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State of the Art of Roadway Sensors Phase 2

ENTERPRISE TRANSPORTATION POOLED FUND STUDY TPF-5(490)

FINAL REPORT

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16. Abstract

Many vendors offer roadway sensors either embedded in pavements, non-intrusively, or attached to infrastructure. These sensors gather data and/or communicate with vehicles to aid roadway operations. A Phase 1 effort sought to understand existing and innovative types of commercially available intrusive and non-intrusive roadway sensors with an analysis of the potential applications, relevance, and drawbacks of each type. Innovative sensors of interest were examined in greater detail, such as the ability of pavement to hold up structurally, operations and maintenance considerations, and placement of the sensors.

In this Phase 2 effort, the five use cases (start/end location and time of work zone lane closure, worker presence, work zone intrusion detection, detecting threats to fiber, precipitation and runoff rate sensors) from the Phase 1 effort were used as a basis to further prioritize and select a sensor to identify a possible evaluation approach that one or more agencies may test in a future test bed environment. Specifically, a wearable sensor to detect worker presence in a work zone was selected as the sensor of greatest interest. Documentation developed as part of this effort and contained in this report includes a high-level system engineering approach that defined the needs addressed, operational concepts, and preliminary requirements, with a goal of having a scientific-based description of the use of the select roadway sensors that can be presented internally by member agencies within their organization for detecting worker presence. Additionally, this effort developed recommendations for common attributes of deployment (e.g., placement, security, communications) such that the individual deployments all contribute to a universal virtual test bed to facilitate evaluation.

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The cover page image is provided courtesy of ArtTower from Pixabay.

Project Champion

Marlon Spinks from the Michigan Department of Transportation was the ENTERPRISE Project Champion for this effort. The Project Champion served as the overall lead for the project.

ENTERPRISE Members

The ENTERPRISE Board consists of a representative from each of the following member entities.

- Illinois Department of Transportation
- Iowa Department of Transportation
- Kansas Department of Transportation
- Michigan Department of Transportation
- Minnesota Department of Transportation
- Ontario Ministry of Transportation
- Texas Department of Transportation
- Wisconsin Department of Transportation

Project Input

ENTERPRISE would like to thank the State Departments of Transportation that provided input to the project through an online survey.

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Executive Summary

This project built on the work of a Phase 1 effort[1] that identified over 100 innovative sensors through a literature review, web search for industry products, and a survey of Department of Transportation (DOT) practitioners. In that effort, ENTERPRISE member feedback resulted in the development of five use cases (start/end location and time of work zone lane closure, worker presence, work zone intrusion detection, detecting threats to fiber, precipitation and runoff rate sensors) on prioritized data elements that were provided by select sensors of interest. Each use case documented the data collected, deployment and operational considerations, applications, and identified sensor vendors.

In this Phase 2 effort, the five use cases from the Phase 1 effort were used as a basis to further prioritize and select a sensor to identify possible evaluation approaches that one or more agencies may test in a future test bed environment. Specifically, a wearable sensor to detect worker presence in a work zone to increase worker safety and generate work zone event data was selected as the sensor of greatest interest. Documentation developed as part of this effort and contained in this report includes a high-level system engineering approach that defines the needs addressed, operational concepts, and preliminary requirements. The goal is to have a scientific-based description of the use of select roadway sensors for member agencies to present within their organization. Additionally, this effort developed recommendations for common attributes of deployment (e.g., placement, security, communications) such that the individual deployments all contribute to a universal virtual test bed to facilitate evaluation.

[1] Available at: https://enterprise.prog.org/download/roadway-sensors-phase-1-final-report-project-summary/

Chapter 1: Introduction

This project developed a high-level system engineering approach and evaluation plan for a wearable sensor to detect worker presence in a work zone to increase worker safety and generate work zone event data.

