RESEARCH & DEVELOPMENT

Using IoT Technology to Create Smart Work Zones

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16. Abstract

This study explores the feasibility of improving road work zone safety by using state-of-the-art Internet of Things (IoT), artificial intelligence (AI), and computer vision technologies. This project included in-depth analysis of the key technologies and systems that have the potential to improve work zone safety. In order to gain an understanding of the major triggers of the most harmful crashes in work zones, the project team analyzed the crash data in North Carolina. Driven by insights gained through an extensive literature review and the analysis of North Carolina work zone crash data, this project developed two proof-of-concept systems using IoT, AI, and computer vision technologies for work zone safety. The developed systems provide capabilities for two functions: (1) work zone intrusion warning and (2) vehicle queue detection. The proof-of-concept intrusion alert system comprised a mobile device attached on a tripod to monitor a restricted area and a system to alert the workers when an intrusion occurs. The workers receive alerts instantly through alarm sounds and vibrations generated by their mobile devices. The systems were tested using a simulated test environment and the findings of the tests indicated their potential to provide a robust technical approach. A proof-of-concept queue warning system was also developed and tested. The results indicated its potential to be used in smart work zones as a low-cost and easy-to-deploy system. Both systems were implemented with the capability to run on Android smartphones. However, the software is extremely portable, and therefore, the technical design can be embedded in any type of hardware. This report also identifies three commercially available devices that have good potential to be used in the field as part of a smart work zone to improve the work zone safety.

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Executive Summary

This study explores the feasibility of improving road work zone safety by using state-of-the-art Internet of things (IoT), artificial intelligence (AI), and computer vision technologies. This project included an in-depth analysis of the key technologies and methods that have the potential to improve work zone safety. The report also explains and illustrates how existing and emerging work zone safety systems and methods are typically implemented through a number of cases. It also reports the development of two proof-of-concept systems geared toward the needs of today's smart work zones and the evaluation of their effectiveness and reliability through lab experiments.

In order to gain an understanding of the major triggers of the most harmful crashes in work zones, the project team analyzed crash data from North Carolina. The team also conducted a thorough literature review to determine the current state of practice in smart work zone implementations in the United States together with the technical capabilities of the most prominent products on the market. The findings of those research activities led the team to focus on two core smart work zone elements: queue detection and work zone intrusion detection. Queue detection is a key technology in many smart work zone applications, such as dynamic lane merge systems and queue warning systems. Intrusion detection is a key element of systems that protect workers from vehicles entering into restricted work areas. This report identifies three commercially available devices that can have the greatest potential to be used in the field as part of a smart work zone to improve the work zone safety.

Driven by the insights gained through the literature review and from the analysis of the North Carolina work zone crash data, two proof-of-concept systems were developed using IoT, AI, and computer vision technologies for work zone safety. The developed systems provide capabilities for two functions: (1) work zone intrusion warning and (2) vehicle queue detection. The first of these systems is a proof-of-concept intrusion alert system, comprising a mobile device attached on a tripod to monitor the restricted area and that runs a software application designed to alert workers when an intrusion occurs. The workers receive alerts instantly through sounds and vibrations generated by their mobile devices. The system was tested in a simulated test

environment and the findings of the tests indicated its good potential to provide a robust technical approach to improving work zone safety. The second system is a proof-of-concept queue warning system, which was also developed and tested as part of this project. The results indicated it had significant potential to be used in smart work zones as a low-cost and easy-to-deploy system. Both systems were implemented to run on Android smartphones. However, the software is extremely portable, and therefore the efficient technical design means it can be embedded in any type of hardware.

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1. Introduction

Work zone crashes constitute a significant problem in the United States (US). In 2013, 579 fatalities and 32,719 serious crashes occurred in the US. Work zones also have a significant impact on the efficiency of the roadway networks. It has been reported that highway work zones trigger around a quarter of the non-recurring congestion, causing a significant amount of delays (888 million vehicle hours of delay in 2014) (Awolusi & Marks, 2019). Work zones alter the existing geometric layout of a roadway and disturb its usual traffic patterns. These changes have significant implications for safety, mobility, and efficiency (Silverstein, Schorr, & Hamdar, 2016). Smart work zones incorporate technical solutions that have been developed to address these problems by combining state-of-the-art sensor technologies, data communication infrastructure, and automated data processing capabilities.

This research report takes a twofold approach to explore IoT-based smart work zone solutions to address the work zone safety problem. This approach involved two parallel and harmonized research activities that aimed to explore the most promising approaches to improve safety in work zones. The first of these activities involved a study of the existing intelligent transportation system (ITS) work zone safety systems that are available on the market. Special emphasis was placed on technical solutions providing connectivity among various system elements. The main outcome of this first element was the identification of three commercially available devices and the associated deployment methods that can provide the greatest potential to improve work zone safety. To gain an understanding of the nature of work zone crashes, the team acquired a work zone crash data set from North Carolina Department of Transportation’s (NCDOT) Transportation, Mobility, and Safety Division and conducted an analysis of the crashes that occurred in North Carolina’s work zones between 8/1/2008 and 1/31/2020. The analysis provided insights into the major crash types and the triggers of the crashes that resulted in serious injury and fatality. Addressing the most common crash triggers and crash types can provide the maximum benefit in terms of reducing the number of crashes in work zones.

Based on the findings of the work zone crash data, the team focused on products and technical approaches that could provide the maximum potential for addressing the crash types identified by the statistical analysis of the work zone crashes. The project team conducted a comprehensive analysis of the available technologies, products, devices, methods, IoT-based approaches and systems that have the potential to improve work zone safety. This report explains and demonstrates how the recommended work zone safety systems and methods can be applied in practical implementation cases. The team further supported the analysis by providing a detailed account of the possible implementation scenarios and by evaluating their limitations, reliability, and efficiency under various variables, such as time of the day, weather, road conditions, specific threats and risks, and traffic patterns.

The second element of this research evaluated and demonstrated two proof-of-concept systems that were developed by the author to be used in smart work zones. One system involved a work zone alert system, while the second one addressed the queue detection problem. The developed systems are based on AI, computer vision, and IoT technologies. The author developed an experimental setup for assessing the proof-of-concept systems using IoT, AI, and computer vision technologies for improving work zone safety. The report provides insights on how the proposed proof-of-concept systems can be practically used in a typical smart work zone setting. The first system comprised a mobile device (smartphone) attached to a tripod to monitor the restricted area within a work zone, which alerts the workers when a work zone intrusion occurs. The second system provides queue detection capability and generates cloud-based alerts that can be disseminated to display boards and other relevant parties.

1.1. Research Need Definition

The impact of work zone-related crashes is substantial in North Carolina. In 2016, there were 5,831 work zone crashes in the state. As a result of those incidents, there were 26 deaths and 3,095 injuries. Among the victims who lost their lives, 24 were travelers, while two were workers. The statistical data indicated that there is a clear need for better and more efficient safety devices and methods in work zones. It is clear that reliable and effective warning systems should be employed in work zones that can generate timely and efficient alerts within the vicinity of the area to help prevent crashes. In this regard, recent advances in the areas of sensor design, AI, low-cost edge computing, IoT, computer vision, and dynamic web applications have the potential to be translated and fused into integrative systems and reliable methods that would enable the implementation and operation of safer and smarter work zones. This research project was designed to explore the potential provided by various technological approaches to achieve this aim.

1.2. Research Objectives

This study addressed the work zone safety problem by pursuing two parallel exploratory research processes. The first process centered around a study of the existing commercially available systems and methods that have the highest potential to improve work zone safety. As a result, three commercially available products were identified that could be recommended to be used in work zones. The second process involved developing two proof-of-concept systems. One of these was focused on detecting work zone intrusions and alerting the workers instantly. The second one provides a capability for detecting queues and for generating and issuing cloud-based alerts that can be disseminated to various users. The designs of these were based on AI, computer vision, and IoT technologies.

This project focused on the following research objectives:

- To provide an account of the key smart work zone technologies and methods that have the highest potential to improve safety, efficiency, and mobility in work zones, and to specify the particular types of threats that those devices and methods can mitigate.
- To explain and illustrate how available and emerging work zone safety systems and methods can be implemented practically in the field.
- To recommend a number of commercially available devices or methods that have the greatest potential to be used in the field to improve work zone safety.
- To investigate the feasibility of using AI, IoT, and computer vision technologies for improving work zone safety by developing proof-of-concept systems that demonstrate the technical approaches proposed by this project.

2. Literature Review

A typical work zone comprises five areas: advance warning area, transition area, buffer space, workspace, and termination area (Fig. 1). The buffer space provides a separation between the workers and the transition area. The workspace is the area where the construction or maintenance activities occur. The length of a work zone varies greatly from project to project. The total length of a work zone can be as long as several miles or as short as a few hundred feet. Larger and more complex projects often require longer advance warning areas equipped with multiple message display boards and traffic channeling devices. They also feature longer transition and buffer areas.

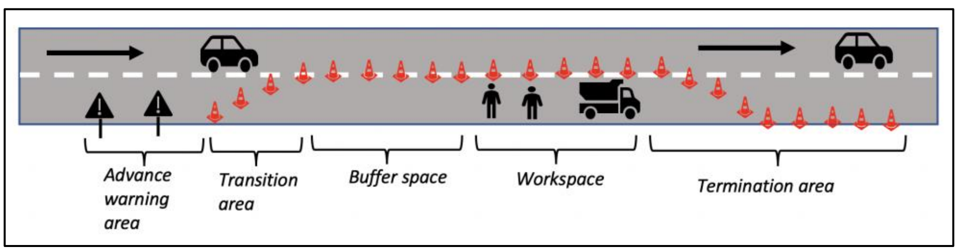

Figure 1 Areas of a road work zone

The term *Smart Work Zone* is also referred to as a *Work Zone Intelligent Transportation System* and is defined as the deployment of intelligent transportation system (ITS) technologies and technical solutions to increase the safety, mobility, and efficiency of work zones. Smart work zone solutions are often deployed for a period of time, but on a temporary basis, typically until the project is completed (TxDOT, 2018). The IoT can be defined as systems of interconnected sensors, actuators, and computing devices that have the capabilities to execute their tasks semi-autonomously or fully autonomously. Most smart work zones are designed to automate certain tasks by processing the data generated by the connected sensors, and therefore, they show the characteristics of an IoT architecture.

A previous study (Gambatese, Lee, & Nnaji, 2017) determined what were the most commonly used work zone safety technologies in highway construction projects in the United States. According to their findings, portable changeable massage signs (PCMSs) constituted the most common technology used in work zones. These were followed by portable rumble strips, Doppler radar-based speed detection, and automated flaggers. Work zone intrusion alert systems were the least popular technology used in highway construction projects. In the United States, the majority of smart work zone applications utilize radar sensors to measure traffic conditions and PCMSs to disseminate warnings and guiding messages to motorists. In addition to the current systems, there are also a number of novel technologies still under development. Some of these novel approaches may provide the potential to lower sensor costs and increase the system efficiency. Bernas et al. conducted an extensive survey and comparison of low-cost novel technologies for road traffic monitoring (Bernas, et al., 2018).

