Smart Work Zone System

October 2022 | Final Report

SAFE-D
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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.
VTTI-00-036

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Smart Work Zone System

5. Report Date
October 2022

6. Performing Organization Code:

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8. Performing Organization Report No
Report VTTI-00-036

9. Performing Organization Name and Address:
Safe-D National UTC
Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg, VA 24061

10. Work Unit No.

11. Contract or Grant No.
69A3551747115/VTTI-00-036

12. Sponsoring Agency Name and Address
Office of the Secretary of Transportation (OST)
U.S. Department of Transportation (US DOT)

13. Type of Report and Period
Final Research Report

14. Sponsoring Agency Code

15. Supplementary Notes
This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program.

16. Abstract

In the previous Safe-D project 04-104, a prototype wearable Personal Protective Equipment vest that accurately localizes, monitors, and predicts potential collisions between work zone (WZ) workers and passing motorists was developed and demonstrated. The system also notifies the worker when they're about to depart geo-fenced safe areas within WZs. While the design supported a successful functional demonstration, additional design iteration was required to simplify, ruggedize, and reduce per unit costs to increase the likelihood of broader adoption. In addition, two new useful components were identified that support a more effective deployment package. One of these components is a Base Station that provides an edge computing environment for alert algorithm processing, consolidates communications of individual worker positions via a 4G link to a cloud computing environment, and can be coupled with a local roadside unit to support the broadcast of WZ information to connected and automated vehicles. The second component is a Smart Cone device that was added to help automatically define safe area boundaries and improve communications reliability between workers and the Base Station. This entire package was developed to support a broader scale deployment of the technology by the Virginia Department of Transportation.

17. Key Words
Smart Vest, Smart Cone, Worker Safety, Work zone safety, C-V2X, Connected Vehicles

18. Distribution Statement
No restrictions. This document is available to the public through the Safe-D National UTC website, as well as the following repositories: VTechWorks, The National Transportation Library, The Transportation Library, Volpe National Transportation Systems Center, Federal Highway Administration Research Library, and the National Technical Reports Library.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page) Unclassified

21. No. of Pages
[insert # pages]

22. Price
$0

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Abstract

In the previous Safe-D project 04-104, a prototype wearable Personal Protective Equipment vest that accurately localizes, monitors, and predicts potential collisions between work zone (WZ) workers and passing motorists was developed and demonstrated. The system also notifies the worker when they're about to depart geo-fenced safe areas within WZs. While the design supported a successful functional demonstration, additional design iteration was required to simplify, ruggedize, and reduce per unit costs to increase the likelihood of broader adoption. In addition, two new useful components were identified that support a more effective deployment package. One of these components is a Base Station that provides an edge computing environment for alert algorithm processing, consolidates communications of individual worker positions via a 4G link to a cloud computing environment, and can be coupled with a local roadside unit to support the broadcast of WZ information to connected and automated vehicles. The second component is a Smart Cone device that was added to help automatically define safe area boundaries and improve communications reliability between workers and the Base Station. This entire package was developed to support a broader scale deployment of the technology by the Virginia Department of Transportation.

Acknowledgements

This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program. The research team would like to acknowledge the support from the Virginia Department of Transportation and the Virginia Transportation Research Council, who assisted with their WZ expertise and live WZ testing. The project team would also like to thank Mike Fontaine (VTRC) for providing his subject-matter expertise throughout this program.

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Introduction

Roadside work zones (WZs) present imminent safety hazards for roadway workers as well as passing motorists. In 2020, 857 fatalities due to motor vehicle crashes occurred in WZs in the US (*Work Zone Traffic Crash Trends and Statistics*, 2022). In 2020, there were an estimated 102,000 crashes in WZs, an increase of 8.5% over 2017 (*Work Zone Traffic Crash Trends and Statistics*, 2022). The increase in WZ crashes can be attributed to a number of factors. The nation's highway infrastructure is aging, causing the need for rebuilding and improving existing roadways. This increased road work is being completed on roadways experiencing increased levels of traffic, especially in urban areas, often resulting in nighttime WZs to avoid peak travel times (Work Zone Management Program, n.d). These factors result in more dangerous situations for workers as well as passing vehicles.

Accidents involving motor vehicle collisions are a leading cause of roadside WZ fatalities. Between 2005 and 2010, vehicle collisions were the second most common cause of worker fatalities in roadside WZs, after runovers/backovers by construction equipment (Work Zone Management Program, n.d.). An average of 121 workers per year lost their lives at roadway WZs between 2003 and 2015 (Highway Work Zone Safety, 2017; Fyhrie, et al., 2016). Transportation events accounted for 73% of these fatalities, and 61% of those were due to a worker being struck by a vehicle in the WZ (Highway Work Zone Safety, 2017).

Roadway workers have to work in close proximity to construction equipment as well as high-speed traffic, exposing them to an elevated risk of collisions, which can lead to serious injuries/fatalities. In fact, WZ fatalities have been largely attributed to unsafe proximity and lack of situational awareness by the workers and/or passing motorists (Guo et al., 2017). WZs and the presence of workers within them often violate driver expectations and, as a result, workers and passing traffic are placed in unsafe proximity to each other. WZ safety management could be enhanced by providing detailed and early detection of threats and sending timely information to workers and passing drivers. Furthermore, advanced warning of worker presence can help both human drivers and connected and automated vehicles (CAVs) prepare for and avoid collisions with WZ actors.

The standard WZ safety signage and personal protective equipment (PPE) worn by workers at highway work sites have not been completely effective in controlling WZ crashes. Previous research conducted by this research team has focused on improving roadway workers' safety through the design of a wearable GPS-based communication system that provides multi-modal warnings (i.e., audio, haptic, and visual) to workers in potentially unsafe situations.

In the previous Safe-D project 04-104, a prototype wearable PPE vest was developed and demonstrated that accurately localizes, monitors, and predicts potential collisions between WZ workers and passing motorists. The system also notifies the worker when they're about to depart geo-fenced safe areas within WZs. While the design supported a successful functional demonstration, additional design iteration was required to simplify, ruggedize, and reduce per unit costs to increase the likelihood of broader adoption. In addition, two new useful components that would support a more effective deployment package were identified. The first of these is a Base

Station that provides an edge computing environment for alert algorithm processing, consolidates communications of individual worker positions via a 4G link to a cloud computing environment, and can be coupled with a local roadside unit to support the broadcast of WZ information to CAVs. The second is a Smart Cone device that can help automatically define safe area boundaries and improve communications reliability between workers and the Base Station. This entire package was developed to support a broader scale deployment of the technology by the Virginia Department of Transportation (VDOT). The refinement of the final product focused on achieving the following goals:

- Maximize effectiveness (i.e., consolidated communications, edge computing, accurate warning, effective warning modes, multiple outlets for data)
- Maximize usability (i.e., lightweight and compact enough for workers to be willing to wear the vest for up to 16 hours, simplified design)
- Improve ease of setup and portability
- Improve cost-effectiveness to support a widespread deployment by infrastructure owner operators in a broader pilot deployment program.

Background

At the beginning of this project, limited products to alert WZ workers were available in the market. Those devices were mostly passive and did not actively track WZ workers' activity or position within the activity area. The Virginia Tech Transportation Institute (VTTI) and the Virginia Transportation Research Council (VTRC) worked together to research a system that helps alert workers using different human-machine interface (HMI) outputs, including lights, audio, and vibration tactors to address the sensory challenges present in different WZ environments.

As such, this project aimed to develop a Smart Work Zone system, including the addition of a connected vehicle-to-everything (C-V2X) Base Station linked to Smart Vests and an array of Smart Cones. The C-V2X Base Station acts as the core of the system by communicating with the vests and cones. CAVs approaching a WZ can communicate with the Base Station over a 4G-LTE network to receive information regarding the location and configuration of the WZ. The Smart Vests, worn by road workers, transmit information regarding worker location to the Base Station. The vests also provide auditory, visual, and tactile feedback to alert the wearers of a potential collision threat or WZ boundary crossing. The Smart Cone array is an add-on component that can be attached to WZ drums or cones to define the boundaries of the WZ for the Smart Vest and extend the wireless link with the Base Station. This Smart Work Zone system has tremendous potential to improve road construction safety by increasing worker and vehicle awareness of threats in the WZ.

