SAFER ROADS SAVE LIVES

ADVANCED TECHNOLOGIES FOR PREVENTING WORK ZONE INTRUSIONS

PREPARED UNDER CONTRACT BY AUBURN UNIVERSITY




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Overview

Vehicle intrusion into work zones is a serious safety issue for highway construction projects. Transportation agencies rarely collect enough details to identify the crashes resulting from work zone intrusions, which limits the extent to which these crashes can be studied. Based on the studies available in the literature, the majority of the intrusion crashes (58.7%) occur at lane-closure operations. Intrusion crashes also commonly occur at work on shoulders or medians (8.9%), during traffic-control setup and removal activities (7.7%), mobile operations (6.5%), and flagging operations (6.5%). Speeding is reported to be a common contributing factor for most intrusion crashes. Other important contributing factors include driver incapacity and inattention. In addition, a considerable portion of these crashes result from deliberate driver decisions and actions to enter the work area.

Over the past years, transportation agencies have introduced various countermeasures to prevent work zone intrusions. These countermeasures range from traditional efforts such as slowing down drivers by doubling speeding fines to more advanced approaches that take advantage of new technologies and intelligent transportation systems (ITS). Since a large percentage of the intrusion crashes result from driver incapacity or distracted driving, traditional approaches, such as doubling speeding fines, are often ineffective in preventing work zone intrusions. Some advanced technologies, introduced in recent years, have great potential to prevent certain types of intrusion crashes that traditional devices cannot.

In this booklet, eight case studies have been developed based on the results obtained from the application of advanced technologies in the work zones to prevent vehicle intrusions into the defined work area. The technologies selected for case studies are the following:

1. Automated flagger assistance devices (AFADs)
2. Mobile barrier trailer (MBT)
3. Sequential warning lights (SWL)
4. Smart drum system
5. Automated speed enforcement (ASE)
6. Advance warning and risk evasion (AWARE)
7. Worker alert system (WAS)
8. Automated truck-mounted attenuator (ATMA)

The above technologies have been selected based on their effectiveness in preventing major types of intrusion crashes and the interest of ATSSA members. For each of the selected cases, a brief description of the technology is provided along with its effectiveness in preventing intrusions observed by different state departments of transportation (DOTs) from field implementation. Additionally, the agency contact person(s) for each case study have been included. The readers can contact the respective persons for the latest information about certain technologies. Finally, a list of potential future technologies is presented along with their initial test results. Interested readers may refer to the cited sources to learn more about the potential future technologies. ■

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AFAD	Automated flagger assistance device
ASE	Automated speed enforcement
ATMA	Automated truck-mounted attenuator
ATSSA	American Traffic Safety Services Association
AU	Auburn University
AWARE	Advance warning and risk evasion
Caltrans	California Department of Transportation
CAV	Connected autonomous vehicle
CDOT	Colorado Department of Transportation
CMS	Changeable message sign
DOT	Department of transportation
DSAS	Driver smart assistance system
DSRC	Dedicated short-range communication
ESC4WZ	Enhanced speed compliance for work zones
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
IDOT	Illinois Department of Transportation
ITS	Intelligent Transportation Systems
LCD	Longitudinal control device
MBT	Mobile barrier trailer
MDOT	Michigan Department of Transportation
MoDOT	Missouri Department of Transportation
MSP	Minnesota State Patrol
MUTCD	Manual on Uniform Traffic Control Devices
NCDOT	North Carolina Department of Transportation
NYSDOT	New York State Department of Transportation
ODOT	Oregon Department of Transportation
PCMS	Portable changeable message sign
P2I	Person-to-infrastructure
P2V	Person-to-vehicle
PSD	Personal safety device
RFID	Radio-frequency identification
SSD	Stopping sight distance
SWD	Safe worker to driver
SWL	Sequential warning light
TA	Typical application
TCD	Traffic control device
TCP	Traffic control plan
TMA	Truck-mounted attenuator
TTC	Temporary traffic control
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
UMTRI	University of Michigan Transportation Research Institute
VDOT	Virginia Department of Transportation
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VSL	Variable speed limit
WAS	Worker alert system
WTI	Western Transportation Institute
WSN	Wireless sensor network

CHAPTER I: INTRODUCTION

Work Zone Intrusion

Work zone intrusion is defined as an entrance of a vehicle into a defined work space or buffer space or into the transition area inside the channelizing devices *(1)*. These areas are defined in the Manual on Uniform Traffic Control Devices (MUTCD) as shown in Figure 1. Intrusion crashes occur when a vehicle enters into the actual work space within the work zone and collides with workers, construction equipment and vehicles, or construction materials and debris *(2)*. Transportation agencies rarely collect enough details to identify the actual intrusion crashes, which limits the extent to which these crashes can be studied.

Work Zone Intrusion Crashes

According to a study of work zone intrusion crashes (2000-2005) from New York State Department of Transportation (NYSDOT) *(2)*, 49.0 percent of the intruding vehicles collide with construction vehicles and equipment; 35.3 percent of the intruding vehicles collide with construction materials or debris; and 15.7 percent of them collide with workers (Figure 2).

This study *(2)* also found that approximately 58.7 percent of intrusion crashes occur at lane-closure operations. Table 1 shows the distribution of intrusion crashes at different types of work zone operations. Intrusion crashes also commonly occur at work on the shoulder or median, during traffic-control setup and removal activities, mobile operations, and flagging operations.

Another interesting finding *(2)* is that the proportion (12.4 percent) of intrusion crashes during nighttime work operations is higher than the daytime (7.5 percent), although 69.9 percent of all intrusion crashes occurred during daytime compared with 30.1 percent during nighttime (Figure 3).