Smart work zone technologies generate data through various sensors, which measure a variety of traffic parameters (e.g., speed, volume, lane occupancy, travel times) and also detect the occurrences of significant events (queues, congestions, dangerous road conditions, work zone intrusions, etc.). The data gathered by the sensors are processed by human or machine-based systems and converted into actions that address the pertinent safety, mobility, and efficiency problems. Smart work zones are typically designed to automate such actions for some of the critical processes. For example, an end-of-queue detection unit can be configured to trigger an alert message to be displayed on the PCMSs. Data can also be processed by operational dispatchers or other stakeholders to help make decisions and gain situational awareness from work zones. Smart work zones can also be designed to record data for reporting and for in-depth analysis for various types of decision-making (TxDOT, 2018).

There are plenty of successful smart work zone applications applied throughout the United States. The Kansas Demonstration Project (Bledsoe, Raghunathan, & Ullman, 2014) is one such example that is useful for illustrating the structure of a typical smart work zone design. The project was developed during the construction of the I-35/Homestead Lane Interchange in Johnson County, Kansas. This particular smart work zone used trailer-mounted sensors to collect vehicle speed, classification, volume, and lane occupancy. Data was gathered for up to 10 lanes of traffic in each direction. Through an Internet connection, the traffic data was transmitted to a remote location, where it was processed by a software system. Depending on the traffic conditions, the system remotely activated messages that were displayed on the PCMSs to provide alerts and guidance to motorists around the work zone.

Another example is an ITS project implemented by the Michigan Department of Transportation for the total closure of the I-496 in downtown Lansing. The setup featured 17 cameras and six queue detectors and “12 CMS [changeable message signs] to display advance traveler information to the public to help alleviate traffic congestion resulting from the full closure of a major freeway” (Ullman, Schroeder, & Gopalakrishna, 2014).

A third example is the New Mexico Department of Transportation’s deployment of ITS during the reconstruction of the I-40 and I-25 interchange in Albuquerque. The system included “eight cameras; eight modular CMS; four arrow dynamic signs; four all-light emitting diode (LED) portable CMS trailers; four portable traffic management systems, which integrate cameras and CMS on one fully portable unit; and four HAR units, all linked electronically to the temporary Big I TMC to better manage incidents during the project” (Ullman, Schroeder, & Gopalakrishna, 2014).

Smart work zones require substantial expenditure for implementation and operation in many construction projects. Currently, in most cases, a significant level of engineering effort is required to integrate the commercially available products into an effective and reliable technical solution for a work zone. Each work zone site has its own unique characteristics. Therefore, the solutions often need to be customized to address the needs of the particular project setting. For example, what constitutes a queue can vary from one project site to another. Consequently, smart work zone designers often allocate a considerable amount of time and effort to customizing the control logic used in their systems. A cost breakdown of the Kansas project illustrates the cost factors involved in a typical smart work zone project (Bledsoe, Raghunathan, & Ullman, 2014). In that particular example, the total cost of the smart work zone system was estimated as $1,650,000. A significant portion (54.7%) of the budget was allocated for the software/consulting and ITS software upgrade activities, which focused on the customization efforts needed for the project. Some cost examples of a number of smart work zone projects are shown in Table 1. It can be seen that the total costs vary between $1,500,000 to $2,000,000. Guidance on the cost factors involved in smart work zone systems can be found in (Decision Tree to Identify Potential ITS/IWZ Scoping Needs, 2019).

Table 1 Examples of smart work zone costs

Project Description	**Smart Work Zone Technology Costs**
Construction of the I-35/Homestead Lane Interchange in Johnson County, Kansas (Bledsoe, Raghunathan, & Ullman, 2014)	Total cost: $1,650,000. Major equipment items: -22 Wavetronix sensors -18 portable changeable message signs -7 variable speed limit signs on I-35 -6 CCTV cameras to facilitate the real-time monitoring of traffic conditions
The Michigan Department of Transportation deployed ITS during a total closure of the I-496 in downtown Lansing (Ullman, Schroeder, & Gopalakrishna, 2014)	Total cost: $2 million Major equipment items: -17 cameras -6 queue detectors -12 CMS to display
The New Mexico Department of Transportation deployed ITS during the reconstruction of the I-40 and I-25 in Albuquerque.	Total cost: $1.5 million Major equipment items: -8 cameras -8 modular CMS -4 arrow dynamic signs -4 all-LED PCMS trailers -4 portable traffic management systems (integrating cameras and CMS) -4 HAR units

The design of a smart work zone constitutes an optimization problem. The efforts often focus on deciding on a system configuration that would provide the maximum benefit that can be delivered with the limited resources available. Therefore, system designers should have a sound process to decide on the elements and features of their smart work zones. The Minnesota Department of Transportation (MnDOT) provides a set of guidelines to help identify the ITS/IWZ technology needs (Decision Tree to Identify Potential ITS/IWZ Scoping Needs, 2019). They recommend the use of their decision tree for these purposes. The decision tree was designed to help decision-makers to determine their resource needs (time and monetary) to achieve the desired goals.

3. Analysis of the North Carolina Work Zone Crash Data

It is important to understand the nature of the traffic patterns that trigger crashes in work zones. That insight can enable decision-makers to identify optimal safety systems to eliminate the major triggers of harmful incidents. This chapter focuses on the analysis of the work zone crash data in North Carolina. Our analysis covered the North Carolina motor vehicle work zone crashes that occurred between August 1, 2008, and January 31, 2020. The data set was provided by the NCDOT Transportation, Mobility, & Safety Division and it contained 4251 observations and 64 variables. The objective of the data analysis was to identify the most significant traffic patterns that lead to the majority of the serious crashes in work zones. Therefore, we focused on the crashes that involved serious injuries and fatality. Those crash types are characterized in the data set as three types: B (crashes resulting in non-incapacitating injury), A (crashes resulting in incapacitating injury), and K (crashes involving fatality). The data set covers the crashes that occurred in or in close proximity to a work zone. The data set contained information on 4,251 incidents. Among these incidents, there were 240 crashes that resulted in fatalities, while 432 incidents involved serious incapacitating injuries, and 3,579 crashes caused non-incapacitating injuries (see Table 1).

Table 2 Breakdown of the incidents according to the crash severity

Severity				
Severity	Frequency	Percent	Cumulative Frequency	Cumulative Percent
A	432	10.16	432	10.16
B	3579	84.19	4011	94.35
K	240	5.65	4251	100.00

The breakdown of the crashes according to the time period of the incidents (Table 3) indicates that most crashes occurred during the afternoon from 1 pm to 5 pm (27.01%) and at nighttime from 8 pm to 6 am (26.23%) despite there being much less traffic at night. This analysis indicated that work zones are most dangerous between 8 pm and 6 am since there is a higher likelihood of a crash per vehicle in the vicinity of a work zone.

Table 3 Time of work zone crashes

Time_Period	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Afternoon_1_to_5pm	1148	27.01	1148	27.01
Evening_rush_hour_5_to_8pm	600	14.11	1748	41.12
Morning_9am_to_12pm	677	15.93	2425	57.05
Morning_rush_hour_6_to_9am	491	11.55	2916	68.60
Night_8pm_to_6am	1115	26.23	4031	94.82
Noon_rush_hour_12_to_1pm	220	5.18	4251	100.00

The crash data set covered eight levels of light conditions for the crashes (see Table 4). The majority of crashes occurred under the conditions characterized as “Daylight” (66.69%), while around 29.79% of them occurred under light conditions described as “Dark”. When we consider that the volume of traffic during dark light conditions is significantly lower than the daylight time traffic, we can conclude that there is a higher probability of a crash occurring during dark lighting conditions in work zones.

Table 4 Impact of the light conditions

Light Conditions				
Light_Conditions	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Dark - Lighted Roadway	465	10.94	465	10.94
Dark - Roadway Not Lighted	791	18.61	1256	29.55
Dark - Unknown Lighting	10	0.24	1266	29.78
Dawn	61	1.43	1327	31.22
Daylight	2835	66.69	4162	97.91
Dusk	83	1.95	4245	99.86
Other	4	0.09	4249	99.95
Unknown	2	0.05	4251	100.00

The impact of the “first harmful event” is analyzed in Table 5. The data indicated that the harmful event type “Rear End, Slow or Stop” constituted 33.9% of incidents, while 12.75% of the crashes occurred with the harmful event type “Fixed Object”.

Table 5 Impact of the first harmful event

First Harmful Event				
First_Harmful_Event	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Angle	382	8.99	382	8.99
Animal	12	0.28	394	9.27
Backing Up	8	0.19	402	9.46
Fixed Object	542	12.75	944	22.21
Head On	138	3.25	1082	25.45
Jackknife	7	0.16	1089	25.62
Left Turn, Different Roadways	128	3.01	1217	28.63
Left Turn, Same Roadway	170	4.00	1387	32.63
Movable Object	108	2.54	1495	35.17
Other Collision With Vehicle	45	1.06	1540	36.23
Other Non-Collision	79	1.86	1619	38.09
Overturn/Rollover	223	5.25	1842	43.33
Parked Motor Vehicle	55	1.29	1897	44.62
Pedalcyclist	31	0.73	1928	45.35
Pedestrian	219	5.15	2147	50.51

Ran Off Road - Left	104	2.45	2251	52.95
Ran Off Road - Right	160	3.76	2411	56.72
Ran Off Road - Straight	23	0.54	2434	57.26
Rear End, Slow Or Stop	1441	33.90	3875	91.16
Rear End, Turn	18	0.42	3893	91.58
Right Turn, Different Roadways	23	0.54	3916	92.12
Right Turn, Same Roadway	14	0.33	3930	92.45
Rr Train, Engine	2	0.05	3932	92.50
Sideswipe, Same Direction	221	5.20	4153	97.69
Sideswipe,opposite Direction	93	2.19	4246	99.88
Unknown	5	0.12	4251	100.00

Table 6 provides a breakdown of crashes according to the work zone project types. The majority of crashes occurred inside an area described as the "Construction work area" (80.26%), while 12.14% of them occurred in an area characterized as the "Maintenance work area."

Table 6 Breakdown of crashes according to the work zone types

Type of Work Zone crash occured in or near				
Type_of_Work_Zone_crash_occured	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Construction work area	3412	80.26	3412	80.26
Intermittent/moving work	139	3.27	3551	83.53
Maintenance work area	516	12.14	4067	95.67
No	45	1.06	4112	96.73
Utility work area	139	3.27	4251	100.00

In addition, the majority of the crashes occurred during "ongoing" work activity (59.06%). Other researchers' work found in the literature indicated that the "fatal crash risk in maintenance work zones was the greatest under nighttime conditions, while construction and utility work zone fatal crashes were the greatest under daylight conditions" (Craig, Achtemeier, Morris, Tian, & Patzer, 2017).

Table 7 Active versus non-active work zones at the time of crashes

Work Activity at time of Crash?				
Work_Activity_at_time_of_Crash_	Frequency	Percent	Cumulative Frequency	Cumulative Percent
No apparant activity	1722	40.94	1722	40.94
On going	2484	59.06	4206	100.00
Frequency Missing = 45				

Table 7 compares the crashes that occurred in an active work zone versus in non-active work areas. The majority of the crashes (59.06%) took place when there was an ongoing activity in the work zone. The majority of the crashes occurred in areas "adjacent to the actual work zone" (47.62%), while 34.62% of crashes occurred a "in a work area approach taper" (see Table 8). When we look at the findings of researchers who have evaluated the nationwide statistics, there are mixed views and conclusions regarding the most dangerous areas of a work zone. One reason that was given to explain this conflicting finding was the variations, incompleteness, and inaccuracies encountered in the crash data. Crash data are compiled based on the entries and reports written by various law enforcement officers, which results in variations in the data. Some researchers' findings have indicated that the activity area is the most significant part of the work zone, representing 40% to 70% of crashes, while the termination area has been found to be the least significant contributor of crashes (Craig, Achtemeier, Morris, Tian, & Patzer, 2017).