Method

Task 1: Project Management

VTTI led Project Management tasks throughout the project while keeping sponsors updated as to the project's status. Status update meetings were held with representatives from VDOT and VTRC consistently via remote conferencing. The technology transfer activities and education and workforce development activities were also conducted under Task 1.

Task 2: Establish Production Pipeline

The VTTI team searched for wearable computing design companies to support the Smart Vest and Smart Cone design and manufacturing efforts that will lead to system commercialization. The VTTI team interviewed seven product design companies with experience in wearable product design. The overall process included the execution of an non-disclosure agreement between both parties and sharing of the Smart Work Zone system concept and discussion of specific Smart Vest design goals. Specific subcontractor activities included:

- Reviewing the original prototype system to gain an understanding of the overall function and design goals.
- Researching and sourcing new lighter-weight buzzers/speakers, haptic motors, string LED lights and batteries that can be utilized in the final design.
- Researching and designing weatherproof housing for the electronics that attach to the vest.
- Researching and identifying the best battery options.
- Ensuring the final design follows the guidelines laid out in the American National Standards Institute (ANSI) standard.

The VTTI team thoroughly analyzed a variety of potential product design companies to work on the product design cycle from concept to manufacturing. VTTI selected the Virginia Tech Fashion Design team, who were able to support the Smart Vest design effort, and the Smart Vest “Pouch” design was discussed and implemented with the following features:

- Lightweight pouch design
- Matching fabric color with Work Zone Vest Class 3
- Velcro attachment for pouch support
- Inner layer with neoprene for protection and better comfort

Figure 1 shows the front/inside/rear view for the initial Smart Vest pouch concept. Due to the Virginia Tech Fashion Design team's lack of availability after the first iteration, the VTTI team searched for a local contractor that could support the manufacturing of the Smart Vest and some additional tweaks for the original design. The VTTI team was able to find a local contractor with wearable experience who built pouch prototypes from the initial design and also continued supporting and adding new features throughout the development stage.

Figure 1. Smart Vest pouch concept.

Task 3: Design and Develop Smart Work Zone System Components

During this task, the VTTI team worked on defining the hardware requirements for each Smart Work Zone sub-system (shown in Figure 2). The subsystems include 1) a C-V2X Base Station, 2) the wearable Smart Vest, and 3) a Smart Cone device. All three subsystems rely on a reliable wireless link using DigiMesh wireless technology, which provides a secure, fast, and reliable wireless mesh network using the 2.4 Ghz band and precise positioning by using a Ublox ZED-F9P GNSS multiband receiver that delivers centimeter-level accuracy when using real-time kinetic (RTK) corrections. The C-V2X technology allows the system to communicate with CAVs that are in range and able to support and exchange SAE J2735 Basic Safety Messages (BSMs) and Personal Safety Messages (PSMs) to alert both CAVs and WZ workers when a collision threat is detected. The 4G/LTE connectivity allows the system to communicate with VTTI's Virginia Connected Corridor (VCC) Cloud Server to share the BSMs received from CAVs and the PSMs generated by each Smart Vest/Cone device and download GeoJSON WZ data generated by the Work Zone Builder app.

Each of these subsystems will be described in the following sections. The hardware/firmware and software for the Smart Vest/Cone and Embedded Edge computing platform residing on the C-V2X Base Station were designed in-house by the VTTI team.

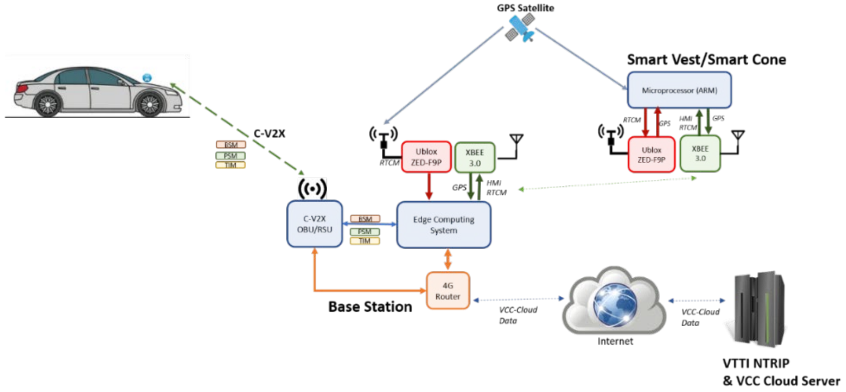

Figure 2. Smart Work Zone system.

Based on the findings from Task 2, the team defined the main hardware components for each subsystem as shown in Table 1. Due to the supply chain disruptions caused by the COVID pandemic, it was necessary to go through two design changes/iterations to secure a bill of materials consisting of available electronic components for all the Smart Work Zone subsystems.

Table 1. Smart Work Zone Hardware Details

Smart Work Zone Subsystem	Component	Description
Smart Vest Device	Class 3 Vest	NiteBeams with integrated LED arrays
	Battery Source	USB Power 5.0 < 50 mA
	Battery Life	Up to 22 hours (GPS Only) Up to 12 hours (HMI Active)
	GNSS Receiver	Ublox ZED-F9P

	GNSS Antenna	Linx Technologies Ceramic Active GNSS Antenna
	Microprocessor	STM32F412 (32-bit ARM MCU)
	Wireless Transceiver	XBEE 3.0 Pro
	Wireless Transceiver Range	Up to 300 meters
	Auditory HMI	Sewable Buzzer 80 dB
	Visual HMI	Front/Rear LED embedded on NiteBeams Work Zone Vest
	Tactile HMI	Precision Microdrive Motor 13.800 rpm @ 7G
Smart Cone Device	Battery Source	USB Power 5.0V @ 50mA
	Battery Life	Up to 20 hours (GPS Only)
	GNSS Receiver	Ublox ZED-F9P
	GNSS Antenna	Linx Technologies Ceramic Active GNSS Antenna
	Microprocessor	STM32F412 (32-bit ARM MCU)
	Wireless Transceiver	XBEE 3.0 Pro
	Wireless Transceiver Range	Over 300 meters using Digi XBEE DigiMesh
C-V2X Base Station	Power Source	PoE 48-53V @ 500mA
	C-V2X RSU	Qualcomm C-V2X DP – Commsignia C-V2X RSU
	Embedded Edge Computing	Raspberry Pi 4 4GB SRAM – 64GB SD Card
	GNSS Receiver	Ublox ZED-F9P
	GNSS Antenna	Maxtena M8HCT
	Wireless Transceiver	XBEE 3.0 Pro
	Wireless Transceiver Antenna	2.4 GHz Whip Antenna
	4G-LTE Router	Teltonika RUT240

C-V2X Base Station

The C-V2X Base Station is the main subsystem device that runs several tasks using multiple communications interfaces including C-V2X, GNSS/GPS, XBEE, and 4G/LTE. Figure 3 shows, at a high-level, component integration within the Base Station. The main features of the Base Station subsystem include the following:

- Self-powered using generator/batteries (solar panel optional).
- C-V2X coverage up to 500 m radius.
- Wireless coverage up to 300 m line of sight (LOS) with Smart Vests and extended range using Smart Cone devices.
- Cloud connectivity to interface VCC-Cloud backend using 4G Link.
- Support RTK corrections transmission over XBEE Link using VTTI proprietary protocol.

C-V2X technology allows the system to communicate with CAVs using C-V2X communications through the integrated RSU, which has two main engines that exchange information with the embedded computing platform using a UDP socket interface and a transcoding data engine that process all the SAE J2735 BSMs/PSMs/traveler information messages (TIM). Information about WZs can be shared with CAVs in the form of standard SAE J2735 (TIMs, PSMs, and BSMs.

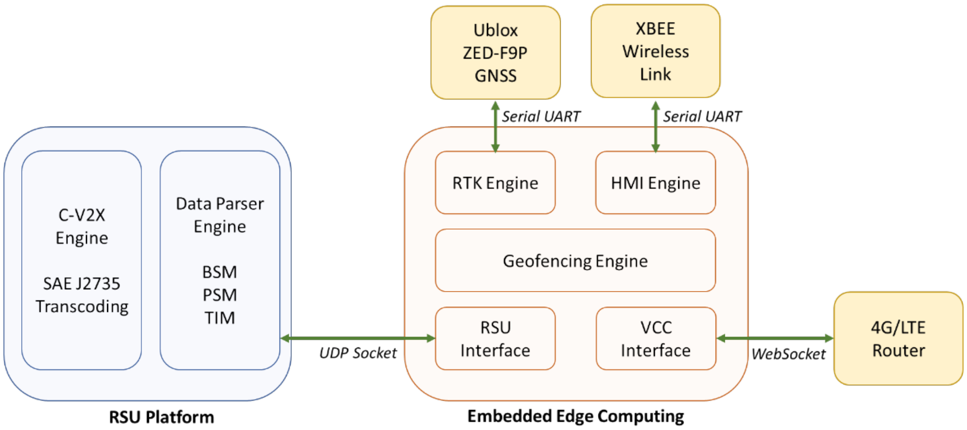

Figure 3. C-V2X Base Station components.

