to 3 seconds)
    - Following at a distance (>3 seconds)
- **Cell phone:** subject driver used cell phone at any point 6 seconds before reaction time to 6

seconds after reaction time regardless of glance location

- **Distraction:** Subject driver was engaged in any type of distraction for 1 second or more (cell phone, eating, personal grooming, etc.), which involved a glance away from the forward roadway during the period of 6 seconds before reaction time to 6 seconds after reaction time
- **Cell distraction:** Subject driver was engaged in a cell phone task (reaching, texting, using), which involved a glance away from the forward roadway during the period 6 seconds before reaction time to 6 seconds after reaction time

Roadway characteristics, such as configuration, and work zone configurations such as type of barrier and configuration were also coded. Around 42% of observations were on four-lane facilities, 53% were on multi-lane facilities, and 5% were on two-lane or other (i.e., on-ramp). Figure 9 shows work zone configuration.

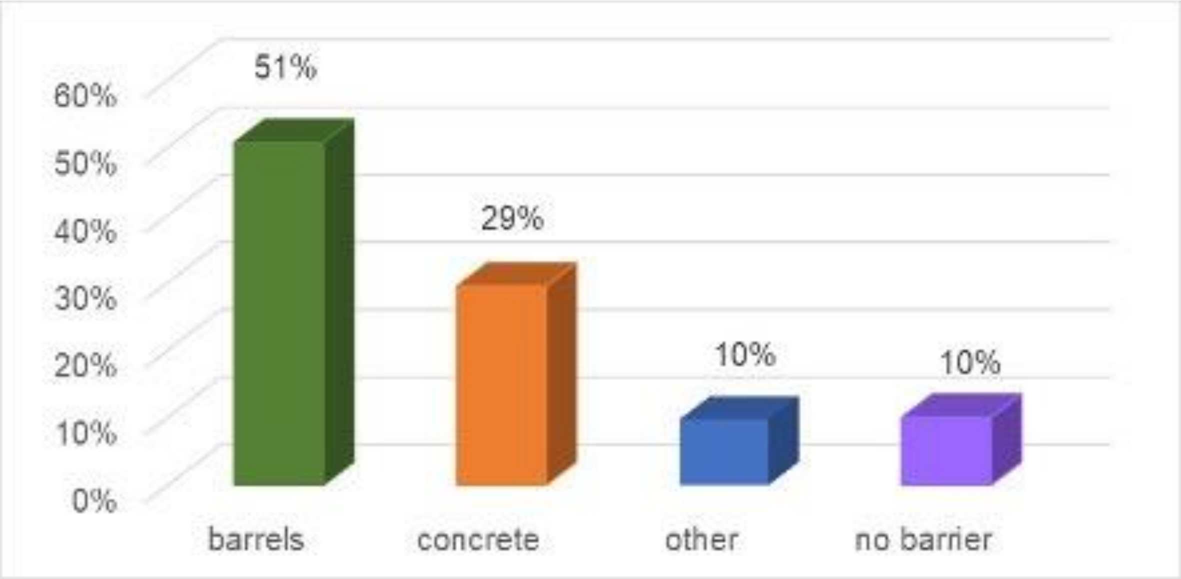


VTTI

Figure 9. SHRP2 BOQ events by type of work zone

As noted, around 26% occurred in a location where no shoulder or lane closures were present. They may have occurred upstream of the actual work or in a work zone with no closures. Around 47% occurred in locations with one or two shoulders closed, and 27% occurred in locations where one or more lanes were closed.

Figure 10 shows types of barrier present.



VTTI

Figure 10. SHRP2 BOQ events by type of barrier

As noted, barrels were present at 51% of BOQ locations and concrete median was present at 29%. Only a few observations were present of other types of barrier (i.e., cones, delineators) so they were combined into one category and were present 10% of the time. Additionally, 10% of back-of-queue events occurred in a location with no barrier present.