Table 8 Breakdown of the crashes according to their position within the work zone

Location of Crash - relevant to work zone				
Location_of_Crash__relevant_to	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Adjacent to actual work zone	2003	47.62	2003	47.62
Before work area	747	17.76	2750	65.38
In work area approach taper	1456	34.62	4206	100.00
Frequency Missing = 45				

Most of the crashes occurred with the Unit 1 maneuver "Going straight ahead" (70.87%), while 9.42% of crashes happened with the Unit 1 maneuver "Making left turn", and 5.67% happened with the Unit 1 maneuver "Changing lanes or merging" (see Table 9). Some researchers (Craig, Achtemeier, Morris, Tian, & Patzer, 2017) have indicated that "rear-end crashes most often occur within the Advance Warning Area, likely due to slowing traffic in response to the work zone, and side swipe crashes increase in the Transition Area, likely due to increased lane changing behavior in this area."

Table 9 Analysis of unit 1 maneuvers during work zone crashes

Unit 1 Maneuver				
Unit_1__Maneuver	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Avoiding object in road	27	0.65	27	0.65
Backing	19	0.46	46	1.11
Changing lanes or merging	236	5.67	282	6.78
Going straight ahead	2949	70.87	3231	77.65
Leaving parked position	1	0.02	3232	77.67
Making U turn	27	0.65	3259	78.32
Making left turn	392	9.42	3651	87.74
Making right turn	54	1.30	3705	89.04
Other	25	0.60	3730	89.64
Parked in travel lanes	24	0.58	3754	90.22
Parked out of travel lanes	16	0.38	3770	90.60
Passing	25	0.60	3795	91.20
Slowing or stopping	161	3.87	3956	95.07
Starting in roadway	49	1.18	4005	96.25
Stopped in travel lane	156	3.75	4161	100.00
Frequency Missing = 90				

Silverstein et al. (2016) concluded that rear-end and side-swipe (RESS) types of collisions constitute the most significant types of crashes recorded in work zones. Their recommendation was for potential smart work zone applications to focus on creating safer traffic flow conditions by encouraging safer driver maneuvers through the inclusion of speed harmonization control methods and vehicle-to-vehicle communication driving assistance systems. They also expressed that the use of some "common control measures, such as speed enforcement cameras, may need to be reevaluated given the marginal difference in the effect of speed limits when comparing work zones to nonwork zones." (Silverstein, Schorr, & Hamdar, 2016). Furthermore, they emphasized the significance of RESS collisions in work zones.

The conclusions of our analysis of the crash statistics within work zones are summarized as follows.

- Greater safety improvements can be achieved by implementing safety measures addressing rear-end, side-swipe, and angle type collisions. Queue warning and dynamic lane merge systems have potential in this aspect.
- Work zone intrusion incidents constitute a small portion of the overall work zone crashes. However, when they occur during an active work zone, they pose a great risk for fatality and serious injury. Although worker fatality and injury constitute a small portion of the overall crashes, they are significant when we look at the issue from an occupational safety point of view. Road construction is one of the most dangerous professions in the United States, and a significant portion of the risks is due to work zone intrusion incidents.

4. Analysis of the Key Smart Work Zone Technologies

This chapter focuses on the most significant technologies that have the highest potential for safety, mobility, and efficiency improvements in work zones. It has to be noted that there are many more technologies and commercial safety systems available in the market; however, here we focus on the systems that are relevant for the scope of this study, which is centered around IoT-enabled smart work zones. The systems covered in this chapter reflect the technical approaches that have demonstrated proven track records in the field and that also have the potential for further improvement and innovation.

4.1. Queue Warning Systems

Queue warning systems have been found to be effective in reducing the occurrences of rear-end crashes in work zones. A queue warning system detects slowdowns and queue formations in a roadway through the use of a capability to measure certain traffic parameters (vehicle speeds, occupancy, etc.) and a control logic to generate appropriate signals to display to drivers. Such systems typically use dynamic message signs and/or flashing lights to alert motorists. In this way, drivers can be informed about slowdowns ahead and can take action to reduce their speed. Queue warning systems have the potential to reduce rear-end crashes, increase travel speeds, and reduce the speed differentials between vehicles (MnDOT, 2008).

Queue warning systems should be carefully designed since the configuration of the elements poses an optimization problem. In particular, roadways that experience unpredictable queue formation patterns (fluctuating and non-recurring queues) are challenging. The locations of sensors and message signs have to be selected optimally. Since it is often difficult to predict the possible locations of queue tails in work zones, there is always a possibility that drivers may encounter stopped or slowdown traffic before they see a warning sign. Therefore, work zone operators have to monitor queue lengths actively to make any necessary corrections (MnDOT, 2008). In addition, system operators need the numbers for the estimated maximum queue length, which would enable them to decide where to place the first warning message displays, as well as an estimate of the average queue length. The quantity and locations of speed sensors will also be determined by those estimations (Fig. 2). The control logic for issuing alerts can be as simple as establishing a set of threshold speeds that trigger a pre-selected mode of messages that will be displayed on the PCMSs. An example of such a simple control logic is provided in Table 10.

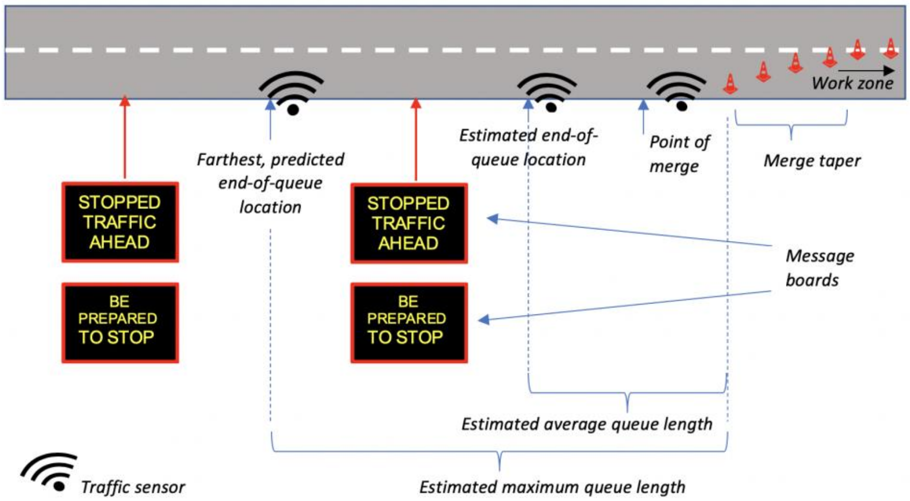

Figure 2 General structure of a queue warning system

Table 10 Typical messages to be displayed on PCMSs (TxDOT, 2018)

Traffic Condition:	Free Flow Conditions	Delays or Slowdowns	Long Delays/Stopped Traffic
Downstream Measured Speed:	greater than 45 mph	less than 45 mph and greater than or equal to 25 mph	less than 25 mph
Messages Displayed on PCMSs:	ROAD WORK AHEAD	SLOW TRAFFIC X MILES	STOPPED TRAFFIC X MILES

Note. Adapted from "Smart Work Zone Guidelines Design Guidelines for Deployment of Work Zone Intelligent Transportation Systems (ITS)", Texas Department of Transportation, 2018, p.18.

The design complexity of the control logic for the queue alerts will be dictated by the specific needs of the work zone site. The following example (Hourdos, et al., 2017) illustrates this point. The Minnesota Department of Transportation developed two different control logics for two sites on the 1-35W and I-94. The project involved the implementation of an active traffic management (ATM) system. They built two separate systems to identify lane-specific shockwaves or queuing conditions and to warn motorists in order to prevent rear-end collisions. The two locations experienced different traffic patterns, which required the development of different control algorithms for the same problem. As this example shows, it is not always possible to apply the same simple speed threshold-based control logic for all queue warning systems. Therefore, to achieve an effective design of a queue warning system, one should configure the elements listed below optimally.

- An effective criterion for what constitutes a queue and/or a slowdown
- Locations of message displays and signs
- Types of messages displayed (and/or activation of flashing lights) on each board (or warning device) for any given traffic mode
- Locations and detection ranges of the sensors
- Types of sensors (radar, loop, machine vision, etc.) used at any given sensor location
- Whether or not the system employs virtual sensors (crowdsourced data or probe data)
- Whether or not CCTV cameras will be used to validate traffic data and/or to provide situational awareness at selected sites
- Control logic (the algorithm that activates the warning messages based on the measurements obtained from the sensors)
- Data communication method to provide connectivity between the various elements of the system (Internet, short range radio, or a mix)
- Whether or not the system will provide a capability to issue alerts on mobile apps

The literature indicates that the control logic can be complicated by the traffic patterns experienced in individual roadways. It is not always straightforward to decide what should be interpreted as a queue in a roadway. Current sensors and detectors tend to capture measurements from a slice of the roadway; therefore, their output is sensitive to the behavior of the limited number of vehicles within their detection range. This can cause certain situations where traffic measurements may fail to depict an accurate representation of the traffic status in a roadway. For example, a few vehicles slowing down within a short segment of a roadway can potentially trigger a false queue alert even when there are no actual queues impacting the traffic flow. The measurement fluctuations should therefore be compensated by carefully designed algorithms embedded into the control logic. In many cases, queue warning systems employ an algorithm that calculates a rolling average of the measurements over a period of time (e.g., 5 minutes) to prevent fluctuating messages on PCMSs. However, this can also limit the reaction times of the system toward actual rapid queue formations and can cause the system to generate delayed warnings, which can decrease the potential for reducing rear-end collisions. These issues indicate that queue warning systems need better sensors, detectors, and predictive algorithms that can more accurately evaluate larger lengths of roadways and help make smarter determinations of the traffic flow.

4.2. Dynamic Late Merge Systems

Dynamic late merge systems constitute a type of smart work zone configuration that optimizes the capacity usage in work zones while improving safety and efficiency. They are also referred to as zipper merge systems. Such systems typically alert drivers of an upcoming traffic slowdown or stopped traffic, instructing them to use both lanes until the designated merge point. In this way, the capacity usage is increased, and queue lengths are decreased. It has been shown that zipper merge systems can reduce the length of upstream queues by 40%. Dynamic late merge systems can also reduce the differential speed between lanes, therefore resulting in a more harmonized roadway and safer traffic patterns (MnDOT, 2008). Vaughan et. al (2018) explained the benefits of zipper merge treatments in North Carolina.