The embedded edge computing system provides RTK GPS corrections to the Smart Vests, processes Smart Vest GPS data, and runs algorithms to trigger HMI alerts based on the virtual geofence created by the Smart Cone devices deployed at the WZ or the activity area defined by the GeoJSON WZ data received from VCC Cloud Server. All received and processed data is forwarded to VTTI VCC-Cloud backend via 4G/LTE cellular communications, which will make it accessible to mobile applications using the VCC Public API or the SmarterRoads.org data sharing portal.

Figure 4 shows the C-V2X Base station hardware. It uses an IP24 enclosure with Power over Ethernet power support. The Qualcomm RSU connects to the embedded edge computing system (RPI) using an ethernet interface along with the 4G/LTE Router. Additional devices including the XBEE, Ublox ZED-F9P, and power regulators are also secured in the enclosure. External antennas for C-V2X, 4G, and XBEE are installed for best performance.

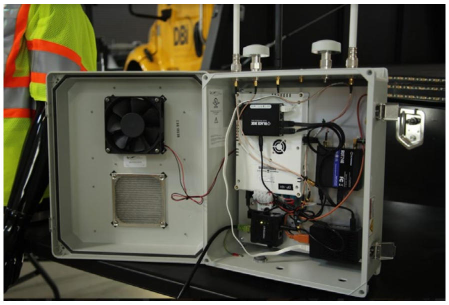

Figure 4. C-V2X Base Station.

Smart Vest

The VTTI team designed the Smart Vest hardware and electronics to be housed by the Smart Vest electronics “pouch” that was built in Task 2. The main features of the Smart Vests include:

- Battery power.
- Low power consumption (up to 20 hours of field operation).
- Up to 1 cm GPS accuracy using GNSS, Glonass, and GPS positioning.
- Lightweight and comfortable.
- Three HMI outputs: visual, auditory, and tactile.

- Fully detachable from a Class-3 WZ vest to allow for regular cleaning.

Due to supply chain disruptions caused by the COVID pandemic, the VTTI team designed two different revisions for the hardware design to overcome the electronic component shortage, including the main processor, GPS, and XBEE chips. The final design is shown in Figure 5.

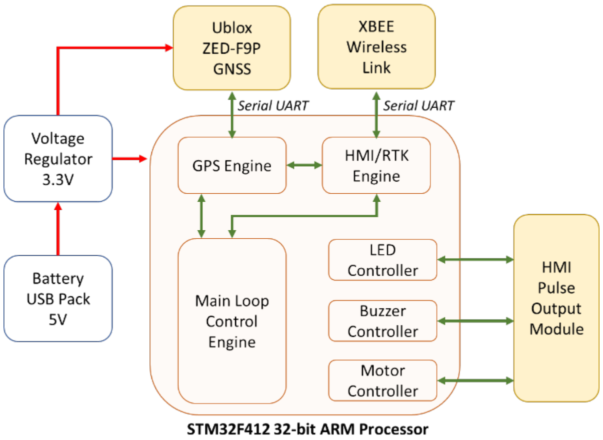

Figure 5. Smart Vest hardware design.

The Smart Vest hardware device was designed to be attachable to an ANSI Class-3 work vest. The VTTI team selected a commercially available NiteBeams Class 3 vest platform which provides built-in LEDs that can be interfaced to the Smart Vest pouch design. The design uses a USB Battery pack providing 5V @ 5,000, mAh, which can power the hardware for up to 22 hours. There is a main voltage regulator that translates the main power input into 3.3 V to power all the sub-systems including the Ublox GPS, XBEE Wireless Link, Main Processor, and the HMI Output modules. The Digi XBee Wireless link provides two different data packets: RTK corrections that are injected to the Ublox ZED-F9P GNSS/GPS receiver and HMI control requests that are processed by the main control engine to trigger pulse width moderation (PWM) Pulses for each HMI output accordingly. Using RTK corrections from Base Station, the local Ublox ZED-F9P provides positioning data to the main processor, which encodes that data in a proprietary protocol, and sends it back to the Base Station in a specific period ranging from 100 ms up to 1 s. The main control engine handles the serial data interfaces for both GPS/XBEE devices using a priority interrupt scheme and is responsible for encoding/decoding all the data exchanged with the Base Station using VTTI proprietary protocols. Along with the aforementioned tasks, the main control engine generates the proper configuration for each independent PWM controller (LED, Buzzer, Motor) to generate the desired alerts consisting of the number of pulses, frequency, and duration. Appendix A provides additional details about the algorithm development for geofencing and alert triggering.

The VTTI team considered all the requirements and feedback gathered from the sponsor and previous deployments to create a Smart Vest device that is simpler, lower weight, hardened to harsh working conditions, transferrable between different PPE garments, and has longer battery life than the design prototype developed in Safe-D 04-104. The team designed two hardware revisions for the Smart Vest and Smart Cone printed circuit board (PCB) housing all the electronics for GPS and HMI functionality. Table 2 shows the different PCB hardware revisions implemented by VTTI team.

Table 2. PCB Hardware Revisions

Original Safe-D project 04-104 PCB hardware: Figure 6a	GPS Ublox ZED-F9P chip incorporated and a header for the XBEE 3.0 3 transceiver. No microprocessor, as that is a stack board to the NXP development board. Powered using a micro-USB connector with a 5 V source.
Smart Vest/Cone Revision A: Figure 6b	Incorporates an STM32F303 Microprocessor, Microchip BLE device, and Ublox ZED-F9P. Header for the XBEE 3.0 transceiver. Powered using a micro-USB connector with a 5 V source. Pandemic meant limited quantities of microprocessors were available in the market—five boards were procured to continue development.
Smart Vest/Cone Revision B: Figure 6c	Uses an updated microprocessor (STM32F412) and two headers for both XBEE 3.0 transceiver and the Ublox ZED-F9P. Uses a two-layer PCB stack and has all the HMI connectors on top. Ten boards were procured.

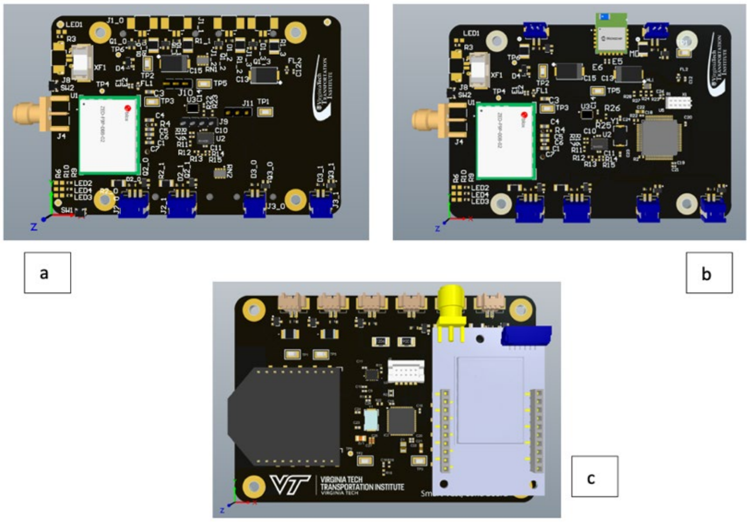

Figure 6. Smart Vest PCB revisions.

Figure 7 shows the different Smart Vest pouch revisions that local contractor built.

Revision A is the baseline design. Internally, it had an elastic band and Velcro to secure the PCB board and USB battery pack. On the rear side, there were two small elastic bands to secure the vibration motor and Velcro to adhere to the Class 3 vest.

Revision B has upgraded fabric that is water repellant, a Neoprene layer for better comfort, and all the metal grommets were removed.

Revision C has snap buttons in addition to Velcro to better secure the pouch to the vest. The GPS pocket was moved to the pouch's top edge for better signal acquisition.