Many vendors offer roadway sensors either embedded in pavements, non-intrusively, or attached to infrastructure. These sensors gather data and/or communicate with vehicles to aid roadway operations. In a Phase 1 effort[2] the ENTERPRISE Pooled Fund Study was interested in understanding existing and innovative types of commercially available intrusive and non-intrusive roadway sensors with an analysis of the potential applications, relevance, and drawbacks of each type. This *State of the Art Roadway Sensors Phase 2* effort built on a Phase 1 effort that identified many innovative sensors, by developing documentation to support the procurement and testing of a sensor of greatest interest to ENTERPRISE members: a wearable sensor to detect worker presence in a work zone to increase worker safety and generate work zone event data.

1.1 Project Background and Summary

This project built on a Phase 1 effort that identified over 100 innovative sensors through a literature review, web search for industry products, and a survey of Department of Transportation (DOT) practitioners. ENTERPRISE member feedback resulted in the development of five use cases on prioritized data elements that were provided by select sensors of interest. Each use case documented the data collected, deployment and operational considerations, applications, and identified sensor vendors for the following data types:

- Start/End Location and Time of Work Zone Lane Closure (Work Zone Event Data)
- Worker Presence (Worker Safety and Work Zone Event Data)
- Work Zone Intrusion Detection (Worker Safety Data)
- Detecting Threats to Fiber (Asset Condition Data)
- Precipitation and Runoff Rate Sensors (Road Weather Data)

This Phase 2 effort used the five use cases from the Phase 1 effort as a basis to further prioritize and select sensors to identify a possible evaluation approach that one or more agencies may test in a future test bed environment. Specifically, a wearable sensor to detect worker presence was selected as the sensor of greatest interest. Documentation developed as part of this effort and contained in this report include a high-level system engineering approach that defined the needs addressed, operational concepts, and preliminary requirements, with a goal of having a scientific-based description of the use of the select roadway sensors that can be presented internally by member agencies within their organization. Additionally, this effort developed recommendations for common attributes of deployment (e.g.,

[2] Available at: https://enterprise.prog.org/download/roadway-sensors-phase-1-final-report-project-summary/

placement, security, communications) such that the individual deployments all contribute to a universal virtual test bed to facilitate evaluation. See Figure 1-1.

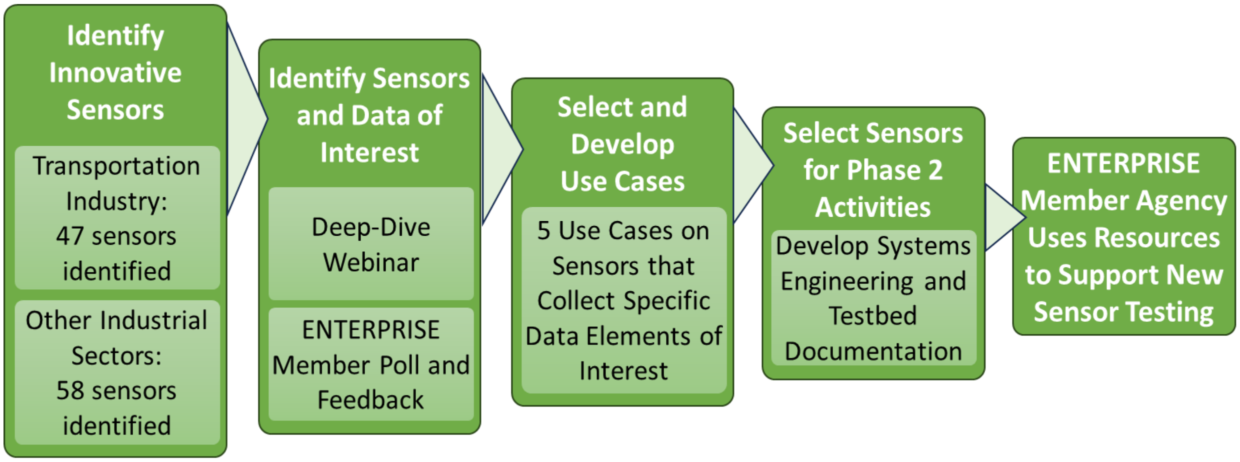

Figure 1-1 Process to Identify, Select, and Develop Phase 1 Use Cases to Select Sensors for Phase 2 Systems Engineering and Testbed Documentation