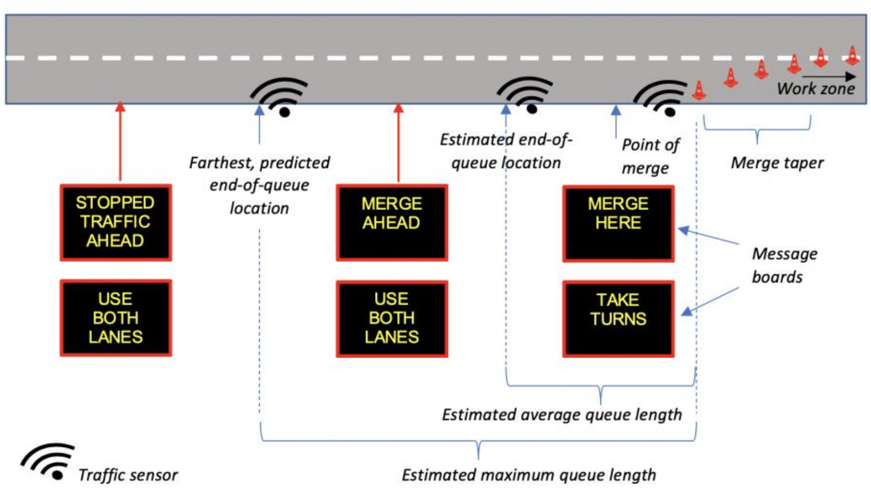

Figure 3 A typical layout for zipper merge treatments

Figure 3 shows the main elements involved in a typical zipper merge system. The message sign placed at the point of merging provides guidance on how the merge should take place. If a queue is present, drivers are instructed to take turns to proceed. If the traffic flows normally, a simple message of “merge here” is often displayed. For more upstream locations, drivers are instructed to use both lanes if a queue or slowdown is present. For locations beyond the end maximum queue length, a message of “stopped traffic ahead” is commonly shown to prevent rear-end collisions. The optimization challenges explained in the previous section are also applicable to zipper merge systems. The effectiveness of a dynamic late merge system is dependent primarily on the accuracy of the queue detection, the capability of the control logic, and the coverage of the range of the message signs.

4.3. Intrusion Detection and Warning Systems

Road construction is one of the most dangerous occupations in the United States. Road workers are 6 times more likely to be injured or killed on the job compared to other professions. More than 2,400 worker injury incidents each year are caused by traffic crashes that occur in work zones in the U.S. (Awolusi & Marks, 2019). Work zone crashes tend to be more severe than crashes that occur outside a work zone (Oregon Department of Transportation, 2020). A work zone intrusion is defined as an incident where a non-authorized vehicle enters into the part of the work zone that is closed to the public. Work zone intrusion sensors detect an intrusion event and the system then issues alerts to the workers present in the work area. Some systems also provide alerts targeting the drivers in the vicinity of the work zone. Each system features different sensor technology to detect the triggering event and different methods to notify workers. The main purpose of an intrusion detection system is to provide sufficient alerts to the workers so that they can escape from the path of an approaching vehicle. Such systems may also provide alerts to drowsy or distracted drivers to prompt them to take corrective measures. Figure 4 depicts the guidance provided by the Minnesota Department of Transportation on the recommended deployment of work zone intrusion systems in work zones. They recommend the deployment of an intrusion warning system or an electronic message sign displaying “workers present” when the workers are located adjacent to open lanes not separated with concrete barriers.

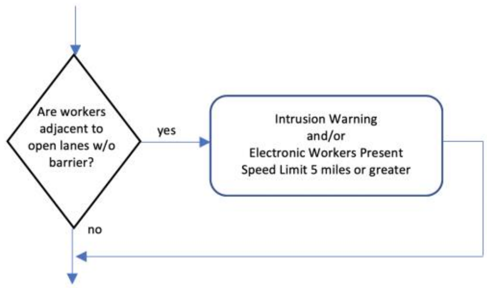

Figure 4 Scoping needs for an intrusion warning system

Note. Adapted from "Decision Tree to Identify Potential ITS/IWZ Scoping Needs" by Minnesota Department of Transportation, p.1. Retrieved from https://www.dot.state.mn.us/its/docs/scopingdecisiontree.pdf.

Marks et al. (2017) provided a detailed review of the technologies available for work zone safety at the time of their report. The study focused on identifying intrusion technologies for improving work zone safety. They selected a number of commercially available technologies and evaluated the performance of the equipment by conducting field experiments in simulated work zones. The researchers concluded that while the current product offerings are limited in numbers, they can be potentially used to provide alerts to highway workers when dangerous incursions are detected. Astro Optics LLC offers a product called the "Traffic Guard Worker Alert System (WAS)", which has some level of usability in work zones. The system uses trigger hoses that are laid in critical detection areas within a work zone. When a vehicle passes over the hose, a strobe light and siren get activated and alert the workers and drivers in the area. The workers' personal safety devices also warn them by vibrating.

Based on the findings of a recent report (Marks, Vereen, & Awolusi, 2017), a successful intrusion detection system should provide the following attributes:

- Avoids or minimizes the working crew's exposure to traffic during the deployment.
- Minimizes the amount of time and level of effort needed to set up the equipment
- Minimizes the rate of false alerts since these desensitize the workers
- Minimizes the space needed for the equipment
- Maximizes the durability of the system
- Avoids potential misalignment problems in the detection area
- Minimizes the cost

Marks et al.'s (2017) study also highlighted the lengthy setup times, false alarms, misfires, and alignment difficulties as the significant shortcomings of the intrusion alert systems on the market, and which "hinder the widespread application of these technologies for work zone safety." That particular study recommended Intellicone and Traffic Guard systems. The study also provided guidance on the selection of work zone intrusion devices according to the project types. They recommended Intellicone for projects lasting longer than one day with a taper longer than or equal to 1,500 ft, while the Traffic Guard Worker Alert system was reported to be useful for short duration projects (one day or shorter) with a taper shorter than 1,500 ft.

Another study (Gambatese, Lee, & Nnaji, 2017) compared three work zone intrusion devices (SonoBlaster, Intellicone, Worker Alert System (WAS)) by surveying a group of ten users. They asked the users to rate the systems based on four product characteristics: ease of use; effectiveness of the triggering mechanism; effectiveness of the alarm; and likeliness of use considering the cost. The ease of use ratings were similar for all three devices, with mean values ranging between 3.30 and 3.50 (within a rating system of 1 to 5). The effectiveness of the triggering mechanism was ranked the highest for the SonoBlaster system (mean rating of 3.30), while Intellicone was rated as the least effective (mean rating of 1.90) among the three systems. The alarm effectiveness was the highest for SonoBlaster. When the survey participants were asked to rate their likelihood of use considering the cost, they rated SonoBlaster the highest with a mean rating of 2.20, while WAS was rated 1.88 on average, and Intellicone received an average rating of 1.30. None of the three devices was successful in obtaining a rating of 3 or better in the area of overall likelihood of using them in the field. A report (Jacobs, 2018) prepared for Scottish Road provided detailed accounts of some anecdotal observations of using the Intellicone system. According to the report, Intellicone is currently used on 70% of the Highway England (HE) network, with its use mandatory in certain areas. Overall, the Intellicone system was considered to have a tendency to generate frequent false alarms since the cone can be accidentally knocked over. However, newer versions of the equipment provide different options for sensitivity to address this issue.

As a result of our review of the commercially available products in the market, three products were identified to demonstrate some level of track record in the industry and had also been covered in a number of research studies and pilot tests. Table 11 summarizes those products by comparing their key technical characteristics.

Table 11 Comparison of work zone intrusion alert products

Adapted from Gamatese et al. (2017) and Awolusi & Marks (2019), p.21.

	Sonoblaster (Transpo Industries)	**Intellicone (Highway Resource Solution)**	**Worker Alert System (Astro Optics, LLC)**
Detection trigger mechanism	Impact-tilt	Impact-tilt Wireless sensor (motion detector) activated	Pneumatic hose
Alert method	Audio	Audio, visual	Audio, visual, personal vibrating
	Device is attached to a channelizer along the taper	Device can be installed on a channelizer along the taper and work zone	Tube placed at the beginning of the taper
Reported issues	Alarm range, false alarm rates, setup time	Issues with the audibility of audio alerts	False alarm rates, short reaction time, limited detection coverage, setup time
Estimated price	$100 each	$2,000 each	$600 each
Estimated cost for a typical work zone	$1,260–$1,980	$2,400–$3,200	$5,940

Many researchers have emphasized the importance of the sound levels when audio-based alerts are used. When sirens or other alarm sounds are used in a work zone intrusion alert system, they must produce sufficient levels of sound. One study (Nnaji, Gambatese, & Lee, 2018) recommended at least 93 dB within 50 ft of the receiving party. Although work zone intrusion detection systems are commonly seen as alert devices, they can also be designed to function as a data collection platform for recording the work zone intrusion occurrences. Therefore, they can potentially serve two purposes: alert generation and data collection. The importance of collecting work zone intrusion data has been articulated by many researchers. One such study (Lin, Chen, & Wu, 2006) developed a method that facilitates a system and a process for recording intrusions. Intrusion data collected in a smart work zone can provide important insights on the overall safety of the work zone and can provide a tool for the work zone operators to evaluate the configuration of their project area. It has to be noted that the majority of commercial products do not provide data logging functionality, although this feature has the potential to improve work zone safety.

4.4. Mobile App Alerts

Today's smart work zones rely on PCMSs to disseminate warning and guidance messages to motorists. However, roadside message signs have their limitations. Some researchers have addressed the importance of optimizing the number of PCMSs used in a work zone and the maximum number of message modes that can be communicated to drivers effectively. The idea is to prevent information overload and distraction, which can lead to drivers ignoring the warnings. A study conducted by Ullman et al. concluded "that sequential PCMSs should not display more than four total units of information" (Ullman, Schroeder, & Gopalakrishna, 2014). Therefore, work zone operators should optimize the separation and number of PCMS units deployed in the work zone. There are also significant cost considerations with the use of PCMSs. Generally, a PCMS costs between $12,000 and $20,000 (FHWA, Guidance for the Use of Portable Changeable Message Signs in Work Zones, 2013).

Mobile alerts have the potential to complement and substitute PCMSs in many smart work zone applications. In-vehicle voice-based mobile app alerts can be particularly effective for disseminating roadway information to motorists within the area impacted by the work zone. A literature review indicated that in-vehicle messages are better understood and remembered by drivers than PCMS messages, and therefore, there are potential benefits of using app alerts as part of an effective smart work zone design. Currently the Waze/Google Maps platform has the highest market share among mobile navigation apps. The Waze Connected Citizens Program enables automated real-time updates from devices in the field, which makes it feasible to generate alerts and guidance from smart work zones into the mobile app platform. Mobile apps can also communicate more information to receivers. For instance, Waze alerts provide 40 characters (even more) versus the 8 characters per line that can be displayed on a typical PCMS. A 2017 study (Craig, Achtemeier, Morris, Tian, & Patzer, 2017) provided insights on the effectiveness of in-vehicle messages. They conducted a number of driving simulation experiments to compare the effectiveness of different messaging interfaces in communicating the hazards to the driver. Their findings concluded that a voice based in-vehicle message is more effective than a message displayed on a roadside board.

4.5. Smart Work Zone Component Vendors

This section summarizes the findings of our review of smart work zone component vendors and manufacturers in the United States. The process to identify the three vendors listed below was based on an evaluation of the track records of the devices offered by these vendors and the volume of smart work zone applications that their product lines were used with effectively. It has to be noted that there are many more vendors in the market with quality products that can be reliably used in various smart work zone settings and the list provided below only reflects the findings of our assessment, which relied on the literature review we performed.

- Wanco Inc.: Wanco in partnership with QLynx (formerly PDP Smart Work Zone Systems) provides smart work zone components, such as radar and Bluetooth detectors, video cameras, and PCMSs. QLynx manufactures *QLynx Nano*, which is a detection system used in queue detection systems, travel time systems, and dynamic lane merge systems. The device can be mounted on trailers, poles, message boards, or other equipment.
- Ver-Mac: Ver-Mac manufactures smart work zone devices. They partnered with Jamlogic Software to develop complete smart work zone applications. The Ver-Mac product line includes PCMSs, portable sensors, cameras, and speed information feedback signs.
- Wavetronix: Wavetronix is a manufacturer of radar sensors for intelligent traffic systems. Wavetronix's SmartSensor HD product line can measure a wide variety of traffic

parameters, such as per vehicle speed, vehicle counts, average speed, 85th percentile speed, and occupancy.