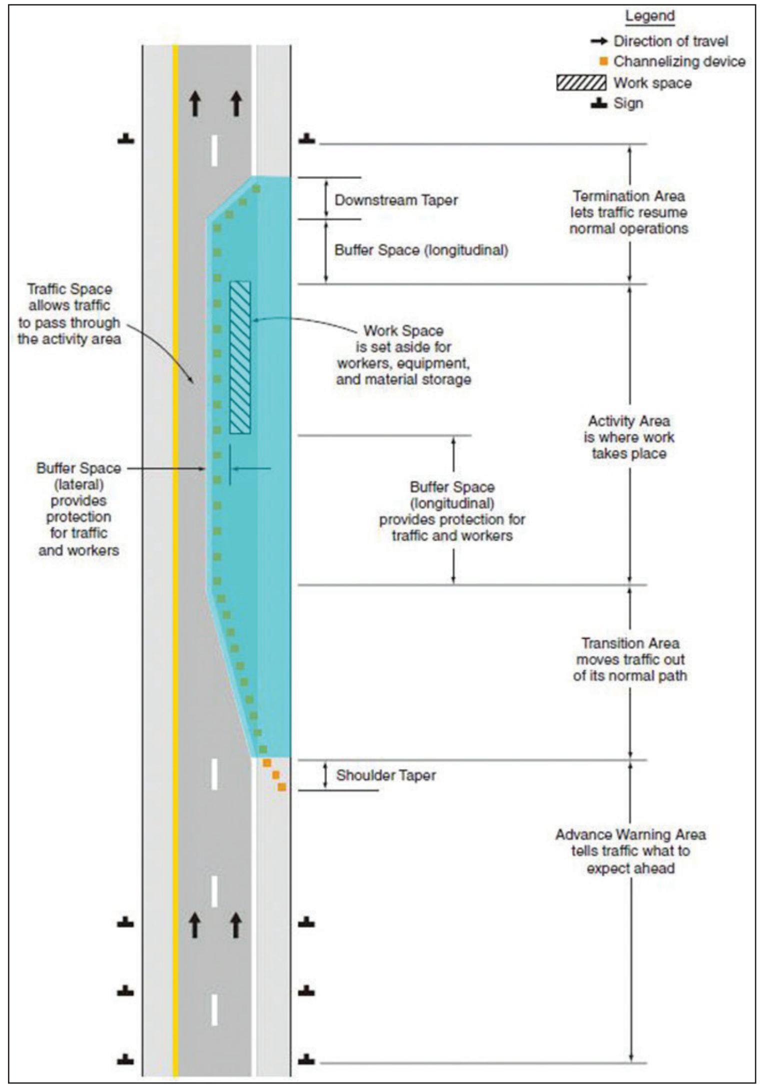

Figure 1.
Defined Areas of a Typical Work Zone in the MUTCD

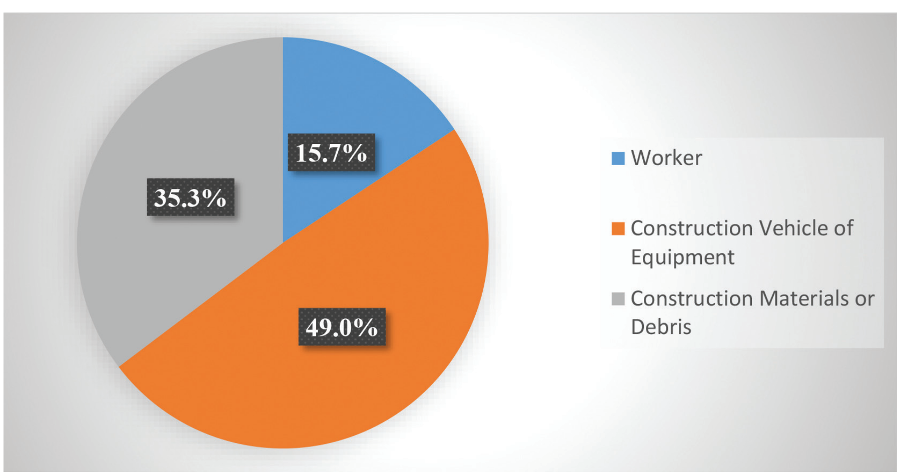

Figure 2.
Distribution of Intruding Vehicle Collisions in Work Zones *(2)*

Table 1.
Types of Work Zone Operations Where Crashes Occurred *(2)*

Type of Work Zone Operation	Percentage of Intrusion Crashes
Lane closures	58.7%
Work on shoulder or median	8.9%
Traffic-control setup and removal activities	7.7%
Mobile operations	6.5%
Activities involving flaggers	6.5%
Work activities involving minor traffic control	4.5%
Full roadway closures	4.5%
Other miscellaneous operations	2.7%

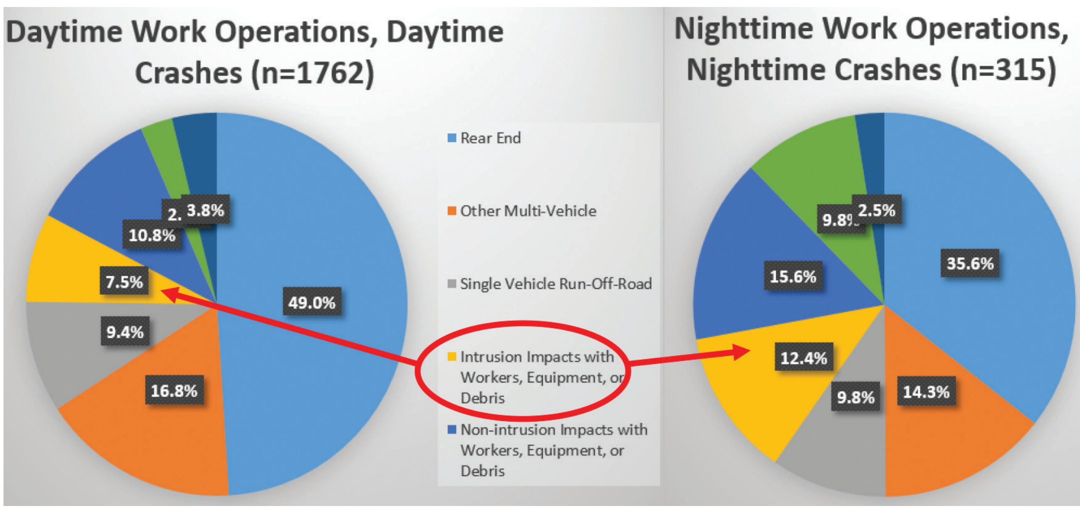

Figure 3.
Proportion of Intrusion Crashes in Daytime and Nighttime Operations *(2)*

Causes of Work Zone Intrusions

Excessive speed, driver incapacity, and driver inattention are the three common contributing factors of work zone intrusion crashes, based on a study of 290 intrusion crashes in New York from 1993 to 1998 *(1)*. The study also found that a significant portion (approximately 44 percent) of intrusion crashes were the result of deliberate driver decisions and actions to enter the work area.

Traditional protection efforts have focused on slowing down drivers in work zones, for instance, by doubling fines for speeding. However, it may have limited impact on drunken or distracted drivers. A drunken driver probably cannot make a rational decision about the risk of entering the work zone and hitting someone. A distracted driver is simply not paying attention. A traditional warning sign probably will not change either's intrusion behavior *(4)*. Therefore, the advanced technologies with enhanced audible and visible effects have recently been tested and installed in work zones by various transportation agencies. This booklet presents eight case studies of advanced technologies that are reported to be effective in preventing intrusion crashes.

Effectiveness of Various Techniques to Reduce Work Zone Intrusions

Transportation agencies are continuously working on improving workers' safety in the work zone. In addition to the traditional temporary traffic-control devices (TCDs), numerous technological and nontechnological techniques are being implemented to reduce the frequency of work zone intrusions. Tables 2 and 3 present a list of advanced technologies to reduce work zone intrusions and their effectiveness.

Table 2.
Representative Advanced Work Zone Technologies for Preventing Work Zone Intrusions

System	Description	Components	Effectiveness
Sequential Warning Light	Provide drivers with directions, especially at night, when lane closures may not be expected	• Traffic cone • Wireless transmission • LED Light • Battery	The device was reported to be effective in reducing vehicles' speed in the closed lane 1000 feet upstream of the lane closure *(2)*.
Smart Drum System	Issues warning to motorists approaching slower work zone areas	• Smart drum • Drum supervisor • Site supervisor	This system was found to reduce driving speed by 1.7 mph or 5 percent from the baseline *(5)*.
Automated Speed Enforcement	Detect speeding vehicles and enforce speed compliance	• Cameras • Radar • Communications	The system was reported to be effective in reducing speed limit violations and improving safety *(6, 7)*. The mean speed decreased by 23.7 percent when photo radar speed enforcement system was active *(8)*.
Advance Warning and Risk Evasion (AWARE)	Applies threat detection and tracking methodology to calculate speed of approaching vehicle, location, and predicted path	• Pneumatic tubes or infrared beams	One hundred percent success rate in triggering flashing light and alarm components *(9)*.
Worker Alert System (WAS)	Personal safety devices trigger audible alerts when an intruding vehicle is detected	• Trigger hose • Signal operator • Personal safety devices	This technology was found to be effective and relatively easy to set up and remove *(10)*.
Automated Truck-Mounted Attenuator (ATMA)	Especially useful in curbing intrusions into work zones where workers are engaged in traffic-control setup or removal activities and are constantly on the move	• Lead vehicle equipped with onboard computer, digital compass, transceiver, and GPS receiver • Follower vehicle equipped with impact attenuator and uses information transmitted by lead vehicle to navigate	Anticipated to be effective in protecting workers in mobile work zones *(11)*.
Intrusion Alarm	Attach to cones and barrels and give off a loud blast when the cone or barrel is knocked over	• Traffic barrel • SonoBlaster	The alarm's sound volume and duration were satisfactory during normal traffic conditions for distances of at least 200 feet, including when ear protection was worn, but no conclusion could be made about hearing the alarm during jackhammer operations *(12)*.
WAZE	This Web-based navigation app provides advance auditory warning to motorists about the presence of a work zone ahead	• Smartphone	The auditory in-vehicle warning helps motorists (especially those who are distracted or drowsy) to become more cautious about an upcoming work zone.