Smart Vest Pouch Revision A

Smart Vest Pouch Revision B

Smart Vest Pouch Revision C

Figure 7. Smart Vest Pouch build revisions.

Smart Cone

The Smart Cone device uses the same hardware design as the Smart Vest, but without HMI support. When the Smart Cones are deployed within a WZ, they can be used to create a virtual geofence. When that geofence is approached or crossed by a worker wearing a Smart Vest, the system triggers an HMI alert to the Smart Vest. The Smart Cone device can also extend the Base Station range and coverage by acting as a mesh node device. The team explored the integration of lighting capabilities within the Smart Cone devices to indicate the presence of a WZ to passing motorists. The main features of the Smart Cone include the following:

- Up to 300 meters communications range
- Small form factor, which can be embedded in a standard WZ cone
- Battery power (up to 24 hours of operation)

The Smart Cone unit consists of five major components as shown in Figure 8: 1) a custom PCB that functions as the brains of the device and allows the unit to participate in the mesh network architecture using XBEE radio communications; 2) a GPS antenna which, when paired with the RTK corrections received from the Base Station, provides for centimeter-level accuracy; 3) a rechargeable lithium battery pack that can power the device for 20 hours on a single charge; 4) a waterproof enclosure with removable top panel for easy access; and 5) a custom designed clamp made to easily and quickly secure the cone enclosure to the top of the standard traffic cones used by VDOT (in a different configuration, the unit can also be attached to a standard drum without the need for the clamp). Appendix B provides further information on the clamp design to secure the Smart Cone to a WZ cone unit.

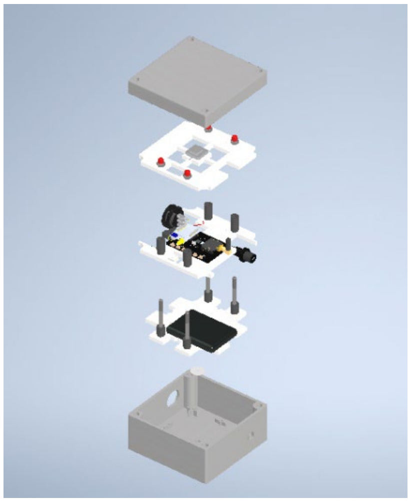

Figure 8. Smart Cone hardware assembly.

The final consideration to revisit for the Smart Cone unit was safety. While there are minimal safety concerns regarding the unit itself, the unpredictable can always occur in live WZs—for example, when a rogue vehicle enters the WZ and impacts the cone(s). Initial low-speed crash testing in a variety of scenarios revealed that the unit would remain affixed to the cone after the collision but would separate from the cone when subsequently impacting the ground. The unit weighs less than 2 pounds and would not travel far, remaining on the ground, posing a minimal projectile risk after low-speed impacts. However, high-speed collisions could result in the unit being thrown as a projectile, which presents a potential safety risk for nearby workers. It is for these reasons that the most recent design change was implemented. While strengthening the plastic by moving to an injection molded plastic with higher strength might reduce risk, it was decided to affix the unit to the cone via a secondary tether. This tether consists of a 1/16” steel cable attached to a 3/16”x 3” steel bolt that runs through the enclosure and through all the tiers to ensure that the unit does not become a projectile and remains primarily one piece. The steel cable is fashioned into a loop that tightens around the top of the cone below the clamp and can be quickly slackened by pulling back on a release button. Figure 9 shows a 3D rendering of the final design.

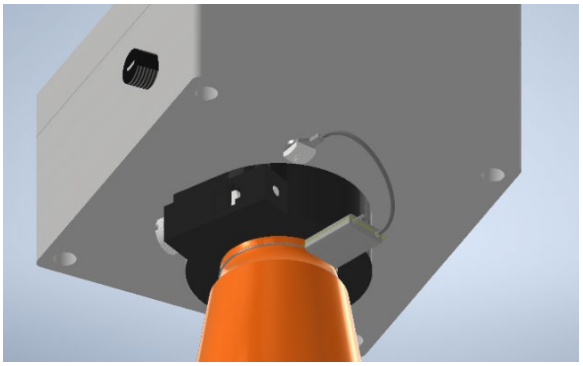

Figure 9. Final Smart Cone clamp 3D rendering.

Future developments for the Smart Cone unit are already being considered, including reducing fasteners needed for the clamp; designing the units to be arrangeable in a rugged case for transport, storage, and charging; and designing a custom waterproof enclosure that will surround the unit to further reduce the projectile hazard to both the driver of an impacting vehicle and workers in the area.

The Smart Cone uses the same PCB hardware as the Smart Vest but does not include any HMI connectivity. Figure 10 shows the internal stack and the waterproof power switch. The waterproof charging port for the lithium battery on the bottom layer is mounted to the opposite side of the enclosure (not shown). The GPS/GNSS antenna resides on the top layer for the best signal acquisition. As mentioned in the previous section, the Smart Cone device can be adapted to be installed on both WZ cones and drums.

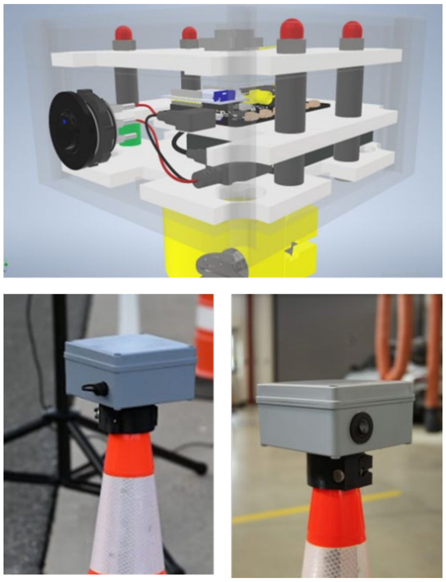

Figure 10. Smart Cone hardware.

The VTTI team evaluated the design by running different tests to verify the Smart Cone cannot be considered a projectile when it is hit at speeds above 20 mph.

Move Over Law System

The team researched technologies that can help to detect motorists who do not follow the move-over law and that can be combined on a deployable system to be used by law enforcement, safety service patrol, and emergency vehicles to provide alerts when a threat or dangerous traffic interaction is detected. The main features of this system include:

- A vehicle-powered computing system.
- Two external sensors, including an HD camera and radar for line perception, vehicle perception, and speed detection.
- A wireless warning system using a compact version of the Base Station.

For the machine vision-based perception, the team implemented and evaluated three technologies including Nvidia Drive Perception SDK, YOLO-V3, and YOLOP. The NVIDIA Drive Perception SDK was ultimately selected based on its performance for both object detection and road marking feature detection. The team also evaluated two radar technologies for vehicle speed detection and considered the fusion effort with the vision-based system.

Figure 11 shows the high-level software implementation for the Move Over Law system consisting of two main software applications: 1) a native C++ application using NVIDIA Drive Perception SDK/API, which runs two deep neural networks and provides a polygon/geofence for the detected adjacent lane and 2) object detection for motorists who enter and exit the geofenced area. The radar sensor provides position and speed information for the vehicle passing through the detection area. The radar data is fused with the vision-based data to generate an object data structure containing a bounding box from the vision-based system and location and speed from the radar sub-system.

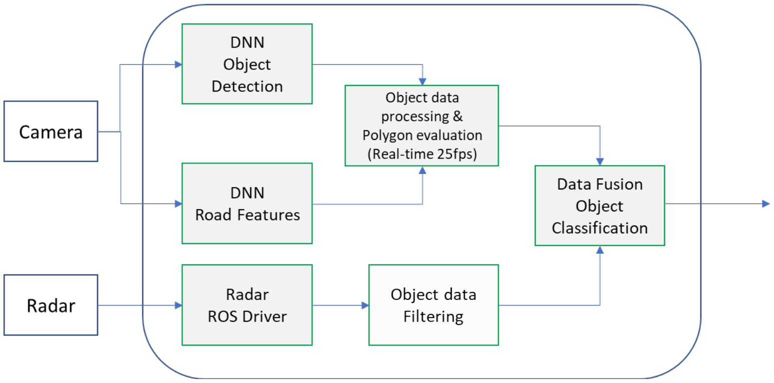

Figure 11. Move Over Law system.