4.6. Key Findings of the Analysis

As a result of the literature review, the analysis of the North Carolina work zone crash data, and the analysis of the prominent work zone design approaches in the United States, the following focus areas emerged:

- Queue detection/warning functions to reduce rear-end collisions
- Dynamic late merge systems to reduce speed differences between the lanes and to promote safer merging behavior
- Work zone intrusion alert systems
- Effective dissemination of work zone alerts and messages

Those points listed above led to the selection of the focus areas for the proof-of-concept system developments. Two critical technology focus areas emerged: work zone intrusion warning and queue detection systems. Currently there are no work zone intrusion alert devices that meet the expectations of work zone designers effectively. A new design approach is thus needed, and this study identified computer vision and AI technologies as the primary drivers of such a new design approach. Similarly, queue detection has its own practical challenges, and although there are a wide range of products on the market, queue and congestion detection still pose challenges for smart work zone designers. This study provides a proof-of-concept approach that can be the first step toward building more holistic, cost-effective queue detection methods that rely on AI and computer vision.

5. Proof-of-Concept Systems for Smart Work Zones

This chapter describes two proof-of-concept systems developed by the author. The developed systems demonstrate the feasibility of building low-cost AI and computer vision-based systems that could be used to build smart work zones. The systems were designed to disseminate alerts over the Internet. The proof-of-concept system development efforts focused on building two functional experimental systems: work zone intrusion alert and queue warning systems. In this chapter, each of the tools are explained in detail and the results of the tests and evaluations are discussed.

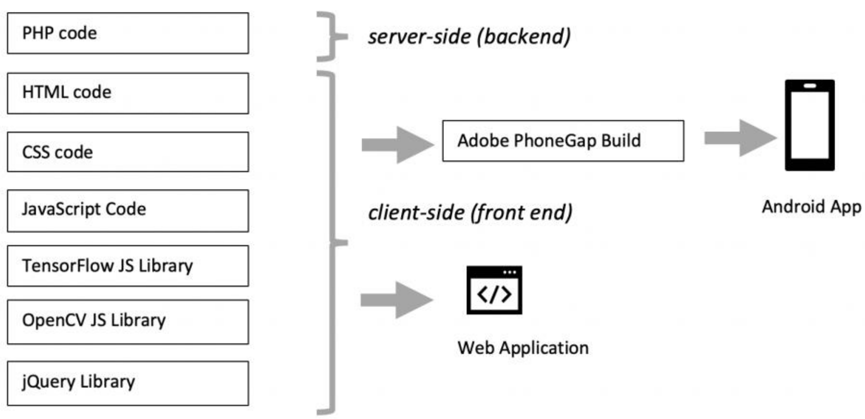

Figure 5 Software development process

Figure 5 outlines the main elements involved in the software development. This project used three prominent open source software libraries: TensorFlow JS, OpenCV, and jQuery. TensorFlow is a prominent open source machine learning application development platform that is used in various AI application development projects worldwide. TensorFlow JS is the JavaScript version of TensorFlow and it enables the development of browser and mobile device-based AI applications. TensorFlow is a complex and comprehensive ecosystem that provides pre-built machine learning models. This project used the *Coco-ssd* object classification model, which provides capabilities for locating and identifying the objects in a given image. Coco-ssd is provided within the TensorFlow platform, and provides the capability to identify vehicles in an image. The application developed for this project utilizes a version of the Coco-ssd model that was specifically designed for mobile devices. The software built for this project was designed to filter the Coco-ssd output to look for objects with the following object classes provided by the Coco-ssd model: “car"; “truck"; and “bus”. The Coco-ssd system has a built-in capability to detect people, therefore, more complex algorithms can be created if there is a need for detecting pedestrians in the area. The other important software library used by this project was OpenCV, which provides an extensive set of built-in functions for complex image processing and computer vision projects. Finally, jQuery is a library that streamlines web application development.

The end products of the software development are in two forms: server-side software and client-side software components (Android mobile apps and web apps). The web apps can be run on a browser on Android mobile devices as well as on desktop or laptop computers. The browser-based web applications were designed using progressive and responsive web development techniques; therefore, they provide a level of performance close to native mobile applications. This project also created Android apps that can be installed on Android smartphones.

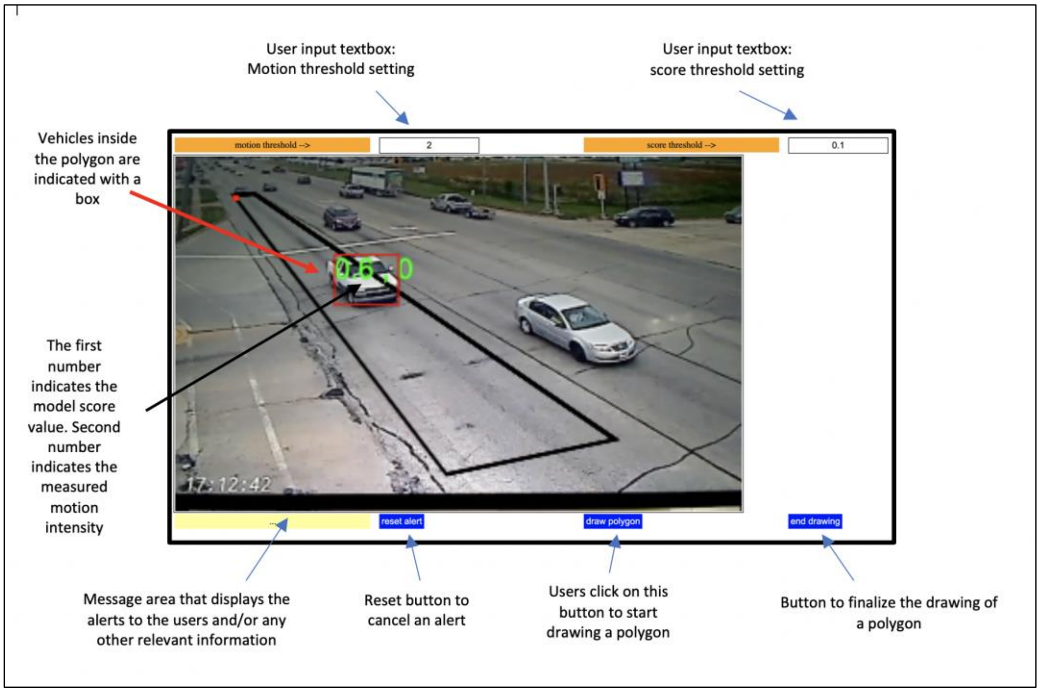

Figure 6 Elements of the user interface

The user interface of the proof-of-concept systems is shown in Fig. 6. The same elements and visual layout are used for both systems. The design features three buttons and two textboxes. There is a text area that displays relevant status messages to users, such as alerts and device readiness. The user input text boxes are used to calibrate the application when necessary.

The image-based vehicle detection constitutes the most critical capability in the proof-of-concept systems developed in this project. There is a considerable amount of literature regarding computer vision-based vehicle detection (Leibe, Schindler, Cornelis, & Gool, 2008); (Robert, 2009); (Xu, Yu, Wu, Wang, & Ma, 2017); (Zhangl, Xul', & Feng); and (Liu, Wu, & Zhang, 2007). The majority of the existing methods and research is based on conventional image-processing methods. One common conventional approach involves background-based methods, which are based on processing the differences between the current image and a constructed image of the background. Another common approach involves gradient-based methods, which detect the vehicle edges in a captured image (Zamin et al., 2003). Satzoda et al. (2012) used these approaches in their research, in which they developed a computer vision-based vehicle queue detection method combining edge detection and binary thresholding to detect vehicles. The performance of most vehicle detection systems is sensitive to the visibility factors of the scene. For example, Zanin et al. (2003) indicated that night conditions were a source of missing alarms. They also stated that shadows can lead to "overestimating the presence of objects on the roadway". The use of AI-based methods in this study provides the potential to overcome some of the challenges imposed by the deployment setting.

There are certain steps that need to be taken to ensure an accurate and reliable detection process. The first step centers around maintaining the physical stability of the mounting instrument. The detection device should be mounted on a sturdy structure (e.g., a tripod or a pole) and the operators should make sure that the system is not impacted by the wind since high speed winds may cause the detector unit to move. Also, since the system monitors a particular polygon area, unintentional camera moves will result in inaccurate detection performances. The system can tolerate slight vibrations and movements, but substantial movements may trigger missed or false detections. The next critical step is to designate the area that will be monitored. Here, the length of the selected roadway segment should be compatible with the requirements of the system.

The detection algorithms used in this project were based on the detection of a vehicle from its visible features. Therefore, the system can demonstrate a level of sensitivity toward elements that may impact the visibility negatively. For example, in dark road conditions, a vehicle's headlights' glare has a tendency to overwhelm the image and the vehicle body then becomes undetectable. Challenging situations can also be potentially experienced during heavy precipitation, fog, and highly reflective roadway conditions. The proof-of-concept systems developed here provide a number of calibration settings that can alleviate some of these environmental problems.

5.1. Proof-of-Concept System for a Work Zone Intrusion Detection and Warning System

As part of this project, the author developed a smartphone-based work zone intrusion detection and warning system to evaluate the feasibility of using AI-based computer vision methods to detect vehicle intrusions in work zones.

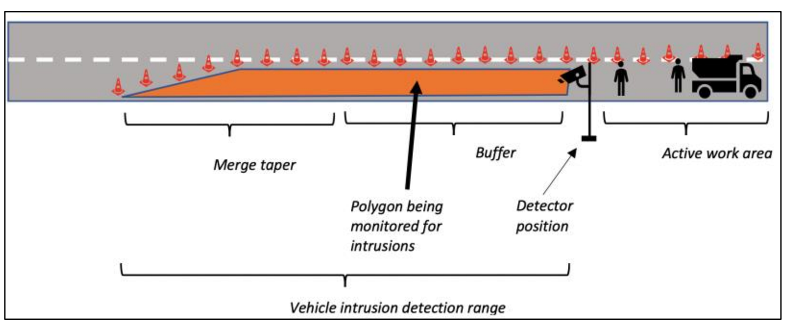

Figure 7 Detector position and detection area in a work zone

Figure7 depicts a typical setup showing the camera position and the detection area within a work zone. The system can function with various camera viewing angles. A typical and recommended setup involves the camera being placed closer to the active work area with the camera pointed toward approaching traffic. Table 12 lists the recommended lengths for the areas to be monitored by the device. The maximum length of the detection area should be 200 m. The minimum length depends on the speed limit posted in the area. Minimum distances between the work area and the detection area are also provided in Table 12. Note, the values provided in Table 12 are linked with the performance of the smartphone used in this project. Faster devices can potentially provide more flexibility in terms of the parameters included in Table 12 and may be used to detect shorter or longer roadway segments than those listed in Table 12.