Table 2.
(continued)

System	Description	Components	Effectiveness
iCone	Provide information about work zone such as location of the end of queue, travel time through work zone, speeds at the taper, or speeds at another location where worker or motorist safety may be a concern	• Traffic barrel • Electronic components: GPS antenna, radar controller, radar transducer, modem, antenna, mounting plate, sealing plate, and a controller board • Battery	iCone matched with a message board provides advance warnings such as DELAY or SLOWED TRAFFIC and ensures more regulated traffic flow through the work zones *(13)*.
Connected Vests	It senses when a vehicle is entering a work zone, then alerts the worker wearing the vest, as well as the oncoming driver of the vehicle	• DSRC embedded into a pocket inside the worker's vest • Onboard DSRC unit	Uses haptic, visual, and auditory alerts to make the motorists aware about upcoming work zone and the workers about the hazards caused by vehicle intrusion.
Queue Warning	Provide warnings to drivers about stopped or slow traffic to reduce the risk of rear-end collisions *(14-17)*	• Traffic data • CMS • Communications	Texas Department of Transportation (TxDOT) deployed an innovative end-of-queue warning system at more than 200 nighttime lane-closure operations. There was 18-45 percent reduction in crashes at the deployed locations compared with an estimated number of crashes considering the system had not been deployed. The observed crash reduction resulted in $1.4 million to $1.8 million savings of societal crash costs ($6,600 to $10,000 savings per night of system deployment *(18)*.
Dynamic Lane Merge	Dynamically instruct drivers to merge at a certain point, based on the traffic condition	• Traffic data • CMS • Communications	The system was reported to be effective in improving the safety and increasing capacity around a work zone *(19, 20)*. The average number of aggressive driving maneuvers decreased from 2.88 to 0.55 *(19)*. The work zone capacity increased significantly from 881 vehicles per hour (vph) to 971 vph using the early-merge system *(20)*.
Variable Speed Limit (VSL)	Dynamically adjust the speed limit to smooth traffic through work zones and finally improve mobility and/or safety	• Traffic data • VSL CMS • Communications	The system was reported to be effective in increasing throughput and speed-limit compliance and decreasing travel time *(21-24)*. Statistical results indicated the mean speed increased and speed variance decreased on weekends during evening peak hours *(25)*.
Real-Time Traveler Information	Provide congestion, delay, and alternative route information to drivers	• Traffic data • CMS • Communications	The system was reported to be effective in preventing and reducing rear-end collisions and enhancing congestion management *(26)*. However, no quantitative benefit of the system was reported *(27)*.

Table 3.
Representative Advanced Traffic Control Devices for Preventing Work Zone Intrusions

Traffic Control Device	Description	Type	Effectiveness
Automated Flagger Assistance Device (AFAD)	Minimize flaggers' direct exposure to traffic by controlling the flagging device away from traffic	• Stop/slow sign mounted on a trailer or movable cart • Red/yellow lens and a mechanically gated arm	The overall assessment of AFADs from workers and drivers is positive, and they are effective at a wide range of traffic volumes *(28, 29)*.
Rumble Strips	Provide both an audible warning and physical vibration to alert drivers as the vehicle tires traverse the rumble strips	• Performed thermoplastic • Pavement marking tape • Adhesive • Manually adhesive • Portable reusable rumble strips	The device was reported to be effective in reducing vehicle speed by up to 10 mph. It may effectively alert drivers to an upcoming change ahead *(30, 31)*.
Positive Protection	Physically prevent vehicles and pedestrians traveling through work zones from entering space occupied by workers, equipment, materials, or roadside hazards	• Mobile barrier trailer • Portable concrete barriers • Ballast-filled barriers • Steel barriers • Moveable concrete barriers • Shadow vehicles with attenuators • Vehicle arresting systems	Limited research is available as to the effectiveness of positive-protection devices *(32)*. However, portable concrete barriers have several positive functions to protect workers as identified by the AASHTO Roadside Design Guide *(33)*. Movable concrete barriers were reported to reduce work zone congestion and delay *(34)*. Workers were found to be safer and more efficient behind the mobile barrier trailer (shadow vehicles with attenuators) *(35)*. Vehicle arresting systems were reported to be useful to prevent access into a closed section of highway *(36)*.

Case Studies

The objective of this publication is to develop case studies on the advanced devices and products that can help protect workers against intrusions by alerting motorists approaching work zones or warning workers of potential intrusions. After a comprehensive literature review of the latest technologies and their effectiveness, eight technologies were selected for conducting case studies for four types of work operations. A synthesis of available safety countermeasures and selected technologies (highlighted) for case studies are listed in Table 4. ■

Table 4.
Synthesis of Countermeasures to Prevent Work Zone Intrusions

Type of Work Operations	Percentage of Intrusion Crashes	Applicable Countermeasures
Lane Closures	58.7%	**Advance Warning Area** • *Smart drum warning system** • *Work zone intrusion warning system** • *Advance warning and risk evasion (AWARE)** • Early merge system • Dual advanced signing • Overhead CMS • Temporary transverse rumble strips • Ensure adequate sight distance to taper • Upstream queue warning (real-time information or general warning) • Conduct work at night or on weekends • Dynamic speed-display trailers • Advance notification of alternative routes, closure location, and duration **Transition Area** • *Sequential warning light system (night operations only)** • Closer or continual spacing of TCDs • Larger, more visible channelizing devices **Activity Area** • *Mobile barrier technology** • Closer or continual spacing of TCDs • Transverse TCDs • Shorter operation length to avoid blocking ramp or driveway • Lane-changing restrictions • Downstream spotter **Identifying Construction Vehicles** • Reconfiguring access point • Construction entrance signing (static or dynamic) • “Frequent Turns” signs (static or dynamic) • Enhanced vehicle warning light system • Alter work area access point and internal TCP procedures **General** • *Automated speed enforcement** • Enforcement present (real, automated, or drone radar) • Continuous patrol or monitoring of work zone • Positive protection

Table 4.
(continued)

<table>
<tr><th>Type of Work Operations</th><th>Percentage of Intrusion Crashes</th><th>Applicable Countermeasures</th></tr>
<tr><td>Traffic-control setup and removal activities</td><td>7.7%</td><td>• Automated truck-mounted attenuators*
• Additional work vehicle on shoulder
• Reduce spacing between work vehicles
• New messages on truck-mounted CMSs to discourage vehicles from entering work convoy
• Work vehicle in front of workers on foot
• Enhanced vehicle warning light system
• Automated TCD setup and removal
• Follow proper TTC setup and removal procedures
• Enforcement present (real, automated, or drone radar)
• Positive protection</td></tr>
<tr><td>Mobile operations</td><td>6.5%</td><td>• Automated truck-mounted attenuators*
• New messages on truck-mounted CMSs to indicate slow-moving vehicles
• Truck-mounted dynamic speed display showing truck speed
• Adjusting spacing between advance-warning vehicle and work convoy as needed to maintain sight distance to work convoy
• Reduce spacing between work vehicles
• Work vehicle in front of workers on foot
• New messages on truck-mounted CMSs to discourage vehicles from entering work convoy
• Enforcement present (real, automated, or drone radar)
• Positive protection</td></tr>
<tr><td>Activities involving flaggers</td><td>6.5%</td><td>Advance Warning Area
• Temporary transverse rumble strips
• Advance warning messages on PCMSs
• Dynamic speed display trailers
• Enforcement present (real)