Modeling and Results for SHRP2 Data

A mixed-effect logistic regression model was developed with probability of a near-crash as the response variable. Various models were tested using predictor variables, which included driver age, driver gender, driver distraction (“Distraction”), cell phone use (“Cell phone”), distraction involving a cell phone (“Cell_Distraction”), maximum speed before reaction, average speed, roadway type, following behavior, type of work zone (i.e., no closures, shoulder closure, lane closure), type of barrier (i.e., concrete, barriers), and time of day.

A logistic regression model was developed to assess the relationship between probability of a near-crash and roadway, driver, and work zone characteristics. The variable Y_i is the event type or hard acceleration level the i-th trace. For the event type model, the possible values are $Y_{ij} = 0$ if the driver had a normal reaction, and Y_{ij} if it was a near-crash.

That is,

$$Y_i \sim Bernoulli(p_i)$$

where, the probability of a near-crash, p_i, is associated to the independent variables through the logit function as follows:

$$logit(p_i) = X_i^T \beta,$$

where, X_i are the covariate values, and β are the fixed parameters. The logit function is defined as follows:

$$logit(p) = log\left(\frac{p}{1-p}\right).$$

The logit function facilitates the interpretation of the parameters β, since it represents the log-ratios. The vector β has a size of $k+1$, representing the parameter estimates for the k covariates plus the intercept estimate. If the j-th entry represents a binary variable (e.g., sex: 1 = male, 0 = female) and $\exp(\hat{\beta}_j) = 1.02$, then it means that observations with the presence of such variable are 2% more likely to have a near-crash reaction.

For both models, stepwise forward selection was used. The selection criterion was the Akaike information criterion (AIC). The final best fit model included whether a driver engaged in glances longer than 1 second, how close the subject car was following the lead car vehicle, and the average speed in the 10 seconds prior to the reaction of the lead car. The latter variable was included through a spline to allow it some flexibility. Model fit statistics are provided in Table 4.

Table 4. Analysis of variance (ANOVA) of reaction type model

Term	statistic	df	p.value
glances_away_over_1s	5.7402	1	0.0166
following	11.0798	2	0.0039
bs(before_react_avg_speed, degree = 2)	5.0076	2	0.0818

Model results are shown in Table 5.

Table 5. Estimates of reaction type mode

Variable	Estimate	Std. error	z value	Odds ratio	Pr(>|z|)
(Intercept)	-0.7453	1.1999	-0.6212		0.5345
glances_away_over_1sYes	1.3339	0.5467	2.4397	3.80	0.0147
followingFollowing (2–3 sec)	-0.3172	0.6054	-0.5239	0.73	0.6003
followingFollowing Closely	1.0698	0.5615	1.9052	2.91	0.0568
bs(before_react_avg_speed, degree = 2)1	-1.3995	2.2424	-0.6241	0.25	0.5326
bs(before_react_avg_speed, degree = 2)2	-2.4256	1.1141	-2.1772	0.09	0.0295

Results are also shown graphically in Figure 11.