Table 12 Recommended criteria for identifying the detection zone for the proof-of-concept work zone intrusion alert system

Roadway speed limit	**Minimum length of the roadway to be monitored**	**Maximum length of the roadway to be monitored**	**Minimum distance between the work area and the edge of the detection zone**
More than 45 mph	80 m	200 m	50 m (or use Equation 1)
45 mph or less	40 m	200 m	35 m (or use Equation 1)

Figure 8 Polygons are drawn on the device screen to designate the area that needs to be monitored for intrusions

At the beginning of a detection session, the user selects the area to be monitored by the smartphone. This is done by drawing a polygon on the device screen. An example of such a polygon is shown in Fig. 8. Any shape of work area that needs to be monitored can be approximated by a polygon. Once the polygon is formed, the device monitors the selected area to detect the entry of a vehicle into the restricted area. The system provides calibration settings that enable the operator to fine-tune the device to compensate for the visibility of the scene at the time. The device typically needs to be calibrated during nighttime operations or during adverse weather conditions (e.g., heavy rain, snow, fog, poor lighting). The system is designed to detect the presence of a vehicle inside the polygon area selected by the operator. The device can also be configured to issue alerts only when the detected vehicle travels faster than a certain threshold speed entered into the system. The detection algorithm is summarized in Fig. 9.

The proof-of-concept system built for this study uses a smartphone as a detection and alert device. The smartphone's camera constantly monitors the restricted area. If the system detects a vehicle in the designated polygon area, it issues alerts to the mobile devices worn by the workers. The alerts are relayed through a server. The mobile devices worn by the workers constantly poll data from a file on the server. The intrusion detection system updates that file when an intrusion occurs. Consequently, whenever an alert is recorded on the server, the alert receiver device worn by the worker sounds an alarm and also vibrates. Workers are able to hear the audio-based warning through their earbuds or through a portable speaker attached to their safety vests. They will also feel vibration alerts at the same time through the mobile device. The test system used the Internet for relaying the alerts in the work zone; however, it is also possible to use the system without an Internet connection. If the system needs to be run without an Internet connection in the work zone, the smartphone can be configured to host the server functionality and can act as the Wi-Fi router in the work zone to relay alerts to the receivers. The system can also be configured to generate alerts toward both cloud-based and local servers simultaneously to increase the system reliability. In this way, if the Internet connection is lost at the work site, the system can still generate alerts. The structure of the intrusion detection and alert activation mechanism embedded in the software is illustrated in Fig. 9.

A simplified representation of the work zone intrusion detection and alert process is outlined in Figures 9 and 10. The system constantly takes snapshots of the scene and processes them using the TensorFlow JS-based object recognition modules. The system only creates an alert when the detected vehicle is inside the polygon identified by the user. The sampling rate of the sensor depends on the computing power of the device being used. Faster mobile devices can process the images faster, which results in better system performance.

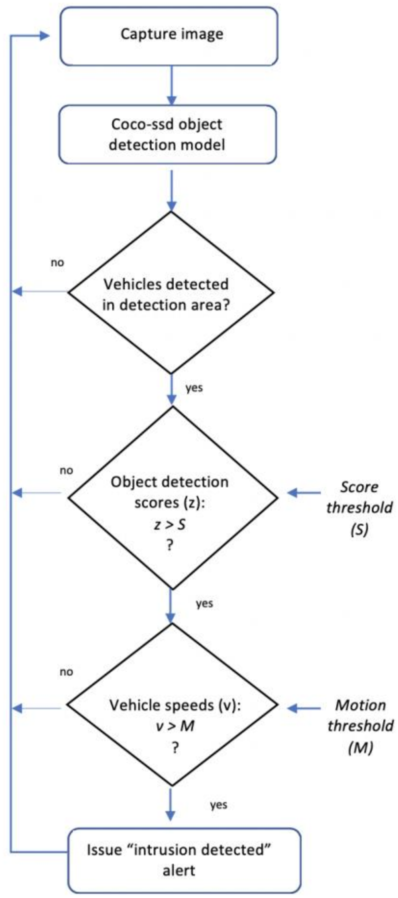

Figure 9 Simplified algorithm for proof-of-concept work zone intrusion detection and alert generation

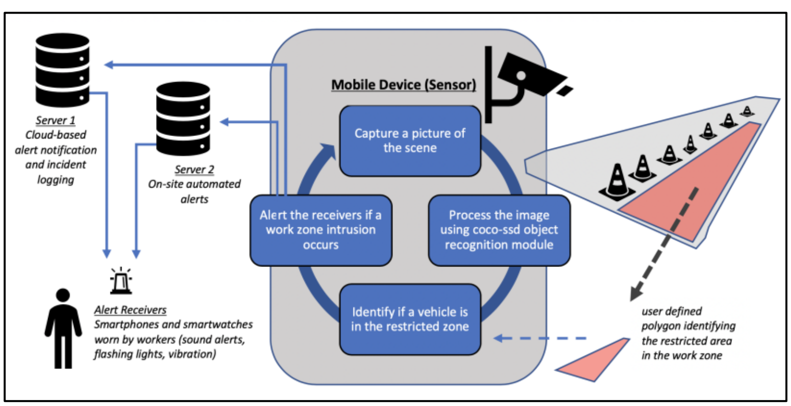

Figure 10 Proof-of-concept work zone intrusion detection and warning system architecture

Table 13 shows the detection speed for three different hardware setups. The tests were based on the web application version of the system, which runs on a browser. That enabled us to include a MacBook Pro computer in the speed tests. The speed values were generated by inserting special JavaScript code into the program to measure the time elapsed in between each frame. The processing time of each frame fluctuates depending on the image complexity and hence computational burden on the device at the time of measurement. The average sampling rate for the Razer 2 Phone system was found to be 3.62 frames per second. The maximum image processing delay recorded was 327.6 milliseconds. As expected, the MacBook Pro performed faster than all the other devices, which is not surprising as the device performance is related to the RAM size. The performance tests were conducted using a Razer Phone 2, which cost $399.99 at the time of this study. It was found to be an optimal selection to showcase the feasibility of building a low-cost AI-based smart work zone application.

Table 13 Detection speeds recorded with different devices

Hardware	**Detection speed (ms)**	**Processor**	**RAM size**	**Operating system**
MacBook Pro	Avg: 126.09 Min: 100.33 Max: 192.64	2.5 GHz Intel Core i7	16 GB	MacOS Mojave
Samsung Note 9	Avg: 327.94 Min: 222.29 Max: 378	Qualcomm Snapdragon 845	6GB	Android 8.1 Oreo
Razer 2	Avg: 276.2 Min: 165.3 Max: 327.6	Qualcomm Snapdragon 845	8GB	Android 8.1 Oreo

If the device uses an Internet connection to connect to the cloud-based server, the bandwidth requirements are minimal as the alerts are composed of minimal data sizes. The alert information is stored in a text file located at a secret URL location allocated to the individual work zone. The devices worn by the workers poll this URL every 10 milliseconds and generate an alert if the polled file indicates an intrusion incident. Alert receivers are registered to the work sites that they belong to. Therefore, an alert generated in one work zone will not trigger an alert in an unrelated work site.

The dissemination of the alerts is almost instantaneous, both for cloud- and local-based deployments, and the time lag between the detection and the notification was found to be unnoticeable to the human eye in lab tests. Web-based notifications are well suited for disseminating the alerts in terms of their speed and low bandwidth data connectivity requirements.

As the distance between the entry point of the intruder and a worker decreases, less time remains for the worker to escape the path of the vehicle. Therefore, for short distances, it may not be possible for a worker to escape from an impending collision even if an alert was issued.
To calculate the distance of the detection area from the active work area, we can use the following equation (1).

$$\mathrm{d} = (1.466).(t+p).v \tag{1}$$

In the above equation, *d* represent the minimum distance between the detection area edge closer to the work area and the active work area, *t* designates the minimum reaction time needed by an average worker in seconds, *p* is used for the time delay (in seconds) between the time of intrusion and the receipt of the alert by the worker, and *v* corresponds to intruding vehicle's speed in mph. It is difficult to estimate the minimum reaction time that is needed by an average worker to escape from the area threatened by the intruding vehicle due to the variations in the work zone configurations, the nature of the tasks being performed, and the individual worker's position at the time of the incidence. Our assumption for that parameter is based on Marks et. al.'s (2017) study, which indicated that, on average, it takes "a worker less than 1 second to respond to warning alerts produced by the tested intrusion sensing technologies" (Marks, Vereen, & Awolusi, 2017). Therefore, we assumed that 1 second is sufficient for the worker to escape from the path of the intruding vehicle and 500 milliseconds is the maximum delay between the time of intrusion and the time the alert is received by the worker; therefore, the minimum distance between the sensor and the active workspace should be 120.91 ft (36.85 meters) for a work zone with a speed limit of 55 mph. For a speed limit of 70 mph, this value was calculated to be 154 ft. It has to be noted that it is difficult to predict the intruding vehicle's speed for all possible intrusion incidents. Similarly, it is also challenging to estimate the reaction time needed by individual workers to escape from the intruder's trajectory. Table 14 summarizes the recommended distances for the position of the detection area relative to the work zone under different predicted speeds.

Table 14 Recommended sensor placement characteristics

Intruding vehicle's predicted speed (mph)	40	45	50	55	60	65	70	75	80
Required minimum distance between the detection area and the active work zone (ft)	88	99	110	121	132	142	154	165	176

The proof-of-concept queue warning system was tested using a number of YouTube video footages showing highway traffic videos from various locations throughout the world. The tests were conducted to cover a variety of environmental conditions simulating daytime and nighttime operations under clear and rainy weather conditions. Various camera angles were incorporated into the tests. At the start of each test experiment, the application output was observed for a period of about 1 minute to observe if calibration was needed to compensate for false and missed alerts. Whenever necessary, the system was calibrated by adjusting two parameters: the speed threshold and object detection model score. The speed threshold is the setting that determines the minimum level of speed that an object in the scene has to have in order to trigger an alert, while the model score is a number generated by the software for each detected vehicle and it represents the level of confidence in the prediction, where the number varies between 0 and 1, where a score of 1 represents a maximum level of confidence (100%). The results shown for the detection speeds in Table 14 indicated that a smartphone with an adequate RAM size could meet the expectations of an intrusion detection system. The Razer 2's performance was found to be adequate since it provided sufficient time to alert workers.

The performance of the proof-of-concept work zone intrusion alert system was evaluated through experiments conducted using a lab setting featuring a large screen television showing video footage and the smartphone pointing at the screen, running the work zone intrusion system. The output of the alert system was observed together with the scene displayed on the screen. The details of each experiment are provided in the Appendix. Table 15 summarizes the results of the experiments. The intrusion alert system performed most reliably during daytime and clear weather conditions (99% accurate alarm rate). The combination of nighttime and rainy weather posed the most challenging case, with an alarm accuracy rate of 92.3%. In general, missed alerts were more frequent than false alarms. As expected, the results indicated that daytime performance was better than nighttime and clear weather was better than rain.

Table 15 Summary of the performance tests for the proof-of-concept work zone intrusion alert system

Daytime/Nighttime	**Clear/Rain**	**Accurate alert rate**	**False alert rate**	**Missed alert rate**
daytime	clear	99%	0.2%	0.8%
daytime	rain	96.7%	0%	3.3%
nighttime	clear	97.7%	1.15%	1.15%
nighttime	rain	92.3%	2.6%	5.1%

Overall, the performance characteristics of the work zone intrusion system indicated it represented a promising approach for actual work zone implementation. The system provided an effective alert solution, especially when used during daytime and in clear weather conditions.

5.2. Proof-of-Concept System for Queue Detection

The queue detection function developed in this project relies on AI-based object classification functionality provided by TensorFlow JS and the background subtraction capability included in the OpenCV JS library. The system uses the same object detection method as was used in the work zone detection.