Flagger Station
• AFADs*
• Portable traffic signal system
• Closer or continual spacing of TCDs
• Replace flagger with police officer
• Transverse TCDs/LCDs
• Advance notice of work activity
• Limit lane-closure length

Activity Area
• Closer or continual spacing of TCDs
• Replace flagger with police officer
• Transverse TCDs
• Limit lane-closure length
• Enforcement present (real)
• Positive protection</td></tr>
</table>

*Note: * Selected for case studies.*

CHAPTER II: CASE STUDIES

Case 1: Automated Flagger Assistance Devices (AFAD)

AFADs can automate temporary traffic control that is traditionally achieved by a human flagger. These devices can improve safety by removing workers (i.e., human flagger) from the traffic stream and enabling them to control the flagging operation from a safe distance. Therefore, AFADs are extremely useful in preventing injuries caused by intrusions into work zones with flagging operations. However, an AFAD should not be a substitute for a qualified flagger. Rather, an AFAD system can be a device that makes flagging operations safer. There are two types of AFADs: the Stop/Slow variety and the Red/Yellow variety. Both types are recognized in the 2009 edition of MUTCD *(3)*. For the Red/Yellow type of AFAD, a mechanical arm is attached along with a mounted signal cabinet to increase conspicuity and driver compliance *(29)*. Figure 4 shows the two types of AFADs. There is little information available on the difference in the safety effects of these two AFADs. A study conducted by TTI revealed that drivers tend to be more compliant to the Red/Yellow AFAD *(37)*.

Case Study

In May 2017, the MoDOT conducted a study to evaluate the safety effects of AFADs at a work zone *(38)*. The study compared the recorded data for an AFAD and human flagger at two different sites. The study focused on work zone intrusions from oncoming traffic in the advance-warning area. Safety performance measures that were collected and compared in this study included: traffic speeds, stop locations, and reaction and waiting times. This data was then used to evaluate the benefits of AFADs.

The average speed decreased from 27.4 mph with a flagger to 23.2 mph for the AFAD. This indicates how the automated technology leads to lower speeds and thereby provides more time for drivers to react and stop. The study additionally noted the full stop locations for the AFAD were approximately 10 feet farther than the full stop locations for the flagger. A farther stop location ensures that drivers approaching the advance-warning area can come to a complete stop prior to causing any damage to the work zone. These safety benefits assist in preventing the work zone intrusions in the advance-warning area of work zones.

One limitation of AFADs is that they may cause slightly longer delays because of increased reaction times. The cost for a set of AFADs varies from $25,000 to $30,000. However, AFADs are also available for renting on a daily or weekly basis for a cost of $3,000-$3,200. It should be noted that rental costs may vary by geographic locations and seasons. ATSSA has published a guideline on usage of AFADs, which might be of interest to agencies who are planning to deploy these devices within their jurisdictions. This document can be found at the website: https://www.workzonesafety.org/files/documents/training/fhwa_wz_grant/atssa_afad.pdf. ■

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Figure 4.
Stop/Slow AFAD (left) and Red/Yellow AFAD (right) *(29)*

Case 2: Mobile Barrier Trailer (MBT)

The concept of MBTs was originally conceived in the state of Colorado after a work zone intrusion crash resulted in two fatalities. The initial deployment of this technology happened in 2008, after four years of a research and development phase *(39)*. MBT involves placement of a steel wall around the work zone to protect workers. This steel wall can be transported to the work zone location using trailer trucks. The steel walls can be installed on either the left or right side of the work zone, depending on the direction of traffic at the site. The end of steel wall exposed to through traffic should be protected by a TMA. A typical MBT can protect work zones extending between lengths of 42 feet to 102 feet. Height of the barrier can be set at 5, 7, or 9 feet *(39)*. No installation or setup time is required for MBT, since driving the MBT truck to the work zone and pulling over will complete the deployment. MBTs are very effective in preventing intrusions into work zones with lane closures. Figure 5 portrays a typical work zone protected by an MBT in Colorado *(40)*.

Case Study

CDOT conducted a study on the use of an MBT at a work zone for guardrail repair along I-70's center median *(41)*. CDOT studied the data observed from two instances of eight-hour nighttime lane closures to perform guardrail repair. One instance utilized the traditional method of using six tandem-axle trucks to protect the work zone from entering traffic. The work zone was a lane closure with workers working adjacent to ongoing traffic, the trucks being the separator. Additional equipment such as lights, portable generator, truck and trailer (for rail and post hauling), and air compressor were also needed in the work zone. This meant that every time workers moved to the next section of guardrail, all equipment plus the six axle trucks must be repositioned. In this instance, an average of seven pieces of guardrail could be replaced in eight hours.

The next time frame observed in the study utilized one MBT. The MBT was able to carry all equipment, including railing and post. This consolidated the work zone area significantly, and allowed for the entire work zone, and the barrier, to simply move along with the workers. The workers utilizing the mobile barrier could replace about 42 pieces of rail in the eight-hour period *(41)*. The consolidation of materials onto one trailer lowered the equipment cost. The increased efficiency significantly reduced lane closure time. The less amount of time a worker is needed for repairs in a closed lane, the safer work zones become. The shortened time in lane closures also decreased traffic congestion. This decreased congestion due to barriers increased the safety of work zone areas along lane closures. In addition to mitigating traffic congestion and decreasing the work time, MBT offers complete protection to workers from intrusions.

MBT cannot be used to protect work zones spanning more than 102 feet. Similarly, MBT is unsuitable for congested city streets and local streets in towns and villages. The cost of an MBT unit varies between $300,000 and $340,000. MBT rental services are available across the country. Best practices for deploying MBT units are outlined in the document developed based on the materials provided by ATSSA for the FHWA Work Zone Safety Grant program. This document can be found at the website: http://www.mobilebarriers.com/images/docs/20160627%20Portable%20Positive%20Protection%20Guide--Mobile%20Barriers%20MBT-1.pdf. ■

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Figure 5.
A Work Zone Protected by MBT *(40)*

Case 3: Sequential Warning Lights

SWLs use wireless transmissions and LED lights and lens technology on top of traffic cones to improve the safety of night work zones. Proportion of intrusions at nighttime work zones is higher than the daytime due to the lower visibility of road work areas. The LED lights used are flashed at a rate of 60 times per minute in a sequential order that will best direct traffic flow away from work sites. The lights for each traffic cone require two 6-Volt batteries to illuminate. The cones with attached lights are placed in a line along the taper of a lane closure for a work zone. This placement allows for the sequential flashing to appear as one light source fluidly moving forward and backward along the lane-closure taper *(42)*. Each flash and its intensity are timed by sensing the location of other lights related to current positions. Figure 6 shows a typical application of temporary traffic barriers on lane-closure operations. The orange channelizers, shown in Figure 6, could all be equipped with sequential lights to facilitate an SWL system.

In addition to improving visibility of work zone boundaries, lights provide visual signals to help drivers stay in newly assigned lanes during construction. The SWLs help with this by ushering drivers toward unobstructed lanes with more warnings, providing a safer merging area near work zones. This technology is effective in preventing lane-closure-type work zone intrusions during times of low visibility. Figure 7 displays an SWL system along with arrow boards in use at a work zone.