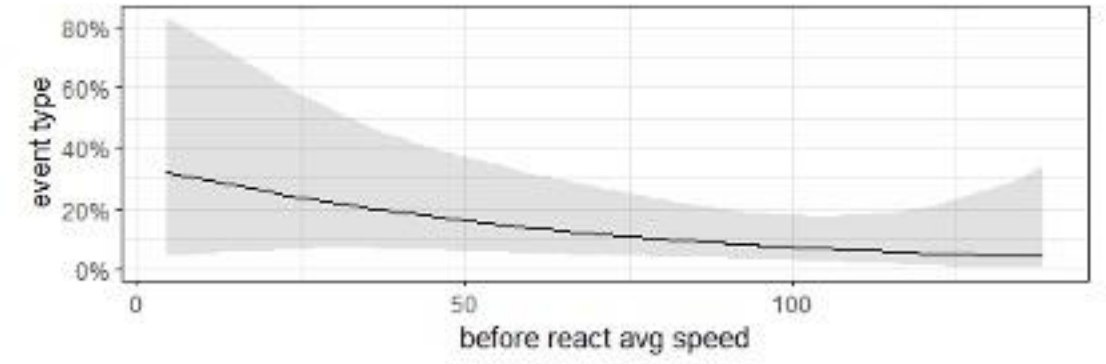


Figure 11. Predicted value for average speed

As noted in Table 5, the odds of being involved in a BOQ safety critical event is 3.8 more likely if the driver was engaged in a glance away from the roadway task of 1 or more seconds (p = 0.0147). When a driver is following closely (<2 seconds), they are 2.91 times more likely to be involved in an SCE (p = 0.0568) than when not following. Drivers following another vehicle (within 2 to 3 seconds) are less likely to be involved in an SCE, but the result was not statistically significant (p = 0.6003). This value was provided since it was evaluated with the other conditions for following.

The average speed of the subject driver was also significant. Since the relationship is non-linear, it was included as a spline. The odd ratios cannot be interpreted directly and are shown graphically in Figure 11. As noted, drivers are more likely to be involved in an SCE at lower speeds than higher speeds. This is counterintuitive since in most cases, it is expected that higher speeds are related to back-of-queue crashes. In most cases, BOQ events occur under congested conditions when speeds are lower. Additionally, only the actual speed of subject vehicle could be determined. In most cases, work zone speed limit could not be determined. Consequently, whether the vehicle was speeding could not be determined. Additionally, the speed of prevailing vehicles could not be determined, so the condition of traveling at a speed too fast for the conditions similarly could not be identified. As a result, while speed was included in the model, speeding could not be determined.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Summary

Rear-end crashes are one of the predominant types of crashes in work zones with estimates ranging from 18% to 65%. Aggressive driver behavior, such as speeding, following closely, forced merges, and distraction have been noted as contributing factors from the literature. Congestion and queueing are also correlated to rear-end crashes in work zones.

In order to address BOQ crashes, many agencies have utilized QWSs. QWSs have been noted as effective, and the majority of QWSs provide a visual warning (i.e., message sign, flashing beacon) to drivers, which ideally helps them be prepared for congestion or queued traffic. However, a driver needs to be properly monitoring the roadway environment to receive the warning and, then, needs to be prepared to take the appropriate actions when necessary. This includes being alert and slowing to a manageable speed. In many cases, drivers are distracted and fail to recognize warnings. In other cases, drivers receive the warning but fail to comply with appropriate speeds. As a result, one of the main needs to address BOQ situations is to understand what drivers are doing so that QWSs can get a driver's attention.

Findings

One of the main objectives of this research was understand what drivers are doing at BOQ situations so that QWSs can get a driver's attention. Additionally, driver behavior may indicate that other countermeasures, such as speed management, may be as effective as a formal QWS.

Back-of-queue crashes are primarily rear-end crashes. In addition to congestion and stop-and-go traffic, aggressive driver behavior has been reported as the most common contributing factor in rear-end crashes. This includes following too closely, which has been noted as a factor in up to 55% of rear-end crashes (Rakotonirainy et al. 2017, Raub et al. 2001, Dissanayake and Akepati 2009). Forced merges were also noted as problematic (Ullman et al. 2001). Speeding has also been recorded as a factor in up to 52% of rear-end crashes (Raub et al. 2001, Dissanayake and Akepati 2009, Johnson 2015).

Driver distraction has also been reported as contributing factor in up to 17% of rear-end work zone crashes (Raub et al. 2001, Johnson 2015).

Driver behaviors were further evaluated in this research using two different datasets. The first was an observational study of BOQ behavior at work zones in Iowa during the 2019 construction season. Potential BOQs were monitored, and near-crashes or conflicts were manually coded. A total of 68 SCEs were recorded. Almost 40% of drivers who were engaged in an SCE were traveling at a speed that was determined to be too fast for the conditions. Drivers involved in an SCE were more likely to be following closely (54%). Additionally, in almost 9% of cases, a forced merge occurred, which contributed to the SCE.