1.2 Report Organization

This report includes the following sections:

- Chapter 2: Project Approach – Describes the approach used to select the wearable sensor to detect worker presence on which to focus this effort, a description of existing deployments of this sensor, and the approach for developing documentation in this effort.
- Chapter 3: High-Level Concept of Requirements and Requirements – Includes a high-level systems engineering approach for a wearable sensor to detect worker presence that defines:
  - Needs to be addressed, including agency needs, worker needs, and traveler needs.
  - Operational concepts for several use cases.
  - Preliminary model system requirements, some of which are optional based on the use case being addressed.
- Chapter 4: Model Evaluation Approach – Includes recommendations for common attributes of deployment (e.g., placement, security, communications) so that individual deployments contribute to a universal virtual test bed to facilitate evaluation.
- Chapter 5: Project Summary and Implementation – Presents a summary of key project findings and how to use these to support implementation.
- Appendix A: Worker Presence Use Case – Presents the Use Case developed in Phase 1 for the wearable sensor that informed development of the documentation for this effort.

Chapter 2: Project Approach

This project was structured to broadly identify a wide range of innovative sensors both within and outside of the transportation industry. Specifically, a primary goal of this effort was to help agencies better understand what sensors are commercially available and may have practical applications to support transportation operations and maintenance but are not widely used by many agencies.

This section describes the overall approach taken to first identify roadway sensors, and then narrow the focus to specific use cases of greatest relevance and interest to agency practitioners.

2.1 Sensor Selection

This project commenced with a further examination of the five sensors (e.g., start/end location and time of work zone or lane closure) that were described in separate use cases in the Phase 1 effort. Appendix A presents the use case that was developed in Phase 1 of this effort for the wearable sensor, while the other four use cases that helped to guide selection of sensors to advance in this effort are found in the Phase 1 report.

A presentation was developed and shared with ENTERPRISE members with recommendations for selecting one or more sensors to examine further in this Phase 2 effort and develop documentation for high-level systems engineering and evaluation. The five sensor types and associated considerations for each are described below.

1. **Start/End Location and Time of Work Zone or Lane Closure.** A range of sensor types are available to collect this data. Some products like smart arrow boards are more widely used, which makes these types of sensors likely to be of less interest given greater agency familiarity with procuring, deploying, and operating this sensor. Additionally, other products that collect this data type have been tested at multiple agencies, which could offer preliminary documentation for a similar testing approach or findings for comparison, if this sensor type is selected.

2. **Worker Presence.** There is currently a single wearable product available that collects this data. This product is being tested by the Michigan Department of Transportation, in cooperation with the vendor, and by a construction contractor in Minnesota, with the Minnesota Department of Transportation observing the test. (Both of these agencies are ENTERPRISE members and may benefit from documentation developed through this effort.) Finally, the available vendor product was initially developed by the Virginia Tech Transportation Institute (VTTI), which has published reports that may offer preliminary documentation for a similar evaluation approach or findings for comparison.

3. **Work Zone Intrusion Detection.** There are two products available in United States for this sensor type. However, the tradeoffs and effectiveness of these products have been documented in several studies, which make these sensors of less interest.

4. **Detecting Threats to Fiber.** This sensor type has been tested in several states who may offer preliminary documentation or findings for comparison for this effort if selected to be of interest. However, no ENTERPRISE member agencies indicated interest in pursuing this sensor type in the near future.

5. **Precipitation and Runoff Rate Sensors.** This sensor type was acknowledged to not be an "innovative" sensor as much as an update to previous offerings that are likely familiar to agencies. As such, this sensor type has a more straightforward or "obvious" procurement or evaluation approach that was determined to not require additional ENTERPRISE documentation through this effort.

These discussions and recommendations between ENTERPRISE members resulted in the following consensus for proceeding with developing documentation in this project:

- Worker Presence – **focus Phase 2 efforts on this sensor type**.
- Start/End Location and Time of Work Zone or Lane Closure – of interest, but not a great need.
- Work Zone Intrusion Detection – not of interest at this time.
- Detecting Threats to Fiber– not of interest at this time.
- Precipitation and Runoff Rate Sensors– not of interest at this time.