Case Study

The state of Missouri examined the safety effects of SWLs. The study was conducted at three different work zones in Missouri. The measures of its safety performance were vehicle speed and speed variability, taper conflict, and closed-lane occupancy. It was found that the SWLs increased speed variance slightly, but decreased overall average speed. An increase in speed compliance was also

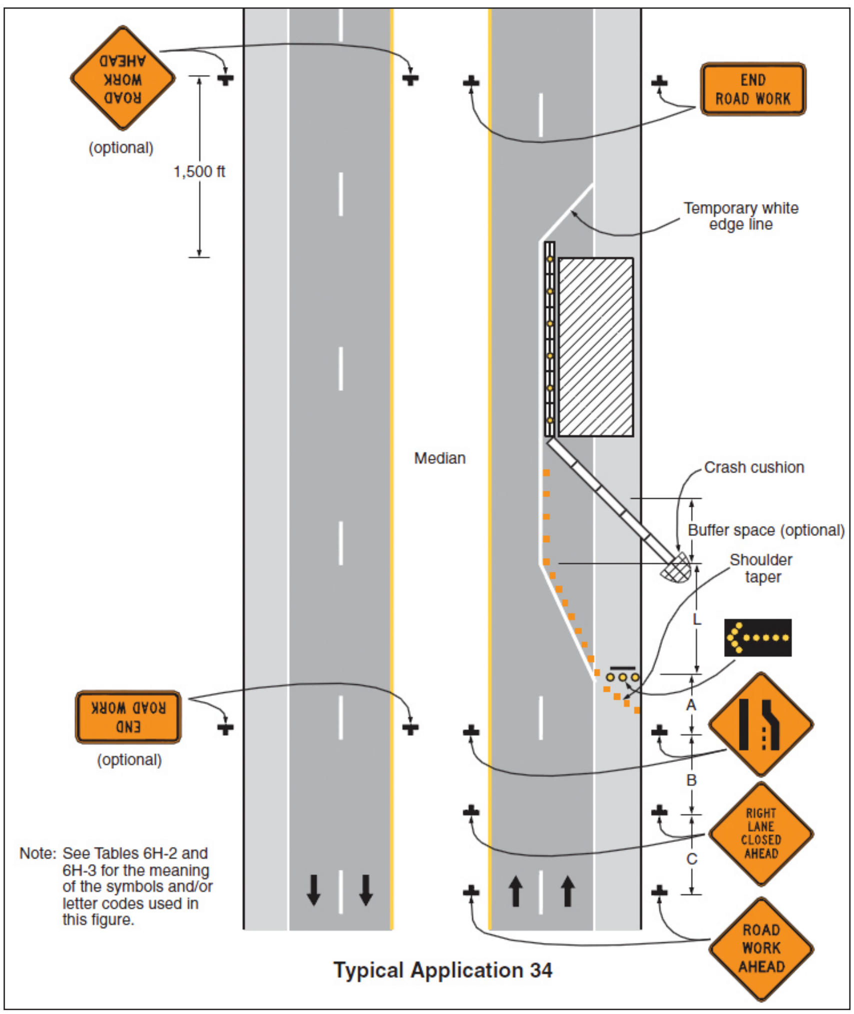

Figure 6.
Lane Closure With a Temporary Traffic Barrier (TA-34) in the MUTCD

observed. The speed distributions displayed a reduction in speeds of both passenger cars and trucks. The distributions additionally showed a reduction in speed for both urban and rural work zones, but this decrease was more prominent at urban work zones.

Since there was no compelling crash data associated with this study, there was no crash analysis completed. Instead, crash modeling was used to loosely determine the improved safety details due to reduced speeds. Installation and removal costs of an SWL system were high for this study. Per Missouri's crash data, the total annual benefits were calculated to be $3.65 million, and total annual cost was calculated to be $705,008 *(42)*. These estimates were based on deployment of SWLs at all nighttime interstate and major highway work zones. The benefit-cost ratio was calculated to be five. Overall, average cost of each injury reduced by SWLs is approximately $25,000. It was also found that the drivers' speed compliance rate was increased by 6.7 percent. The 85th percentile speed was reduced by 1.5 mph by the SWL deployments *(42)*.

Figure 7.
Sequential Warning Lights at a Work Zone *(43)*

The case study conducted on SWL systems in Missouri noted that this technology is less effective in urban work zones. Similarly, SWL systems caused some drivers to drive aggressively at the taper since the taper has become more visible. The cost of each lamp used in a SWL system is around $100. Each lamp consumes electricity worth $0.2 per night (eight hours). The cost of an SWL system thus depends on the number of lamps used and duration of deployment. The MUTCD 2009 edition contains guidance on the deployment of SWL systems. This innovative technology was also used as part of a low-cost safety countermeasure evaluation exercise undertaken by Arizona DOT. The more information can be found at this website *(44)*. ■

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Case 4: Smart Drum System

A smart drum is a work zone safety system brought to engineers by UMTRI *(45)*. This device collects data to make decisions on warnings issued to motorists approaching slower work zones. The data collected included approach speed, queue tail location, and speed differential.

Each system of smart drums at a work zone contains multiple barrel units that collect their own data and report to a drum supervisor. The drum supervisor is another drum that receives the collected data and then sends warning messages. The data is transferred through the transmitters/receivers located in each drum. This technology is effective in preventing lane-closure-type work zone intrusions. Figure 8 illustrates a typical layout of a smart drum system.

Case Study

A smart drum system made up of 28 orange smart drums alongside the orange cones to mark work zone lane closures was developed in 2013, by Caltrans and the Montana State University WTI *(5)*. If a smart drum system detects an incoming vehicle speed greater than the limit, orange lights atop the drums begin to flash. This flashing warns drivers to slow down when approaching work zones. Additionally, if a vehicle is approaching the work zone above the set speed, the system activates a pager to alert workers of oncoming traffic. During a four-week test of the system on SR 152 near Los Banos, Calif., the pagers vibrated at the detection of a vehicle traveling 20 mph over the speed limit. Using this limit, the smart drums reduced driving speed by 1.7 mph, or 5% from the baseline speed *(5)*. The study indicated that installation and retrieval of the system daily was quite labor-intensive. The system needs to be further developed for an easier installation and take-down method.

Researchers noted that rural areas must rely more on signage to slow motorists down. This is due to the lack of staffing and law enforcement to help maintain traffic speeds in rural work zones. In such cases, the smart drum technology can be an effective solution for safety and staffing issues. Not only does the smart drum system reduce oncoming vehicle speeds, it also alerts workers of speeding vehicles. These important features assist in further reducing collisions in work zones.