The team collaborated with the Global Center for Automotive Performance and Simulation (GCAPS) on the data fusion effort to match the vision-based object detection data with the radar-based data. Using the Robot Operation System, both teams injected data into the fusion algorithm to generate a new fused data structure that can be used to alert when a threat situation is identified. Appendix C provides further details about the developed fusion algorithm.

The team also worked on the mechanical design of the system. One of the design requirements is the ability to install the system on a wide variety of vehicles with the main goal of monitoring the adjacent lane when parked on the shoulder of the road. The mechanical sensor system consists of three main parts: 1) a magnetic base, 2) a mounting arm, and 4) an equipment plate that holds the radar, camera, and infrared illuminator. The magnetic base is made up of two rubber pucks housing a total of 24 rare-earth magnets that allow for rapid magnetic surface mount of the system to metallic body panels or vehicle structures. These rubber pucks are fastened to a powder-coated steel bracket and a 6061-aluminum plate via M8 stainless steel screws. Connected to the plate is the base of a 6” Panavise pedestal mount that allows for 360-degree rotation and over 210 degrees of tilt so the equipment plate can be oriented in any direction. The equipment plate measures just 6” x 7” and is cut from 1/8” aluminum that holds the two sensors and illuminator securely facing the same direction.

VTTI had the opportunity to install the Move Over Law system in a VDOT truck mounted attenuator (TMA) truck in Lynchburg, VA. Figure 12 shows the sensor unit, which is connected to a computing platform housed in a separate enclosure. In the most recent installment, the power and USB cables from the sensory unit were run to a waterproof enclosure affixed to the same magnetic mounting base that housed a small PCB and a USB distribution block. Power was run to this box from the vehicle, in this case, a TMA vehicle. Data was passed to VTTI's data acquisition system mounted underneath the truck bed. Figure 12 shows an installed system. Though the system is shown here mounted to the superstructure of the TMA bed supports, the system can just as easily be placed on the hood, roof, trunk lid, etc. of any other vehicle.

Figure 12. TMA install for Move Over Law system.

Task 4: Demonstration in Live Work Zone

Under this task, the team conducted a demonstration of the Smart Work Zone system in a live WZ. The team worked with VDOT and was able to deploy and demonstrate system functionality in a live WZ environment and a parking lot demonstration. These two opportunities were identified and evaluated by the VTTI and VDOT teams to minimize any potential safety concerns while maximizing the benefit of the demonstration. The team collected data during these demonstration activities, including communications latency between each system component, GPS accuracy, and general feedback from system users. The Pennsylvania DOT has also asked to borrow the system for evaluation but as of this writing, the VTTI and Penn State legal teams were still reviewing the material transfer agreement terms that will govern the loan.

Wise County Demonstration

The team worked with VDOT personnel in the effort to identify a live WZ deployment that provided adequate safety margins and the ability to deploy the Smart Work Zone system. Both teams collaborated with GeoStabilization International (GSI) and selected a WZ deployment in US-23SB Wise County to be the target WZ (see Figure 13a) . The VTTI team provided a short presentation and introduction to the technology to the GSI crew and provided a live demonstration of the system using the C-V2X Base Station, four Smart Cones, four Smart Vests, and a portable Smart Vest box for vehicle mounting.

The VTTI team collected feedback from the workers and VDOT crew members regarding system functionality and features that will be discussed in the following sections.

Northern Virginia Demonstration

The team organized a demonstration event in Northern Virginia to showcase the Smart Work Zone technology to VDOT team members and local contractors. The event took place at McLean Bible Church parking lot, Vienna, VA (see Figure 13b). VTTI team provided a short presentation and introduction to the technology followed by a live demonstration using the C-V2X Base Station, four Smart Cones, five Smart Vests, and the portable vehicle unit. The VTTI team was able to showcase all of the system's features including dynamic geofencing using the Smart Cone devices, Smart Vest alerting, the portable Smart Vest box for vehicle mounting, and communications with the VCC Cloud Server.

Figure 13. a) Wise County live WZ deployment and b) Northern Virginia Event.

Results

Smart Work Zone Field Testing

System Validation

The team developed additional waterproof enclosure and magnetic mount features for use when the Smart Vest hardware is installed on a vehicle or machinery. Figure 14a shows GPS points during testing at the Virginia Smart Road. The developed algorithm triggers an alert only when the vehicle is moving, or the speed is higher than 2 mph. Several test runs were executed at the Smart Road simulating vehicle movement and collecting data for accuracy analysis. The first plot shows red points around the vehicle's location, and blue and green points show locations outside of the vehicle's threat area.

The team evaluated RTK when the C-V2X Base Station is deployed near buildings. Average RTK accuracy was 30–40 cm and the geofencing algorithm engine classified the Smart Vest GPS position entries as expected. Different GNSS/GPS antennas were evaluated during these tests and the team picked the Maxtena GNSS Antenna, which provided quick GPS/GNSS signal acquisition and showed the best performance near buildings with the lowest dilution of precision (DOP) values. Figure 14b shows green and blue points within the safe polygon/geofence area and the red points shows GPS position classified as threat/non-safe.

The team also tested the dynamic Smart Cone geofencing polygon evaluation against the Smart Vest GPS data points as shown in Figure 14c. The current logic detects Smart Cone movements larger than 5 cm to update the geofencing polygon and provide alerting detection.

Figure 14. VTTI Smart Road System testing.

Wise County Field Demonstration

During this WZ field testing, the smart WZ was deployed using four Smart Vests, four Smart Cones, one portable Smart Vest unit for vehicles, and the C-V2X Base Station. After attending a safety briefing. Workers wearing the Smart Vest units performed their normal activities while the portable unit was installed on a drilling machine. Spare Smart Vest units were also used for demonstration purposes by other VDOT crew members who assisted in this field demonstration. Figure 15 shows the WZ field site deployment.

Due to the geography and location near the concrete wall work, the Base Station was not able to acquire enough satellite signals to lock and survey the location to provide RTK corrections to the Smart Vest and Smart Cone devices. The average position accuracy for the Base Station's GPS receiver was around 1.5 meters using only four satellites. Under normal conditions, the system uses 8–9 satellites to lock position and the survey process takes around 15 minutes to generate RTK corrections, which provide accuracy down to 20 cm.

Figure 15. Wise County system deployment.

The lack of GPS signal in this location and the topography of the work site made maintaining geospatial accuracy a challenge. For this reason, false alerts were triggered during the deployment, which significantly impacted the ability to demonstrate the benefits of the system. However, the workers who wore the vests liked the overall concept and felt that it would be valuable if the position accuracy were improved, resulting in a reduction in false alarms. The feedback from workers also indicated that they'd like to get warnings about their proximity to construction equipment only when the equipment begins to move. With the collected data, the team analyzed the collected GPS and trigger points to better understand the system precision under non-RTK conditions. Under this non-RTK condition, the following actions can be taken to improve GPS quality:

- Raise GPS antenna by using a trailer with extended antenna pole.
- Remove GPS/GNSS constellations affected during the WZ deployment.
- Swap GPS antenna for a better/higher sensitivity antenna.

Northern Virginia VDOT Demonstration

The VTTI team coordinated with VDOT and VTRC teams for another demonstration opportunity in Northern Virginia. The demonstration included local contractors and the team was able to implement and adjust the system's operation based on the feedback received from Wise County field testing, with a focus on the portable Smart Vest device for vehicle mounting alerting using speed detection and improved settings for GPS/RTK signal acquisition and correction streaming. Attendees had the opportunity to wear and try the Smart Vest units and provide feedback about the safety features while they crossed the virtual geofence created by the Smart Cone units. Figure 16 shows how the virtual WZ was set up at the parking lot for the technology showcase. Additional images of the Northern Virginia VDOT demonstration are included in Appendix D.

Figure 16**. Northern Virginia VDOT demonstration.**

Discussion

Position Accuracy

The system uses GPS-RTK technology to track Smart Vest and Smart Cones during field deployment. While GPS technology provides precision up to 10 cm, three main factors can impact GPS quality and performance: 1) the position of satellites, 2) the features of GPS receivers, and 3) the environment.

Position of Satellites

Satellite geometry directly impacts the quality of the position solution estimated by the receiver. GNSS is designed so that at least five satellites are above the local horizon at all times. The position DOP provides a measure of the prevailing satellite geometry. Low position DOP values, in the range of 4.0 or less, indicate good satellite geometry, whereas a position DOP greater than 7.0 indicates that a satellite geometry is weak.