The second dataset was the SHRP2 NDS. Back-of-queue events including 46 SCEs and 283 normal events, which were used as controls, were identified. Driver behaviors were coded including glance location, distraction, and cell phone use for 6 seconds prior to and 6 seconds after the subject vehicle encountered a stopped or slowed lead vehicle . Type of work zone (i.e., lane closure), roadway type, and type of barrier present were reduced from the forward roadway video. Vehicle speeds (average, maximum, and standard deviation of speed) were extracted from the times series data for the 10 seconds prior to when the subject vehicle encountered a slowed or stopped lead vehicle. Following behavior in the queue was also noted.

A mixed-effect logistic regression model was developed with probability of a near-crash as the response variable. The model found that the odds of being involved in a BOQ SCE is 3.8 times more likely if the driver was engaged in a glance away from the roadway task of 1 or more seconds ($p = 0.0147$). This includes any type of glance away from the roadway task including distractions. When a driver is following closely (<2 seconds), they are 2.91 times more likely to be involved in an SCE than when not following. The average speed of the subject driver was also significant but found drivers are more likely to be involved in an SCE at lower speeds than higher speeds, which is likely due to most BOQ SCEs occurring during congestion.

As a result, this research confirmed that speed, following too closely, forced merges, and inattention were major contributors to BOQ incidents.

Recommendations

QWSs have been demonstrated to be reasonably effective to reduce crashes. Studies have indicated QWSs reduce crashes from 22% to 66% and up to 66% for incidents. QWSs also have been shown to be effective in reducing forced merges, erratic maneuvers, and speed variance. They are also likely to be effective for tailgating if drivers have heightened awareness of the potential for BOQ situations. However, QWSs may not be as well targeted to high-risk drivers and are not geared to address some of the behaviors that contribute to BOQ crashes. For instance, intention and following closely were two key factors noted in this research as well as other studies. Drivers who are not paying attention may miss CMS and other messages from QWSs. As a result, a few other recommendations for addressing BOQ events are noted.

Speed Management Countermeasures

QWSs are likely to be effective for speeding. Other countermeasures may also be effective when combined with QWSs. For instance, multiple studies have indicated DSFSs are effective in reducing speeds (Figure 12).

www.streetsmartrental.com/products/radar-speed-trailers-rental.html/?portfolioID=10822

Figure 12. DSFS

Thompson (2002) studied the effect of a trailer-mounted radar-activated CMS at the end of taper for a left lane closure along an interstate in Maine. The CMS displayed either the speed limit when the vehicle was not speeding or "YOU ARE SPEEDING!!!" when the vehicle was speeding. When the sign was active, the percentage of speeding vehicles decreased from 65% to 54%, and average speed decreased by 7 mph, and mean speed was reduced from 55 mph to 48 mph. Fontaine (2017) evaluated trailer speed displays and found an average decrease of 5.2 mph for both passenger vehicles and trucks before the taper and 3.9 mph for passenger cars and 2.4 for trucks in the activity area. McCoy et al. (1995) evaluated the effectiveness of speed monitoring displays in a work zone on an interstate highway in South Dakota. Mean speed of vehicles was reduced by 4 to 5 mph. The sign was also able to reduce the percentage of vehicles exceeding the advisory speed limit by 20% to 40%. Carlson et al. (2000) found reductions of 2 to 7.5 mph upstream and 3 to 6 mph within the work zone with speed display trailers. Meyer (2003) evaluated an effect of radar actuated speed display on two-lane rural commuter routes. Both mean and 85th percentile speed were decreased by about 5 mph. Percentage of drivers speeding above 5 mph dropped from 30% to less than 5%.

Enforcement may also be a strategy to reduce speeds in queue areas in work zones.

Wayfinding App Messages

Several wayfinding apps have the potential to provide in-vehicle messaging to drivers, which could assist in alerting drivers about the upcoming presence of BOQs. This may be particularly helpful for distracted and inattentive drivers who may not notice on-road messaging.