One drawback of this system is that it is labor-intensive to deploy. Another drawback detected from the case study is that the pager range is shorter than expected *(5)*. The smart drum system is not commercially available at this time. Therefore, a reasonable estimate on the costs associated with this system cannot be provided. The same is true for the best practices of deployment. ■

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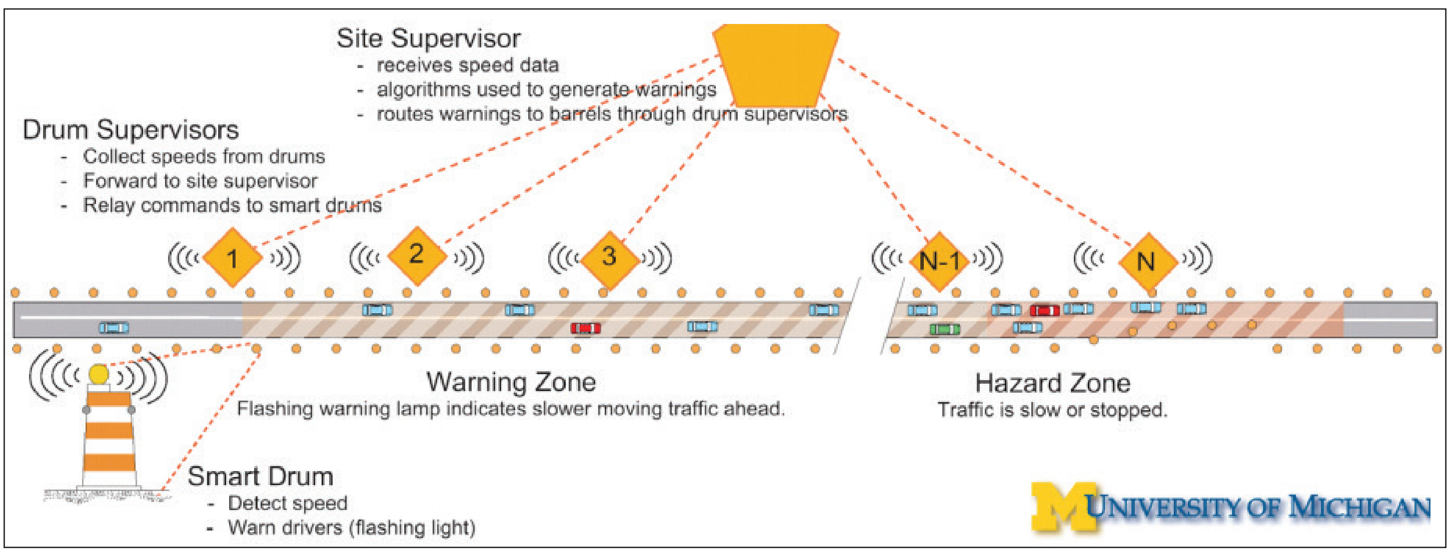

Figure 8.
Layout of a Smart Drum System *(45)*

Case 5: Automated Speed Enforcement (ASE)

ASE technology is either a portable or fixed-position roadside traffic-control device *(46)*. An ASE has speed detection and photographic capabilities. Figure 9 shows an ASE device contained in a van with two radars. One radar is called the down-the-road radar, which detects vehicle speed being displayed on the LED display on top of the van. This radar has a range of about one-fourth to one-half mile. The other radar, called the across-the-road radar, measures vehicle speeds at about 150 feet up road from the van *(46)*. Two onboard cameras are activated when the across-the-road radar reads a speed of a passing vehicle that is greater than the specified limit. One camera at the rear of the van is used to capture the face of the driver and front features of the car. The second camera takes a picture of the rear of the car. Along with the two photos, the speed of the vehicle, location, time, and date are recorded for possible ticketing purposes *(46)*. ASE technology can help reduce work zone intrusions caused by speeding, since past studies showed that speeding remains the top contributing factor for all intrusion crashes.

Case Study

Approximately 31% of fatal work zone crashes are caused by speeding (46). Any device or technology that can address the problem of speeding at work zones will help in mitigating work zone intrusion crashes. The ASE is one such technology. IDOT researched the effects of ASE on average speed and degree of speeding (46). The results were then compared with other speed management methods for work zones with and without police enforcement. These other speed management methods are speed display trailers, police presence with patrol lights on, police presence with patrol lights off, and using both display trailers and police presence together. Two work zones were used to collect three different data sets. Spatial effects were observed at both the ASE system location and 1.5 miles down road in the work zone area. Temporal effects are the halo effects of police presence and ASE effects when drivers leave the work zone. Passenger cars' speed in the median lane was decreased by about 5.1-8.0 mph, and 4.3-7.7 mph for the shoulder lane. Trucks' speed slowed by about 3.7-5.7 mph in the median lane and 3.9-6.4 mph in the shoulder lane (46).

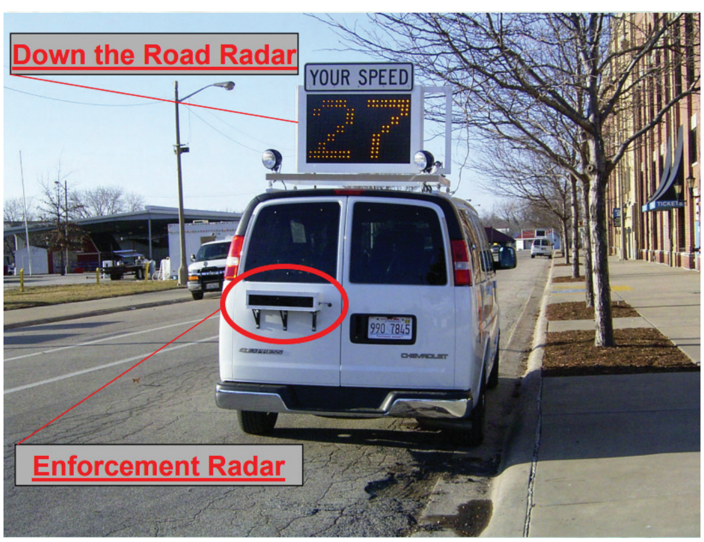

Figure 9.
Van-Mounted ASE System *(46)*

The average speed was decreased below the speed limit every time. The study showed that the ASE systems are as effective as police presence with lights off. Two data sets showed a spatial effect of 2.0-3.8 mph speed reduction for free-flow cars (cars not part of a platoon, free to choose their speed) and 1.1-1.9 mph speed reduction on general traffic cars (cars part of the general traffic stream. Speed choice restricted by platoon speed). For trucks, all three data sets had spatial effects of 0.8-5.3 mph for free-flow and 0.9-3.2 mph for general traffic. More importantly, the percentage of drivers speeding downstream decreased by 44 percent. The halo effects were also observed in this study. Halo effects were observed for the ASE on free-flowing heavy vehicles in a single work zone and on free-flowing cars in the second work zone, but there were no halo effects for police-presence work zones (46). Overall, the ASE technology proved to be effective in reducing speeding at work zones. Consequently, ASE can be helpful in reducing work zone intrusion crashes caused by speeding.

One limitation of ASE technology is that, in certain jurisdictions, deployment of ASE is prohibited or restricted by laws. In terms of cost, ASE is relatively inexpensive compared with manual speed enforcement. In Illinois, the ASE vans were rented by IDOT at a rate of $2,950 per month from the vendor. The National Cooperative Highway Research Program (NCHRP) Report 729 published in 2012 deals with the best practices to be adopted for deployment of ASE technology. The report can be found at this link: safety.fhwa.dot.gov/speedmgt/ref_mats/fhwasa1304/resources2/27%20-%20Automated%20Enforcement%20for%20Speeding%20and%20Red%20Light%20Running.pdf). ■

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Case 6: Advanced Warning and Risk Evasion (AWARE)

Preceding intrusion alarm systems depend on detecting vehicles that cross a previously determined perimeter. This perimeter is typically defined with pneumatic tubes or infrared beams. A new system, AWARE, applies threat detection and tracking methodology to calculate the approach vehicle speed, location, and future path. Threats are detected in two triangular zones, as shown below in Figure 10 *(9)*.