Features of GPS receivers

GNSS receivers use different frequency bands to acquire GPS signals and they are classified as Upper L-Band and Lower L-Band. The receiver's performance will be better when it supports more GNSS systems and frequency bands.

Environmental Factors

Since the signals from satellites to GPS receivers need to travel a long way, the propagation environment affects the signal strength and positioning correctness. The ionosphere and troposphere can cause errors occur due to signal blockage and reflections.

Survey Results

During the two demonstration events, the VTTI team collected feedback from workers and safety operators regarding the operation, comfort, new features, and improvements to the system.

Regarding the Smart Vest's comfort and alerting, the results showed that the weight and positioning of electronics were good—workers mostly did not notice having an additional pouch on the vest. The combination of light, sound, and vibration was noticeable at two different alert levels: soft and hard alerts. An accessible power/disable button was suggested to temporarily disable the alerts, and an alert variation such as blinking lights or different auditory levels was desired.

Regarding the Smart Vest operation, during the Wise County field testing, the workers noticed false alerts related to the RTK issues due to mountain and multi-level access of the WZ. For the vehicle/portable Smart Vest device, workers also suggested issuing alerts only when the vehicle is moving so workers only get warnings only for motion actions and not for positioning. Another comment was related to a waterproofing feature for the Smart Vest pouch to ensure full operation in different weather scenarios.

Conclusions and Recommendations

This project consisted of the designed and development of a wireless Smart Work Zone system that alerts workers and potentially CAVs during dangerous situations within the WZ and more specifically the WZ's activity area. The Smart Work Zone system works under the following operation conditions:

- Good GNSS/GPS Signal to support RTK corrections and position accuracy < 20 cm
- Smart Vest range up to 500 m from C-V2X Base Station
- V2X support using C-V2X technology and SAE J2735 BSM/PSM/TIM messages
- Dynamic safe geofence delimitation using Smart Cone, Work Zone Builder App, or Geo-Plotter devices
- Up to 22 hours of operation for Smart Vest units and 20 hours for Smart Cone devices.

The Smart Work Zone system successfully monitors and tracks Smart Vest devices within the safe geofence area created by Smart Cones and generates the proper alerting mechanism (Soft/Hard) based on the threat level detected by the system. Along with Smart Vest monitoring, the C-V2X Base station can process BSMs from vehicles equipped with C-V2X technology and generate alerts when those vehicles represent a threat while passing through the WZ activity area. The system supports communications with VTTI's VCC Cloud server to exchange WZ information and forward BSMs and PSMs generated from the WZ deployment.

The team gained valuable insight when working with the Virginia Tech Fashion team to understand the challenges for a wearable device such as the Smart Vest, which were addressed during the project execution. There is still an opportunity for Smart vest improvement, including waterproofing, weight reduction, and charging port features.

The team also learned about Manual for Assessing Safety Hardware (MASH) testing during the Smart Cone design process and the different test cases required to be fully compliant with the standard. Unfortunately, the MASH testing cost was not scoped on this project. However, the team prepared and designed an updated Smart Cone enclosure, which the team believes will be MASH certified.

In addition to achieving the major technical objectives, VTTI successfully worked with VDOT/VTRC teams to obtain additional feedback and insight about the Smart Work Zone system and how it can help reduce accidents and fatalities in the WZ deployments. The following are suggestions received during the field-testing survey process:

- Easy system configuration focusing on a quicker polygon reconfigure
- Alert broadcasting to all Smart Vest for imminent threat situations (SOS)

The VTTI team will incorporate the above suggestions into a Smart Work Zone Application that will be developed under the VCC 2023 project. Specifically, a Supervisor Application will be developed to provide further details about the system status, Smart Vest/Cone location, alert triggering status and configuration settings.

The Smart Work Zone system technology relies on GPS/RTK for positioning accuracy under 10 cm. There are some limitations and conditions as to where this technology can provide the required position resolution. Additional technologies such as ultra-wideband could be a potential add-on to the current design; size and cost directly affect how such technologies can be integrated into the Smart Vest/Cone devices.

The VTTI team is currently evaluating future enhancements that can be applied to the system and possible new form factors for the Smart Vest wearable device. In parallel, the team is working with a commercial company to license the technology and add additional features to the Smart Vest hardware.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project are described below and are listed on the Safe-D website here. The final project dataset is located on the Safe-D Dataverse.

Education and Workforce Development Products

The team submitted an entry to the American Traffic Safety Services Association's (ATSSA's) Innovation Awards 2022 contest. The team's entry was a video called "Smart Work Zone system," which shows the system components, their functionality, and how they can provide an additional layer of safety on WZ field deployments. The team focused on describing each component and its role within the overall system and how the algorithm works to track Smart Vest and Cone devices along the WZ activity area. The team presented this video at ATSSA 2022 and won 2nd place.

Video Link: https://vimeo.com/672585523

Technology Transfer Products

IP Disclosure

A Smart Work Zone technology package invention disclosure has been filed with Virginia Tech's LINK + Licensing + Launch intellectual properties team. This includes the hardware, firmware, and software designed, developed, and integrated into the three main Smart Work Zone system components: C-V2X Base Station, Smart Vest, and Smart Cones. Also, a provisional US Patent Application was submitted to the US Patent office on January 12, 2022. Appendix E shows details about the Virginia Tech Highlight shared by the VTIP team.

Technology Transfer

Dr. Michael Mollenhauer presented the current work on the Smart Work Zone system during PA AV Summit Series #3 - Work Zone on April 29, 2021. He discussed the Smart Vest, Work Zone Builder Application, and C-V2X work that VTTI was conducting.

Dr. Michael Mollenhauer presented the Smart Work Zone system technology and demonstrated the Smart Vest functionality during a demo session at VTTI for an Army group on July 20, 2021. The demonstration covered the Smart Vest and C-V2X Base station functionality on a virtual WZ setup outside VTTI's Intern Hub.

Dr. Michael Mollenhauer presented the Smart Work Zone system, Work Zone Builder application, and Smart Intersection technologies and demonstrated the Smart Vest functionality during a demo session at VTTI for the Falls Church Smart City team on July 22, 2021. The demonstration covered the Smart Vest and C-V2X Base station functionality on a virtual WZ setup outside VTTI's Intern Hub.

Dr. Michael Mollenhauer and M.Sc. Jean Paul Talledo Vilela presented the Smart Work Zone system as part of the Innovation Awards contest for the work performed with our partners Audi, Qualcomm, America Tower Corporation, and TTS using the C-V2X Base Station and Smart Vest devices on the first C-V2X Work Zone and Traffic Light information alerting in the US. This presentation was held in Charlotte, NC on December 07, 2021.

The Smart Work Zone technology had been used in two research projects: C-V2X Work Zone and TLI Demonstration and Safely Operating ADS.

Data Products

The data uploaded to the Dataverse includes 1,455,451 data points collected at three different locations/events: the Virginia Smart Roads, Wise County Work Zone Field test, and Northern Virginia showcase. The collected dataset includes data entries for several Smart Vest devices while moving around a virtual polygon area defined by the Smart Cones devices and the portable Smart Vest system for vehicle mounting. The virtual polygon area was defined using four and five-point polygons. The Smart Vest devices were worn inside and outside the virtual polygon and their GPS location was processed to calculate their classification and alert triggering (soft/hard) using the HMI warnings accordingly when crossing between safe zone, low-level warning areas, and high-level warning areas. The dataset can be accessed at https://doi.org/10.15787/VTT1/JNJFX5.

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Appendices

Appendix A: Geofence Validation

VTTI developed an algorithm to ensure the geofence created would be of what was intended from the positions of the Smart Cone devices. The algorithm ensures the polygon is constructed correctly and is dynamic allowing it to change when cones are moved, added, or removed from the WZ. This section describes how the algorithm ensures the geofence is constructed correctly. The Smart Cone devices are in constant communication with the embedded systems in the C-V2X Base Station to constantly track the positions of each connected device. As a result, the geofence gets created by adding the cones that are received first and are updated upon each new cone that is added. Without geofence validation, the WZ may result in overlapping areas that were not intended. Figure 17 demonstrates the results that may occur without validation and overlapping has occurred.

Figure 17. Overlapping geofence.