2.2 Wearable Sensor Deployments

To understand current agency needs for documentation as a part of this project, and inform the development of that documentation, the research team contacted two ENTERPRISE agencies that were involved with efforts using a VerMac Smart Vest as a wearable sensor for worker presence: Michigan and Minnesota, as well as the vendor, to provide input. A description of how these two states are deploying the VerMac Smart Vest prototype are presented below.

One vendor, which is testing wearable sensors in two ENTERPRISE member states, provided input to this effort. However, this document is written generally with the expectation that similar products are or will soon be available from other vendors.

Michigan. The effort in Michigan with worker presence stemmed from a legislator's request to have flashing lights on signs when workers are present in a work zone. Laws in Michigan were modified to allow digital signs for that purpose in work zones. Specifically, digital signs display work zone speed limits that are reduced due to work zone geometries and also worker presence (e.g., a 70 mph roadway may have a 60 mph speed limit for a work zone and 45 mph speed limit when workers are present). Initially, digital speed limit signs were to be manually updated, but the project staff and construction contractor were unable to keep up with that. A study conducted by Michigan State University showed a 5-7 mph reduction in vehicle speeds when digital speed limit signs with a flashing light indicated that workers were present.[3]

Michigan leveraged a commercial motor vehicle (CMV) grant to test two VerMac Smart Vests in a work zone on I-96, as well as 12 additional modified sensors containing the same technology. This concrete patch project work zone was a long-term static project without concrete barrier. The work zone was approximately 10 miles long and divided into two 5-mile segments with a digital speed limit sign at the upstream end of each segment and spaced every ½- to 1-mile through the work zone. Work zone "markers" were placed at the work zone start and end points. Work activity sometimes moved quickly, and the focus of testing was on accurately changing digital speed limit sign displays based on when workers were present in a respective segment.

The presence of one worker (or multiple workers) wearing a Smart Vest prototype sensor was used to automatically change the speed limit posted on the digital speed limit sign in the segment that the worker was present. That is, Michigan divided the work zone into two segments with a digital speed limit sign at the upstream end of each segment, such that the digital speed limit sign only displayed a reduced speed when a worker was present in that specific segment. The Smart Vest provided updated location data once per minute. Additionally, the worker presence information was broadcast to CMVs via a cellular connection and by VerMac to Waze (not necessarily using the work zone data exchange (WZDx) specification).

Michigan identified a variety of challenges that need to be addressed in future deployments:

- Reducing speed limits when multiple crews are present in non-consecutive work zone segments (i.e., is it better to have a reduced speed in the middle segment(s) where workers are not present or to lower the posted speed limit only where workers are present and have the higher speed limit in the middle segment(s) where workers are not present?).
- Digital speed limit display when work crew is immediately upstream of a digital work zone speed limit sign (e.g., a work crew in front of the digital speed limit sign will not trigger a reduced speed on the digital speed limit sign that the workers are adjacent to).
- Appropriate spacing of digital speed limit signs (i.e., the length of work zone segments; the I-96 project was about 10 miles long and was divided into two 5-mile segments with digital speed limit signs spaced approximately every ½ mile).
- Equipping an entire work crew with Smart Vests and whether that impacts system functionality (i.e., not all workers had a Smart Vest, but the idea is that everyone would in the future).
- Providing worker alerts via the Smart Vest (i.e., the Smart Vests were only broadcasting data, not receiving data to support worker alerts).

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[3] Work Zone Speed Limits and Motorist Compliance. Oct 2022. Accessed 15 Apr 2024: https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2022/10/wz_speed_limits_and_motorist_compliance_w_cvr.pdf.

Michigan plans to deploy up to 50 more Smart Vests in work zones in the 2024 construction season. In addition to adjusting digital speed limit sign displays based on worker presence, Michigan is considering the use of worker presence data to determine wage income driven repayment, understand when employees are on a project, better understand what equipment is being used, and for internal documentation purposes.