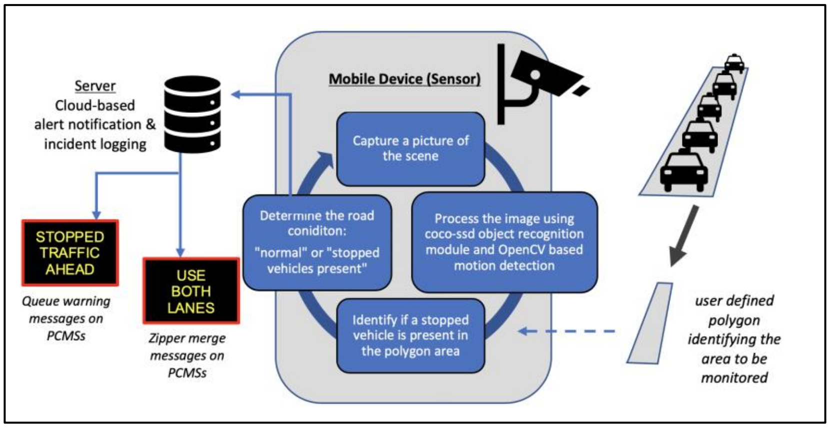

Figure 11 Proof-of-concept queue detection system architecture

The main functionality of the system is illustrated in Fig. 11. At the beginning of each session, the user selects the area to be monitored by the smartphone. This is done by drawing a polygon on the device screen. Once the polygon is formed, the device will monitor the selected area to detect stopped vehicles. The areas that will be monitored by the camera are defined by the polygons drawn by the operator on the device screen. The polygons should be selected in such a way that they cover a narrow band in the center of the roadway. Some examples of ideal polygon selections are shown below. Figure 12 shows a polygon selection example where two lanes are being monitored, while Fig. 13 demonstrates a polygon drawn for detecting queues within only one lane.

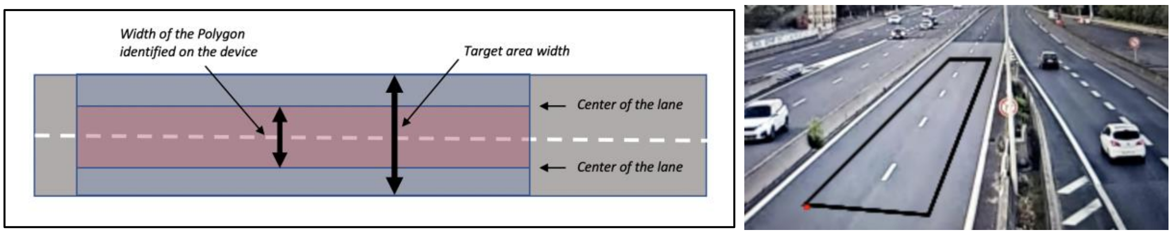

Figure 12 Recommended selection of the polygon area for queue detection

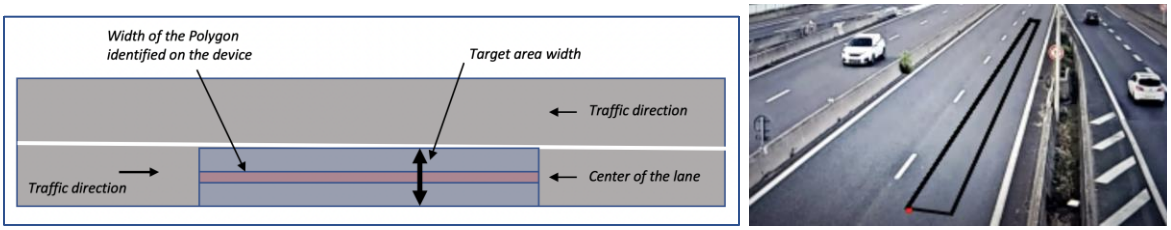

Figure 13 Recommended polygon selection for detecting queues within only one lane

For each work site, during the setup of the detector, the system has to be calibrated. The calibration is needed for the system to detect the stopped vehicles accurately. The proof-of-concept system displays numeric values that correspond to the level of movement for each vehicle. By observing the traffic flow and the numeric values displayed on the screen, the operator can determine a threshold value for the queue (stopped vehicle) alerts. Once that numeric threshold is determined, it can be entered into the system and the device will then start issuing queue alerts whenever the measured motion intensity falls below the threshold identified by the operator. The system is typically designed to detect stopped vehicles inside the polygon area. It is assumed that the detection of at least one stopped vehicle (or a motion intensity measurement below a threshold) inside the polygon area indicates the existence of a queue in the roadway. For future implementations, it will be possible to adjust the detection algorithm depending on the roadway operators' preferences. For example, it would be feasible to develop complex algorithms where the system can issue multiple conditions and where the system makes its determination based on various observed variables, such as the number of stopped vehicles versus the number of moving vehicles, slow but not stationary traffic, and the distance between vehicles. The algorithm embedded in the proof-of-concept queue detection system is explained in the diagram provided in Fig. 14. It has to be noted that in an actual smart work zone application, one would need to develop additional software elements, including a control algorithm (control logic) that ingests the output of the sensor and then uses a pre-defined algorithm to activate messages to be displayed on the PCMSs.

In addition to the Coco-ssd object classification model, the proof-of-concept queue detection system uses OpenCV's *BackgroundSubtractorMOG2* function to detect motion in the area monitored by the smartphone camera. This is a function available in OpenCV library and is based on the *Gaussian Mixture-based Background/Foreground Segmentation Algorithm*. The algorithm identifies and activates the optimal number of Gaussian distributions for every pixel included in the image. It can better tolerate variations in the input image, such as the ones typically caused by varying levels of illumination.

The performance tests used the same methodology that was described for the work zone intrusion warning system. The system was calibrated at the beginning of each experiment whenever a need for calibration was determined. Calibration was mostly needed for nighttime scenes. It may also be needed during adverse weather conditions that impact visibility, such as heavy precipitation.

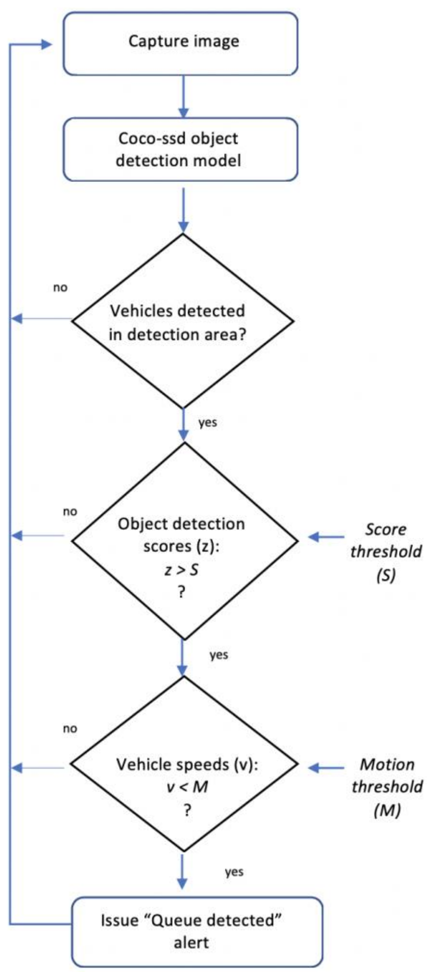

Figure 14 Simplified algorithm for the proof-of-concept queue detection and alert generation

Table 16 Summary of the performance tests for the proof-of-concept queue detection system

Daytime/Nighttime	**Clear/Rain**	**Accurate queue detection rate**	**False queue detection rate**	**Missed queue detection rate**
daytime	clear	93.4%	6.6%	0%
daytime	rain	66.6%	14.3%	19.1%
nighttime	clear	80.7%	15.45%	3.85%

The tests returned satisfactory results in daytime road conditions (see Table 16). The system was able to detect vehicles accurately virtually from all angles and made satisfactory predictions for stopped vehicles. Nighttime and rainy weather conditions, however, posed some problems. In such conditions, careful calibration is needed. Rain caused more inaccuracies than all the other condition types in the experiments conducted.

5.3. Summary of the Findings of the Proof-of-Concept System Development

This project demonstrated the feasibility of using open source machine learning and computer vision platforms in the development of technical design solutions for smart work zones. The results showed that when machine learning methods are combined with the capabilities of edge and mobile computing, it is possible to create cost effective systems, which expands the possibility for the implementation of smart work zone solutions for smaller lower budget projects. Although there are certain challenges with image-based detection systems, a video data stream is a rich information source that offers unique design possibilities. AI and high performing edge devices enable innovative designs that can augment the capabilities of the future generation of smart work zones.

6. Recommendations

There are many products geared toward use in work zones on the market. This study focused on the devices that can be utilized in work zones that can support an IoT architecture. We focused on technologies that have proven track records with demonstrated usability in the field. Because of their capability of being used under various environmental settings and the fact that they can be installed in the field without requiring any invasive alterations on the road surface, radar-based sensors are commonly used in queue warning and dynamic late merge systems in the United States. Magnetic loops can also provide acceptable functionality for traffic measurements; however, they require an invasive process to be installed on the roads and require lane closures for installation, which limits their usability in temporary installations that are typical in work zones. Video-based traffic measurement systems are used in some smart work zones but not as often as radar sensors. Cameras are more often deployed in work zones for surveillance and for situational awareness in work zones. They are also used for obtaining visual validations of the measurements and alerts generated by the sensors at a site. Therefore, at the moment and in the near future, radar-based sensors are likely to be more commonly used in smart work zones than other detection technologies. Thermal cameras have a potential to be used in work zones; however, most current thermal imaging solutions focus on intersection applications or long-term stationary type detection projects rather than temporary work zone installations.

Table 17 lists the products recommended by this study to be used in queue warning and dynamic late merge systems. It has to be noted that many of the performance variables of a smart work zone project depend on the configuration of the whole system rather than the performance of the sensors solely. Therefore, it is critical to focus on developing effective control logics that can process the sensors' output reliably.

Table 17 Recommended smart work zone products

Manufacturer	Key Product/Service	Potential Applications
Wanco *(in collaboration with QLynx Technologies)*	Wanco ITS Solutions	Queue Detection/Warning Dynamic Merge – Dynamic Late Merge System
Ver-Mac	Ver-Mac Speed-Mac 2.0 Sensor with JamLogic CT-2320-MW Trailer-Mounted Microwave Sensor	Queue Detection/Warning Dynamic Merge – Dynamic Late Merge System
Wavetronix	Wavetronix SmartSensor High Definition Radar	Queue Detection/Warning Dynamic Merge – Dynamic Late Merge System

This study further provides the following three recommendations to advance the capabilities of smart work zones.

<u>(1) Expanding the range of smart work zones via the use of probe data to display warning/guidance messages on boards:</u> The effectiveness of queue warning systems and dynamic late merge systems greatly depends on the accuracy of the sensor readings that measure the traffic speed and lane occupancy in the roadway. It would be desirable to use a large number of sensors with wider detection ranges; however, that is often not feasible due to cost considerations. Since highway construction projects are designed to optimize the number of sensors deployed in smart work zones, there will always be gaps in the detection area, which will eventually cause errors in determining actual queues and slowdowns. To complement the coverage of the physical sensors, work zone operators can consider incorporating probe data into

their system. Probe data can fill the gaps in the area of detection and can also provide measurements from locations beyond the range of the sensors. It is theoretically possible to generate guidance and warnings on dynamic message boards using the probe data automatically. The strategic use of probe data can reduce work zone safety costs and can also increase the overall system reliability and efficiency.