The algorithm ensures that the positions of cones are reordered if need be to ensure overlapping does not occur. The algorithm uses a center point of the cones and the angle of each cone to that center point to reorder the cones in a counter-clockwise direction. The geofence area is then created by defining edges in the new order of the cones. In addition, when a Smart Cone has been detected as moving more than 5 cm from the previous position, the algorithm is restarted and a new geofence is created.

In the rare event that two or more cones fall on the same angle, the validation may not work fully as intended as the device that communicated first will be ordered first. This typically only occurs in one of two scenarios depending on the number of Smart Cone devices in use and the intended shape of the geofence area. First, a Smart Cone device that is not part of the intended WZ is on and sending its position data, and second, one of the intended Smart Cone devices is no longer communicating with the Base Station or has shut off. This may result in the wrong geofence being generated.

Appendix B: Smart Cone Design Details

The Smart Cone is based on a 3-tier design, made to be removed from the enclosure entirely without disassembly so parts can be quickly inspected. Each tier contains a different component: the first level is the battery, the second level is the proprietary PCB and XBEE radio chip, and the third level, the top-most level, includes the GPS antenna for clear, unobstructed satellite communication. To ensure the unit was easily reproduced, VTTI sourced a commercially available high-strength ABS IP67 box enclosure to serve as the outer shell for the unit. The box measures approximately 5 ¾” square by 3.5” tall to be as minimally cumbersome to carry in large quantities in a single case as well as to not appear imposing or unbalanced when affixed to the cone. Each unit has a waterproof on/off switch and a waterproof Micro-USB port for charging the battery.

Figure 18 shows the clamp design.

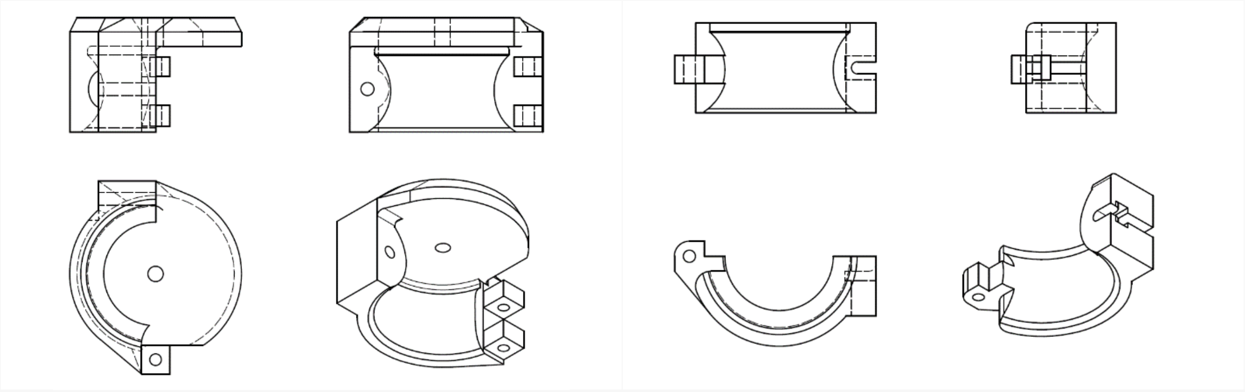


Figure 18. Clamp mechanical design.

The component that went through the most iterative revision is the cone clamp, having approximately 5 major versions with only 3 being viable and further refined. Some versions were too complex while others were unappealing for a variety of style and mechanical reasons when fully flushed out. The first design, covered the entire concave portion of the top of the cone, consisting of two major portions assembled with a short shoulder screw and clamped with a cam-handled screw into a captured nut. Figure 19 shows the first clamp design diagram

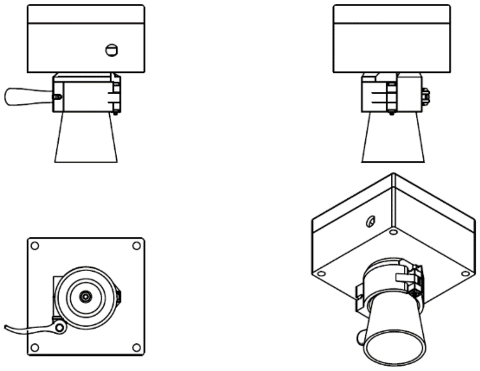


Figure 19. Initial clamp design.

Successive iterations attempted to accomplish various goals such as strength or disassembly/reassembly time; iterations ranged from attempting to incorporate commercially available hose clamps all the way to eight-part spring-loaded custom plastic assemblies designed to lock and release with just a squeeze of the neck. However, ultimately, the original design received slight modifications to increase strength by reducing stress concentration areas, speed up production by reducing the height of the components while still maintaining effective contact portions for security, and decrease mounting time by swapping the cam handle for a thumb screw; drawings can be seen in Figure 20.

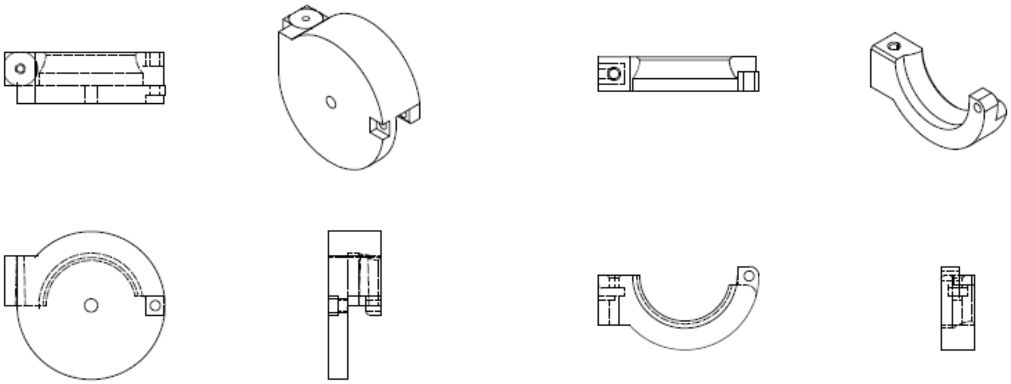


Figure 20. Final clamp design.

Appendix C: Camera and Radar Sensor Fusion for Vehicle Speed Calculation

VTTI and GCAPS collaborated on the algorithm development for calculating vehicle speed for traffic that is not following the Mover Over Law rule. This section describes at a high level how the algorithm works and how the data is being fused.

The program reads object detections (bounding boxes) and radar detections (positions and velocities with target identifiers). For each bounding box, a matching radar detection, if any, is sought. The horizontal image resolution (1920 pixels) and the horizontal field of view of the camera (69 degrees) are the only constants that need to be known. In addition, the maximum age (temporal gap) of a radar track is a tuning parameter. The chosen default value of 0.1 seconds is slightly larger than the expected update interval of the radar.
The algorithm for matching radar detections to bounding boxes works as follows:

- First, whenever a new set of bounding boxes is read, the existing radar targets (i.e., those radar targets whose latest observations are newer than the chosen maximum age) are predicted to the bounding box arrival time. The expired radar targets are discarded. The radar prediction is done by simply using the previous target velocity and assuming constant velocity.
- Secondly, the predicted radar positions are mapped to horizontal image coordinates. This can be done easily because the image resolution and field of view are known, and the radar can be assumed to point in the same direction as the camera.
- In the third and last step, the bounding boxes and radar targets (in image coordinates) are associated with each other. In most cases, this is simple: If a radar target (in image coordinates) is between the left and right edges of a bounding box, then the radar target and the box correspond to each other. However, the actual algorithm is slightly more complex to deal with subtleties related to multiple or conflicting associations. Thus, before computing the box-radar correspondences, all boxes are sorted such that the closest box becomes first, and similarly, the radar targets are sorted in ascending order based on the longitudinal positions of the targets. The "closeness" of a bounding box is defined by the vertical image coordinate of the bottom edge; the larger the image coordinate (i.e., the further away from the top of the image), the closer the box. Now that boxes and radar targets are sorted, we loop through the boxes, and for each box, we loop through the radar targets. If there is an overlap as described above, and if the radar target is not already associated with another box, then a box-radar association is created.

Assuming perfect bounding boxes, the algorithm can produce wrong matches in two different ways: A bounding box can be associated with a wrong radar target or a bounding box can lack the associated radar target altogether. If the radar is not properly aligned with the camera, then both types of failures are expected. However, the hardware setup should guarantee reasonable alignment amongst the sensors. Even if the camera and radar were mutually aligned, the narrow field of view of the radar could result in situations where a vehicle is only detected by the camera. These situations become more common if the sensors were not properly aligned with the road. In particular, a curve in the scene could cause problems. On the other hand, all vehicles are typically observed by the radar at some point as they pass the radar's field of view (at least if they don't change lanes), but too short an observation period could decrease the quality of the output values.