Minnesota. A contractor in Minnesota initiated a test of the wearable vest for worker presence, which Minnesota DOT is observing. An initial test is being conducted with four wearable vest sensors being used in an active work zone, which are supporting the testing of different types of applications in a virtual environment. There were some initial challenges with a sensor, but a second generation sensor is being deployed soon. Data from the sensors are being provided via a WZDx feed to Waze but not to the Minnesota DOT. Finally, the work zone type where this sensor is being deployed are those without concrete barrier positive protection.

Virginia. The wearable sensor for worker presence described in this report only recently became commercially available through a vendor. It was developed and tested in Virginia by the Virginia Tech Transportation Institute (VTTI). In that demonstration, it was deployed in conjunction with smart cones used to define a “safe area” for the work zone activities and a base station that would collect and process location data from the vest and cones, which was then used for broadcasting alerts to worker vests, when warranted, and information via both cellular communications to agency systems and also vehicle to everything (V2X) communications to passing connected vehicles to support safety applications alerts and warnings. VTTI designed initial smart vest hardware and electronics to be battery powered and have low power consumption for up to 20 hours of field operation. Additionally, alerts were provided to workers via visual, auditory, and tactile means. For instance, knowing the specific location of workers was used to provide alerts to them when they leave the “safe area” designated by other smart work zone devices. The foundational smart vest research efforts conducted by VTTI are documented in a report: https://rosap.ntl.bts.gov/view/dot/67373. Note that VTTI is currently conducing research and development on a Smart Helmet that could be worn by workers and be serve a similar function as the Smart Vest.

2.3 Development of Sensor Documentation

After identifying the key sensor of interest, the remaining project activities centered around the development of systems engineering and evaluation documentation specific to that sensor. The goal of these documents is to have a scientific-based description of how the selected worker presence sensor could be used that can be presented internally by member agencies to identify possible test bed approaches that can be applied for evaluating the sensor in a future test bed environment.

Specifically, a high-level systems engineering approach was developed that defines needs to be addressed, operational concepts, and preliminary requirements for a worker presence sensor. This is presented in Chapter 3. Additionally, Chapter 4 describes a model evaluation approach that can help separate agency deployments contribute to a universal virtual test bed.

Chapter 3: High-Level Concept and Requirements

A variety of methods have been developed and demonstrated to understand where workers are present in a work zone. This chapter presents a high-level systems engineering approach, specifically for a wearable sensor to detect worker presence, that defines:

- Needs to be addressed, specifically agency and contractor needs which also incorporate worker needs.
- Operational concepts from a worker perspective and from an agency system perspective.
- Model system requirements.

It should be noted that the wearable sensor to detect worker presence described below is generally part of a larger intelligent transportation system (ITS) service, such that additional components (e.g., the ability for staff to enter geofence information about the work zone, connectivity with other ITS devices) are required in order for the sensor to provide value to the agency or impact driver behavior.

3.1 Needs to be Addressed

A high-level understanding of worker presence is important to agencies for work zone worker safety and contracting purposes. Many jurisdictions have laws relating to speeds or fines in work zones that specifically relate to whether or not workers are present in order to encourage safer driving behaviors. Similarly, contractors may also benefit from providing worker presence information to devices in the work zone or traveler information systems that automatically generate messages or make adjustments (e.g., lower work zone speed limits) when workers are present.

The list below describes high-level needs from an agency or contractor perspective for a wearable sensor to detect worker presence. Agencies may desire this sensor for worker presence information about maintenance staff in the field for short-duration activities or to monitor contractor locations for various use cases. Similarly, contractors may desire this sensor to help improve worker safety or to help mitigate other mobility or safety impacts caused by the work zone, for instance. Given the similarities, the needs below are written for both agencies and contractors that may wish to procure and operate a wearable sensor to detect worker presence. Of course, additional needs and considerations may factor into the selection of a wearable sensor, such as the level of effort to conduct routine maintenance or integrate sensor data with agency systems, the cost of the sensor, and the expected lifecycle of the sensor. Note that the needs below are written for a work zone application of this sensor.