(2) Expanding the dissemination of mobile app alerts from smart work zones: Mobile app-based alerts are becoming more significant as the market adoption of such applications increases. Many drivers already rely on mobiles apps, such as Waze and Google Maps, during their daily commutes and on long-distance routes. Mobile apps can address the limitations posed by dynamic message displays, which require considerable costs per unit. It is often not feasible to place a PCMS at every possible location that can be potentially impacted by queues triggered by the work zone. Work zone operators can use mobile apps strategically to extend the efficiency and range of the alerts and the guidance provided to motorists. The research indicates that in-vehicle voice-based warnings are more effective than roadside messages. Therefore, issuing guidance through mobile apps has the potential to augment the effectiveness of the dissemination of the alerts in work zones. Currently, there is no comprehensive report on drivers' use of mobile apps during their daily driving patterns. It would be beneficial to conduct a study to learn more about the general public use cases of those apps and their overall market penetration. When the usage rates exceed a certain threshold, the need for many of the PCMSs is eventually likely to diminish, which would reduce the cost of smart work zones.

(3) Proof-of-concept systems: This study built two proof-of-concept systems that represent low-cost solutions for two significant areas that need improvement in work zones: work zone intrusion alert and queue detection. It would be beneficial to continue working on exploring the potential of AI, edge computing, and computer vision technologies for the purpose of work zone intrusion detection and alert generation. The proof-of-concept work zone intrusion alert system described in this study could be easily deployed in a test site to evaluate the system performance at an actual highway construction site.

NCDOT has been actively using dynamic late merge systems in work zones and they have plans to increase the use of such applications. We consider this an effective safety improvement approach. The next stage of the effort can be the inclusion of mobile apps in the dissemination of alerts and merge messages to motorists around zipper merge sites and other work zones. NCDOT is also active in this particular domain and they are in the process of establishing a system to generate Waze alerts to disseminate roadway information to motorists.

7. Conclusions and Future Work

This project demonstrated the feasibility of using computer vision, IoT, and AI technologies in work zone intrusion alert and queue detection systems. The results indicate that it is possible to create cost-effective smart work zone elements using state-of-the-art technologies. This project's goal was to create two proof-of-concept systems. The next stage should involve the prototype design and the field tests in actual work zones for a period of time under a variety of environmental conditions. It is also important to observe how users interact with the systems to optimize the usefulness of the systems within an actual work project setting. Here, the human element is critical in evaluating the performance of alert and warning systems. More work needs to be done to gather and evaluate user feedback. This study developed functional detection and alert systems using smartphones. The resulting designs constitute the first smartphone-based work zone intrusion and queue detection algorithms at the time of this report's writing.

The proof-of-concept system software developed in this project can be embedded in edge computing devices, which can provide better performance with less cost. Future work should focus on implementing the technical solution on faster and more cost-effective hardware platforms. The fast pace of innovations in edge computing hardware will create more application areas for machine learning, computer vision, and IoT technologies in transportation systems. The algorithms implemented in this project can be further refined and more complex and robust image processing capabilities can be added. For example, the system can be further developed to enable it to function reliably during dark road and unfavorable weather conditions. The use of thermal cameras can also eliminate many of the problems that we experience with optical cameras. With thermal cameras, the impact of environmental obstacles can be eliminated effectively. Thermal cameras provide visibility in dark road, heavy rain, and foggy road conditions. They are also less prone to headlight glare and reflective road surfaces. Therefore, replacing optical cameras with thermal cameras should increase the performances of the proof-of-concept systems developed in this project. The literature also indicates some new approaches (Satzoda R. K., 2020) to tackle nighttime vehicle detection. These novel methods can be incorporated into the systems.

There are important areas that this study was not able to address due to time and resource limitations. One such important area involves the overrepresentation of large trucks in work zone crashes. The statistical data indicate that large trucks are frequently involved in work zone crashes and such incidents often result in more serious injuries and fatality. Therefore, more research is needed for developing alerts and guidance systems customized for the large trucker community.

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8. Appendix

8.1. Control Logic Configurations in Selected Smart Work Zones

Table 18 Sensors and control logic used in smart work zone examples

Project Description	Types of Sensors	Description of the Control Logic
MnDOT’s Queue Warning System on I-94 (Hourdos, et al., 2017)	Loops and MVDs	“The inputs to the algorithm are the crash probability and the filtered vehicle speeds. A moving median filter, or average filter, is applied to the crash probabilities to reduce noise and outliers. A dynamic average window methodology is used to calculate the adjusted crash probability for real-time traffic conditions. Based on this adjusted crash probability, user-defined thresholds, and the result of a speed test, the decision as to whether to raise the alarm is made by the system. Once the alarm is raised, it remains active for a minimum of one minute regardless of whether the crash probability drops below the threshold. This assures that the sign will remain active throughout the trajectory of the shockwave that raised the alarm. Each subsequent alarm renews the one-minute extension.”
MnDOT’s Queue Warning System on the I-35W south of Minneapolis, MN (Hourdos, et al., 2017)	Loops (Video stream also used to check the effectiveness of the system.)	“Triggering queue warning messages is based on the real-time estimation of queue length.” “Both the queue estimation algorithm and message triggers are lane-based. Once a stopped queue begins and propagates a certain distance, the queue warning message [is] shown on the VMS of that lane. The distance threshold value should be large enough to confirm the queuing state and avoid false alarms, but not so large as to delay the message for too long. The distance threshold value was selected to be 1000 feet by trial-and-error. Once the queue is cleared at the downstream detector or has already reached the location near the VMS, the warning messages are no longer displayed.”

Metropolitan area queue detection in Houston, TX (Pesti, et al., 2007)	Machine vision detectors to measure the speeds of vehicles approaching the area in which congestion generally occurs	"When the system detects three consecutive vehicles with speeds lower than 25 mph, lights flash above a warning sign."
Queue warning system deployed on a congestion-prone freeway in Eugene, OR (Hourdos, et al., 2017)	The system measures freeway occupancy using three side-fire, dual-beam traffic detectors	"When the freeway vehicle occupancy exceeds thresholds established by the Oregon Department of Transportation (ODOT), warnings are displayed on the PCMSs until the occupancy no longer exceeds the threshold along with a minimum display time of 5 minutes."
ITS system in a construction work zone on the I-35 Hillsboro, Texas TXDOT (FHWA, 2008)	Portable side-fire microwave detection trailers (plus, streaming video from three portable camera trailers)	"For each approach to the work area, two sensors monitored traffic and sent messages to two PCMS based on pre-determined speed and occupancy thresholds." "TXDOT dynamically adjusted queue thresholds, had message pre-emption capabilities, and had notification capability to alert appropriate personnel of problems." "Based on speed and occupancy thresholds, the system warns drivers about the delays and stopped traffic ahead."
US-131 in Kalamazoo, Michigan. MDOT deployed the Dynamic Lane Merge (DLM) (FHWA, 2008)	Remote traffic microwave sensor (traffic sensors)	"The closed loop system operated based on traffic occupancy. For example, when sensor #1 detected the threshold occupancy, sensor #1 sent a message to sensor #2 alerting it to activate the flashing lights. The occupancy thresholds for sensors 1, 2, 3, and 4 were 5 percent, 7 percent, 9 percent, and 11 percent, respectively. Each sensor had a 5-minute minimum activation period. System directs traffic to merge early to smooth traffic flow and reduce aggressive driving at the merge point."

Experimental Queue Detection and Alert System on Minnesota State Highway 100, at the crossing of Glenwood Ave. and Minnesota State Highway 55 intersection, Rhode Island Ave. and Minnesota State Highway 55 (Morris, Schwach, & Michalopoulos, 2011)	Machine vision traffic sensor	"The premise of the algorithm is that vehicles traveling slowly over a given presence detector will occupy the image region of the detector for a length of time proportional to speed and their distance from the camera. The algorithm consists of a real-time regression ladder approach, which utilized Boolean logic (logic operations) and occupancy for estimating queue length and stopped vehicle events. The queue detection was done as a per-approach detector set rather than a per-lane set in order to minimize occlusion and pixel resolution errors."
Construction of the I-35/Homestead Lane Interchange in Johnson County, Kansas (Bledsoe, Raghunathan, & Ullman, 2014)	The trailer-mounted sensors collect vehicle speed, classification, volume, and lane occupancy data for up to 10 lanes of traffic in each direction	"Preconfigured messages on the portable changeable message signs, as well as the speed displayed on the variable speed limit signs, were activated based on the analyzed Wavetronix data. The messages would indicate current travel times to various downstream exits or some type of delay message (when queues were present) that would encourage diversion to an alternate route. Travel times were estimated by taking the measured speed at the sensor and extrapolating it upstream and downstream from that sensor location for a given distance to estimate an average travel time over that distance. Linking the various sensor 'segments' together provided an estimate of the current travel time through the project."

8.2. Test Results for the Proof-of-Concept Work Zone Intrusion System

Twenty-one test experiments were conducted using YouTube videos from various roads. Table 20 contains the findings of the experiments.

Table 19 Test results (accuracy of the proof-of-concept intrusion detection alert system)

#	Accurate alert	False alerts	Missed alerts	Daytime versus nighttime	Weather	Notable conditions	Vehicle direction/ camera viewing angle
1	52	0	0	daytime	clear		90º front
2	23	0	0	daytime	clear		90º front
3	62	0	1	day	clear		45º rear
4	54	1	0	daytime	clear		45º front
5	56	0	0	daytime	clear		Mix of all directions
6	65	0	0	daytime	clear	Extremely bright scene with dark shadows	45º front
7	24	0	1	daytime	clear	Extreme lighting differential in the scene (dark focus area within a bright scene)	90º front
8	9	0	0	daytime	clear		45º front
9	9	0	0	daytime	heavy rain		45º front
10	21	0	1	daytime	heavy rain		45º rear
11	10	0	0	daytime	clear		-45º front
12	22	0	0	daytime			90º front
13	135	0	1	daytime	clear		135º front
14	55	0	0	daytime	clear		Intersection all directions
15	16	0	0	nighttime	clear		135º rear
17	2	0	0	nighttime	clear		45º rear
18	23	0	3	nighttime	heavy rain/storm	Thunderstorm, heavy rain, poor video quality, high	45º front

						level of vehicle headlight glare, reflective roadway surface	
19	60	0	1	nighttime	clear	Dark road, vehicle features hard to see because of the shadows	0^o side view
20	49	2	1	nighttime	heavy rain	Poor video quality, high levels of vehicle headlight glare, reflective roadway surface	45^o front
21	26	1	0	nighttime	clear		45^o rear

8.3. Test Results for the Proof-of-Concept Queue Detection System

Five test experiments were conducted using YouTube videos from various roads. Table 21 summarizes the findings of the experiments.

Table 20 Test results (accuracy of the proof-of-concept queue detection system)

#	Accurate queue detection	False alerts	Missed alerts	Daytime versus nighttime	Weather	Notable conditions	Vehicle direction/ camera viewing angle
1	44	2	0	daytime	clear		90º front
2	32	4	0	daytime	clear	bright scene with dark shadows	45º rear
3	9	0	0	daytime	clear		45º front
4	14	3	4	daytime	rain	heavy rain	45º rear
5	21	4	1	nighttime	clear	reflective roadway	45º front