Waze is a navigation app owned by Google, which can provide turn-by-turn directions as well as a travel-submitted travel times and route details. Waze users can report crashes, congestion, speed, and enforcement. Using this crowd-sourced information, the system can indicate conditions such as debris in the road or a crash ahead. The app provides a web interface that can be used by agencies to broadcast reports and alerts. In particular, it has been used by television news stations (Wikipedia 2019). Google Maps is integrating a similar option that will allow users to report crashes, enforcement, congestion, construction, lane closures, disabled vehicles, and road debris (Lekach 2019).

Several work zone product vendors, including iCone, have data sharing partnerships with Waze. Agencies also have the ability to provide input. The Iowa DOT, for instance, already sends messages to Waze. Protocols for providing messages about upcoming BOQ events could be developed using existing tools. For instance, the Iowa DOT already monitors congestion, which is formatted to send via text message. Messages could also be tailored to high-risk drivers.

Tailgating Countermeasures

Following closely has been noted as one of the main contributors to BOQ events. Beyond alerting drivers about the presence of upcoming queues, QWSs and other solutions such as speed management or in-vehicle notifications are not geared to address tailgating.

No specific solutions were found to address tailgating besides enforcement.

Addressing Distraction

The main drawback for QWSs is that they may be less effective for distracted or inattentive drivers who may not notice the queue warning system. This research evaluated factors associated with BOQ safety critical events in general. As noted, those factors included speeding, glances away from the roadway, following too closely, and forced merges.

QWSs are less likely to be effective for distracted drivers who may not be paying attention to work zone traffic control. One strategy to address both speeding and distracted drivers is use of portable rumble strips, which have been shown to be effective in conjunction with QWSs. Portable rumble strips provide a tactile warning to drivers, which may be effective for distracted drivers. The drawback to portable rumble strips is that it may be difficult to pinpoint a distinct back-of-queue point to place the devices. Additionally, portable rumble strips may not be appropriate for all roadway types.

The models used to assess the SHRP2 data were not able to find a statistically significant relationship between cell phone use and safety critical events. However, a simplistic analysis of the data indicated drivers who were involved in SCEs were twice as likely to be engaged in some cell phone task. Additionally, glances away from the driving task of 1 or more seconds was found to be statistically significant. This included glances related to cell phone tasks (i.e., texting) as well as other distractions. As a result, the study found evidence to reinforce laws prohibiting cell phones in work zones.

Recommendations for Future Work

Recommendations for future research include:

- Further evaluate the effectiveness of DSFSs in conjunction with QWSs
- Identify other audible attenuator countermeasures that may target distracted drivers
- Develop Iowa-specific crash modification factors for QWSs

Application of Queue Warning Systems in a Connected Vehicles Environment

Current QWSs rely on fixed sensors to monitor speed and detect a queue. Connected vehicles have the potential to provide feedback on traffic speeds and potential slowdowns. This has the potential to greatly improve system ability to detect slowed and stopped traffic. Additionally, relay of queue messaging can be delivered through in-vehicle systems rather than relying solely on CMSs or other static warnings. The main challenges for integrating connected vehicles into QWSs is that without a sufficient number of connected vehicles, developing and maintaining a system that accommodates both regular and connected vehicles may be resource-intensive compared to the benefit.

A study by Khazraeian et al. (2017) used simulation modeling to assess different market penetration scenarios at which sufficient connected vehicles could be present in the traffic stream so that they could be used to provide an accurate and reliable estimate of queue length and back-of-queue location. They found around 3% to 6% of the fleet was needed for accurate queue length detection in a congested freeway scenario. They also found BOQ identification was feasible with a 3% market penetration. A significant benefit in terms of safety effects with a market penetration of 15% was estimated.

Another application for connected vehicles is delivering targeted messages about upcoming work zones. Most agencies already monitor traffic conditions including work zones. Information about BOQ situations, crashes, and other work zone information can be conveyed to connected vehicles through basic safety messages (BSM).

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