The algorithm does not attempt to detect or ignore false bounding boxes. That is, if the given object detections include vehicles that are not traveling on the adjacent lane and thus not of interest, they are still matched with radar detections and included in the output.

Likewise, the algorithm does not attempt to fix errors in the radar data. In particular, the radar target identifiers are used without further processing. As a result, the number of unique target identifiers in the output may exceed the number of actual vehicles, because the radar data includes false positives ("ghost targets"), and in some cases, a single vehicle is split into multiple radar targets. It should also be mentioned that the target identifiers in the raw radar data wrap around after reaching the value 255. The statistics below are gathered after unwrapping the identifiers.

Based on initial testing, it seems that false object detections and wrong radar target identifiers are the dominating failure modes. As a result, the number of unique target identifiers in the output is larger than the number of vehicles manually identified from the video. For one video, 93 vehicles were manually identified, whereas the processing yielded 130 different vehicles. For another video, the numbers were 77 and 106, respectively.

As an additional feature, the program can also detect situations where a vehicle changes lanes (i.e., "moves over"). The lane change detection requires successful matches between bounding boxes and radar. Thus, only lane changes that occur relatively close to the sensors can be detected. The algorithm for detecting lane changes works as follows.

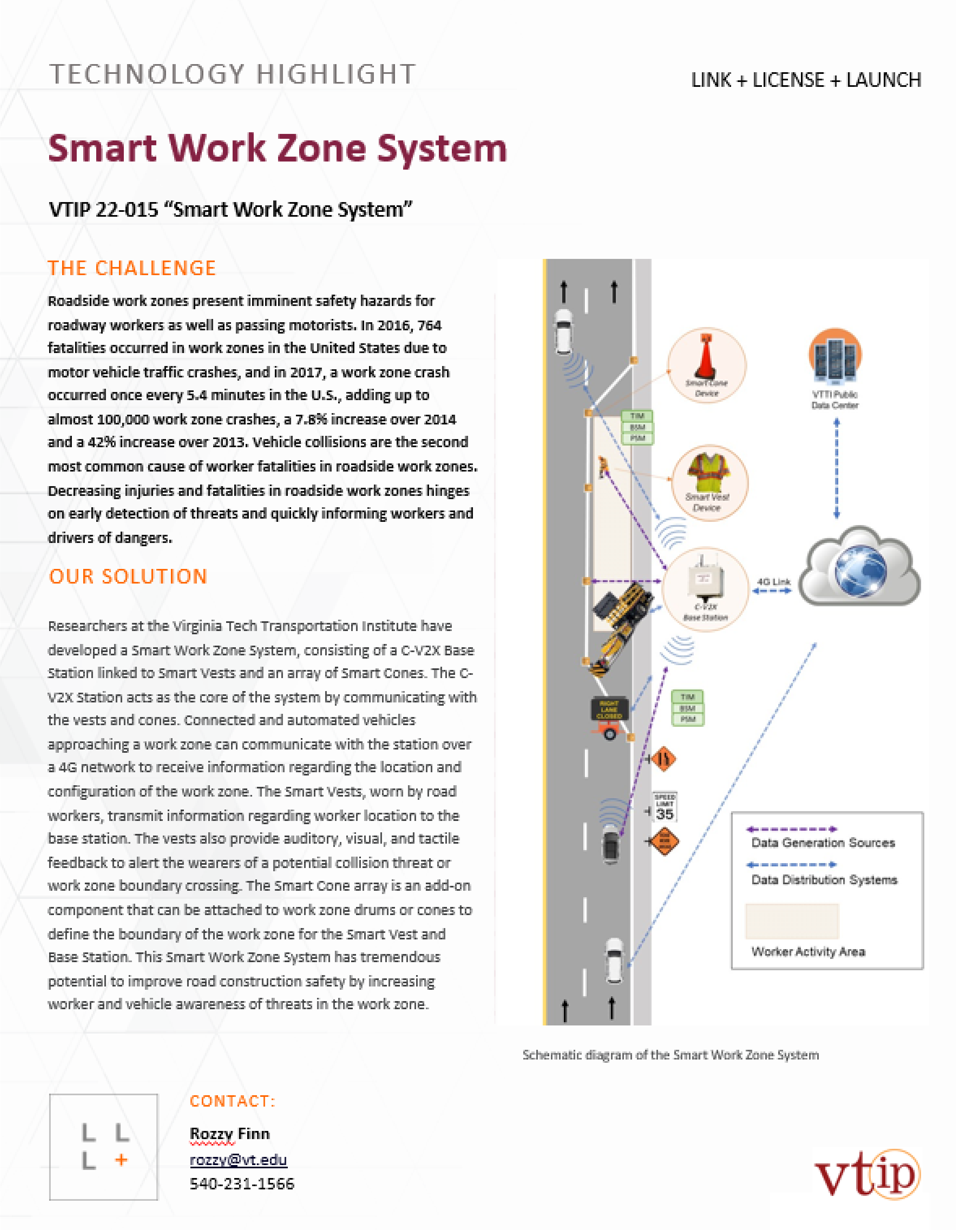
The basic idea of lane change detection is simple: Whenever a radar target that is first associated with a bounding box continues to exist without a box association, there is a lane change. The reason is that the radar has a much narrower field of view than the camera, so the only way a bounding box can disappear is because the vehicle moves to the area from where the boxes are not detected. This means changing lanes from the closest lane to another lane. A few tuning parameters need to be set for improved lane change detection. First, a bounding box timeout value specifies how long a radar target can exist without a box association before a lane change is triggered. The default is 0.1 seconds. Second, to reduce false lane change detections, a sufficient number of boxless radar observations are needed for each target. By default, eight observations are needed. Lastly, it has been observed that quite often the bounding box is missing when the vehicle is very close to sensors, even though the vehicle stays in the closest lane. Thus, to reduce false lane change detections, a minimum distance (measured by the longitudinal radar target position) is required for the lane change detection algorithm. The default is 12 meters.

For the same test videos as above, the algorithm detected 9 and 2 lane changes, whereas the respective numbers for manually identified lane changes were 17 and 13. However, it is believed that many of the manually identified lane changes were completed before the vehicle entered the zone where bounding boxes are detected. Those lane changes cannot be detected with the algorithm using the current measurement data. In addition, lane change detection seems to be more sensitive to the errors in the radar data than the box-radar association.

Appendix D: Northern Virginia VDOT Demonstration

Figure 21. Northern Virginia VDOT Demonstration additional images.

Appendix E: Smart Work Zone VTIP Technology Highlight



TECHNOLOGY HIGHLIGHT

LINK + LICENSE + LAUNCH

Smart Work Zone System

VTIP 22-015 “Smart Work Zone System”

THE CHALLENGE

Roadside work zones present imminent safety hazards for roadway workers as well as passing motorists. In 2016, 764 fatalities occurred in work zones in the United States due to motor vehicle traffic crashes, and in 2017, a work zone crash occurred once every 5.4 minutes in the U.S., adding up to almost 100,000 work zone crashes, a 7.8% increase over 2014 and a 42% increase over 2013. Vehicle collisions are the second most common cause of worker fatalities in roadside work zones. Decreasing injuries and fatalities in roadside work zones hinges on early detection of threats and quickly informing workers and drivers of dangers.

OUR SOLUTION

Researchers at the Virginia Tech Transportation Institute have developed a Smart Work Zone System, consisting of a C-V2X Base Station linked to Smart Vests and an array of Smart Cones. The C-V2X Station acts as the core of the system by communicating with the vests and cones. Connected and automated vehicles approaching a work zone can communicate with the station over a 4G network to receive information regarding the location and configuration of the work zone. The Smart Vests, worn by road workers, transmit information regarding worker location to the base station. The vests also provide auditory, visual, and tactile feedback to alert the wearers of a potential collision threat or work zone boundary crossing. The Smart Cone array is an add-on component that can be attached to work zone drums or cones to define the boundary of the work zone for the Smart Vest and Base Station. This Smart Work Zone System has tremendous potential to improve road construction safety by increasing worker and vehicle awareness of threats in the work zone.

Schematic diagram of the Smart Work Zone System

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