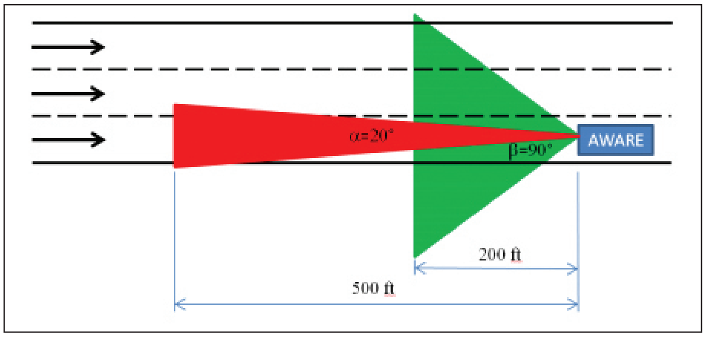

Figure 10.
AWARE Detection Areas *(9)*

The red region is known as the long-range region, and it detects threats up to approximately 500 feet of the alarm system. The total detection angle is α=20 degrees, or 10 degrees on each side of the centerline. The green region is the short-range region. The short-range region can only detect threats up to 200 feet upstream from the alarm system. Also, this region can have a detection angle of about 35 degrees more on either side of the centerline than in the long-range, making the total deflection angle β=90 degrees for the short-range *(9)*.

A vehicle will enter the perimeters of the long-range and short-range regions, and the AWARE system can detect vehicle speed and heading. The system will then perform calculations to infer the future path, or trajectory, of the approaching vehicle. For the AWARE system to alert the motorist of infractions and notify workers of an intrusion threat, the approaching vehicle must be exceeding speed limits set for the regions or the trajectory must be calculated to be a potential intrusion into the work zone. The AWARE system alerts the motorist of infractions by activating flashing LED lights. The system alerts workers by enabling an audible alarm. These alerts are intended to be enough to catch an approaching vehicle's attention, slow its speed, and deter it from entering the work zone. The device will still help if an intrusion does occur, by giving workers in hazardous zones an alert in time to move out of the way of the approaching vehicle. The AWARE system is intended to be used in preventing work zone intrusions in lane-closure-type and flagging-type traffic operations *(9)*.

Case Study

The AWARE technology was tested by TTI in August 2016. A passenger car and a pickup truck were used in the test. AWARE systems were tested under two basic operating modes: stationary lane closures and flagging operations *(9)*. Different vehicle trajectories were tested for each operation mode. The trajectories included:

- Lane Closure Operation
    - Trajectory A – Lane change into adjacent lane within 200 feet of the AWARE vehicle
    - Trajectory B – Passing by the system in an adjacent lane
    - Trajectory C – Vehicle crossing the intrusion detection region
    - Trajectory D – Vehicle approaching at a speed below alarm threshold
    - Trajectory E – Vehicle approaching in closed lane and penetrating the Stopping Sight Distance (SSD) threshold
- Flagging Operation
    - Trajectory F – Lane change during SLOW PADDLE operation
    - Trajectory G – Lane change during STOP PADDLE operation
    - Trajectory H – Decelerate below SSD during STOP PADDLE operation
    - Trajectory I – Passing queued traffic on the left during STOP PADDLE operation
    - Trajectory J – Passing queued traffic on the right during STOP PADDLE operation
    - Trajectory K – Lane change passing queued traffic on the left during STOP PADDLE operation

For every trajectory, each type of vehicle approached the work zone in the specified manner, and data was collected regarding the activation and response time of AWARE technology. Multiple test runs were conducted at two travel speeds (45 mph and 60 mph) *(9)*. In total, 273 test runs were conducted. The study reported that the flashing light and alarm components of AWARE system were triggered when the approaching vehicle had sufficient distance to make a safe stop and avoid intrusions. A 100 percent success rate of the AWARE system was reported by this study *(9)*.

The AWARE system has not been tested for mobile work zone conditions. The performance of this technology in such conditions is unknown. Given the fact that the AWARE system is still in its conceptual stage, it is premature to comment on the monetary costs of deployment. ■

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Case 7: Worker Alert System (WAS)

WAS is an alarm system that utilizes audible and visual alerts to prevent intrusions of work zones *(10)*. The system utilizes a trip hose that contains a transmitter and sensor that can detect compression due to contact, such as a vehicle crossing. The trip hose standard is 12 feet long, but this length and the configuration of hose links can be easily adjusted to different work zone perimeters. Components of WAS are shown in Figure 11. If the trip hose is crossed, it sets off the alarms in the system. One alarm that would turn on is the portable alarm case that can rest on any surface or be magnetized to a metal surface. The portable alarm case would project a pulsing sound blast and start utilizing LED flashing lights if the trip hose detects an intruding vehicle. A second set of alarms are PSDs, such as a headset and pager, to be worn by workers in the work zone. These alarms will vibrate to alert workers of any loud ambient noise. Additionally, if the trip hose detects an intruding vehicle, these PSDs will produce audible alerts as well. Because of the portability of this system, WAS can be mobilized and demobilized quite simply. WAS is mainly used to prevent work zone intrusions in lane-closure-type sites *(10)*. WAS improves the safety of workers by utilizing multiple individual alarms to alert workers.

Case Study

In June 2017, ODOT conducted field tests on WAS technology at three different locations *(10)*. The tests were conducted during day and night times, at three different locations to accurately measure the effectiveness of WAS in alerting the workers in various environments. The three locations were under an overpass, on a bridge, and in a rural locale.

The tests took place in a work zone where a paving operation was going on. Three types of equipment — rollers, pavers, and a grinder — were present at the testing locations. Each work zone spanned at least 200 feet *(10)*. A different set of workers was involved at each testing location. A minimum of 10 workers participated in every test. The WAS alert was triggered at least four times, to ensure that workers present near every piece of equipment were alerted. Every test was videotaped to estimate the reaction times of workers.

After the test, each worker was asked to rate the effectiveness of WAS, on a scale of zero to five, for five evaluation criteria, including ease of use and effectiveness of alarm. WAS technology received a mean rating of 4.0 for effectiveness of alarm and 3.3 for ease of use. Video evidence showed that workers could notice the alarm within one second after activation. This gives them ample time to safely move away from the work zone in case of intrusions. The ODOT personnel opined that WAS technology is effective and relatively easy to set up and remove *(10)*.

One drawback of WAS technology as reported by users is that it has poor coverage range. The noise level of the alarm was also found to be inadequate for some workers. The cost of a WAS unit is approximately $600. ■

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Figure 11.
a. Demonstration of WAS; b. WAS Components (Left to right: trip hose, signal repeater, personal safety devices)

Case 8: Automated Truck-Mounted Attenuator (ATMA)

ATMA vehicles are a synthesis of traditional truck-mounted attenuators and connected-vehicle technology *(14)*. This technology consists of two vehicles, a leader and a follower. The leader vehicle is human-driven and is equipped with an onboard computer, digital compass, transceiver, and GPS receiver. The leader vehicle continuously shares its velocity, location, and heading information with the follower vehicle. The driverless follower vehicle carries the impact attenuator and uses information transmitted by the leader vehicle to navigate *(15, 47-48)*. The leader and follower vehicles are shown in Figure 12.

A pilot program conducted by FDOT in late 2015 tested the performance of ATMA vehicles. In the pilot program, performance of ATMA vehicles was tested on a closed roadway. Parameters such as vehicle mobility, navigation around obstacles, g-force sensing, and an integrated safety system were tested. Results of the pilot study gave deeper insights into automation of road construction vehicles and application of connected-vehicle technologies in work zones *(14)*. ATMA vehicles would be especially useful in curbing intrusions into work zones where workers are engaged in traffic control setup or removal activities and are constantly on the move, where deployment of stationery traffic-control devices is impractical.

Case Study

ATMA technology has not been widely deployed yet. CDOT is planning to begin using ATMA vehicles at their mobile work zones by the end of 2017. In CDOT's jurisdictions, between 2013 and 2014, there were 26 incidents where a protection vehicle was involved in a crash at mobile work zones *(11)*. By introducing the ATMA technology in Colorado, CDOT hopes to remove the driver of a protection vehicle and replace with an ATMA truck to effectively protect workers in mobile work zones *(11)*. An analysis of TMA crashes in the state of Virginia revealed that 121 TMA crashes occurred in that state between 2011 and 2014. All the injuries from those crashes could have been avoided by the implementation of an ATMA unit. Nationwide application of ATMAs might take a long time until the technology matures and the cost is reduced. ■

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Figure 12.
A Leader and Follower Vehicle With Truck-Mounted Attenuator *(15)*

CHAPTER III: FUTURE TECHNOLOGIES

As the future of transportation is centered toward CAVs, most future work zone technologies are related to communications between CAVs and construction areas. Though CAVs will be able to solve the problem of distracted or DUI driving of human drivers to a great extent, the actual safety effects of CAVs in work zones are still not well-known. The setting up of work zones varies widely at different locations. For example, ITS technologies are used to manage traffic in some work zones, while only limited traditional TCDs are used at other locations. CAVs use sensors in the vehicles to determine road conditions, lane closures, weather, queue warnings, platooning, and speed harmonization. The sensors "speak" to other vehicles, and also can receive information from roadside infrastructure units as well. For instance, when a vehicle is entering a work zone, the vehicle receives a notice to slow down or is notified of a lane closure from a roadside unit in the work zone. These alerts in theory would "wake up" a distracted driver who may not notice the typical work zone warning signs on the roadways *(49)*.

Introduction of CAVs will greatly influence the approaches for managing traffic through highway work zones. In the navigation apps, the maps change many times per day due to the addition of work zones. Roadway closures may not be reported in time, and some short-term ones may never be reported. Moreover, the lane closures on rural roads may be installed with bad line of sight. If the autonomous systems are unable to recognize these work areas and react appropriately, then it can cause a great threat *(50)*. Therefore, it is important to find an efficient way to inform CAVs of all work zones.

Based on the above discussion, the core of the future technology is primarily about the method and quality of the communication, which can be approximately categorized into three parts: P2V communication, P2I communication, and V2I communication. P2V systems can provide an audio/vibration warning or instruction to drivers when the distance between vehicles, vehicles and infrastructure, or vehicles and workers is less than the threshold. Therefore, the drivers have sufficient time to prepare to decelerate or stop. Meanwhile, the workers will be warned when a potential incoming work zone intrusion occurs and can step out of the work zone through P2I communication.

Existing wireless communication technology such as Bluetooth, Wi-Fi, radio frequency identification (RFID), etc. can help form a mesh network. To be mentioned, several aspects of the network and devices should be taken into consideration:

- **Accuracy of detection**
  As more and more CAVs show up on the road, various types of devices may be installed along the road, under the pavement, or mounted overhead. Lowering the false alarm rates and improving the detection accuracy will be the priority of a robust work zone safety system in the future.

- **Efficiency of communication**
  A fast and consistent communication network provides quick transmitting and responses. Not only can the devices and vehicles talk to each other, but also the administration console will be able to monitor the situation of the work zone and plan/adjust the work remotely.

- **Power capacity of devices**
  Though these devices may be temporarily installed near infrastructure or carried by workers, battery life needs to be long enough so workers do not have to replace and charge them frequently, as it may cause unexpected incidents or crashes.

- **Environmental adaptability of devices**
  Dirt and/or moisture on devices or temperature getting too high/low could alter some CAVs' abilities to communicate with the devices.

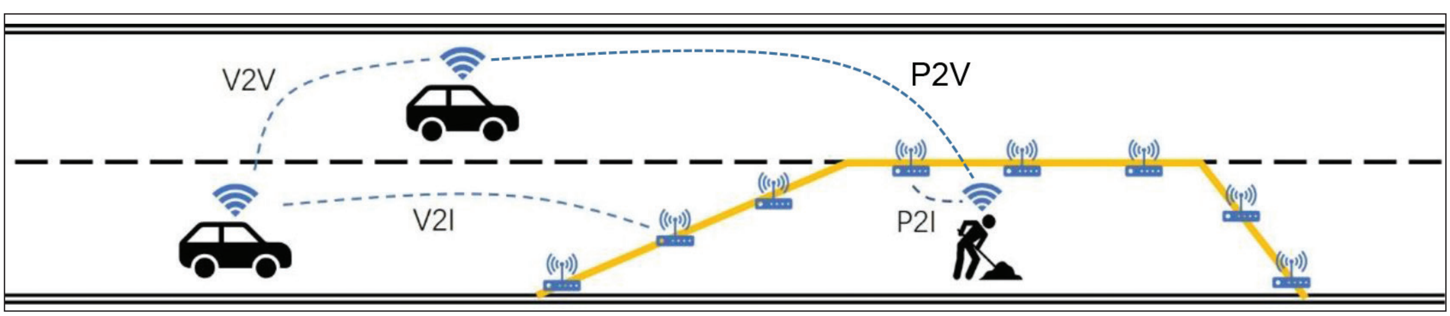

Figure 13.
Communication Between Vehicles, Workers, and Infrastructure

The future technologies may also consider some other factors such as roadway types, traffic conditions, weather, and illumination. For example, one technology may work well for the interstate system but not for rural highways. Guidelines are needed for different traffic conditions under a variety of weather and illumination conditions. In addition, a backup system, consisting of conventional or intelligent work zone safety systems, should be in place to be initiated when sudden change/failure of the current system happens.

A number of potential future technologies to prevent work zone intrusions have been reported in the literature. Many of these technologies are based on active communication between the approaching vehicles and work zones. When market penetration of CAVs reaches a significant level, these technologies will be essential for safe work zone operations on highways. Table 5 shows a list of potential future technologies for managing traffic movements around work zones. Interested readers can refer to the cited sources to learn more about these technologies. ■

Table 5.
Future Technologies for Preventing Work Zone Intrusions in CAV Environment

Technology	Communication	Testing Environment	Test Results
Driver Smart Assistance System (DSAS)	RFID	Driving Simulator	Enhances safety by inducing drivers to accelerate smoothly, keep longer headway distance, stop earlier for a hazardous situation in the work zone, and reduce speed significantly *(51, 52)*.
P2V Wireless Communication	Wireless Communication via Bluetooth, RFID, Smartphone, or Wi-Fi	Driving Simulator	Results showed that the drivers were able to recognize the work zone earlier than usual, obtain useful instant guides to avoid any risky situations, and react on time to the changing situations. The subjects recruited in the driving simulation highly appreciated the application of audio warning *(53-55)*.
Smart Work Zone Merge Management *(56)*	DSRC	N/A	N/A
DSRC-based V2I Communication in Work Zone	DSRC	Field Demonstration	Results from the field demonstration have shown that the system can adapt to changing work zone environments smoothly under various congestion patterns on the road *(57)*.
Wireless Sensor Network-Based Intrusion Alert System	WSN	Field Demonstration	The system was evaluated under real conditions and found to be effective and useful to the target scenario (short-term work zones) *(58)*.
Safe Worker to Driver (SWD) App	Android-Based Smartphone Application	Driving Simulator	Results showed that participants drove slowly with less variation in the scenarios with the voice warning messages. Additionally, the sound and voice messages were able to guide participants to decelerate earlier when driving through the work zone *(59)*.
Enhanced Speed Compliance for Work Zones (ESC4WZ)	3G Cellular Modem (communication via 4G modem is recommended for future installations)	Field Demonstration	A field demonstration was conducted in Minnesota at Interstate 35E just south of the County Road J overpass. The results showed that there was reduction in speed violations with enforcement present during the Aug. 8 week. However, speed violations increased during the Sept. 12 week of enforcement. Overall, the system received positive comment from MSP *(60)*.

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