Need #1. Worker Location: Agencies/contractors need to know when workers are present in specific work activity locations (e.g., particularly instances when the worker is vulnerable by being in close proximity and/or unprotected from traffic flows), regardless of harsh, inclement, or remote conditions (e.g., related to working conditions and activities, weather or precipitation, or geography).

Need #2. Communications: Agencies/contractors need to reliably receive worker presence information via readily available communications.

Need #3. Ease of Use: Agencies/contractors need workers to maintain focus on work duties to maintain a safe environment and not incur additional duties during their work shift.

Need #4. Flexibility: Agencies/contractors need different information for different uses and policies (e.g., in consideration of user privacy or archiving information).

Need #5. Security: Agencies/contractors need to know any worker presence information is secured and can be trusted.

Need #6. Durability: Agencies/contractors need the wearable sensor to be durable for harsh work conditions and climate (e.g., related to work activities and weather or precipitation), such that a sensor continues to maintain sufficient charge through a work shift after at least one year of daily use and recharge.

3.2 Operational Concepts

The generation and use of worker presence data with a wearable sensor is summarized in two operational concepts described below from the worker perspective for generating worker presence data and the agency system perspective for using worker presence data.

3.2.1 Worker Perspective for Generating Worker Presence Data

This operational concept describes the worker experience with wearing and interacting with the wearable sensor.

3.2.1.1 **Wearing the sensor.** To prepare for work in an active work zone at the beginning of a work shift, the worker puts on safety attire, including a hard hat and safety vest. As a part of this preparation, the worker also obtains a wearable worker presence sensor, which may be charging (e.g., plugged into a charging station or electrical outlet), and affixes it to their garments (e.g., on or inside a pocket on the vest or hard hat) in a way that is does not distract or interfere with worker activities.

3.2.1.2 **Sensor operations.** The wearable worker presence sensor is automatically activated (i.e., does not require the worker to flip a switch to an "on" position) to begin communicating worker presence data and requires no action by the worker during the full work shift, regardless of the worker's location within (or beyond) the work zone area.

3.2.1.3 **Sensor impacts on workers.** Workers wear the worker presence sensor while performing work activities and are not bothered by it, as it is securely attached, not bulky or heavy, and does not distract or interfere with their job duties.

3.2.1.4 **Solution impact on workers.** Workers may feel safer with the knowledge that the traveling public is better informed about their location via traveler information sources or digital speed limit devices that reduce the posted speed limit in the specific area of the work zone where the workers are active. Workers may notice that passing vehicles are driving at slower speeds in work zones where wearable worker presence sensors are being used. Note that the way in which the sensor is used, as well as the presence of other solutions like positive protection barrier, may affect the degree to which the worker presence sensor solution has an impact on worker perceptions of safety. There is a risk that workers may have privacy concerns about the sensor tracking their movements.

3.2.1.5 **End of shift and charging.** The worker ends the work shift and removes the wearable worker presence sensor from the garments. Depending on the specific nature of the product, the wearable worker presence sensor may need to be charged at the end of every shift or may have an indicator that either displays the remaining battery charge or that the battery is low and needs to be charged. As needed, the worker will charge the worker presence sensor according to product specifications. Note that if the sensor is designed such that it continues to broadcast data while charging, the worker may need to either switch the sensor "off" when charging, ensure the sensor is charging outside of the geofenced area of the work zone, or take some other action so that data from the sensor is not incorrectly indicating worker presence while it is charging.

3.2.1.6 **Maintenance and replacement.** The worker may infrequently notice that the wearable worker presence sensor is not active or charging. Depending on the vendor manual instructions, warranty, and age of the wearable sensor, the worker may be able to change a battery or other part to restore sensor functionality. Alternatively, spare units may be available to swap out with uncharged or non-functioning units. Otherwise, a non-functioning sensor may be returned to the vendor for repair or, at the end of its lifecycle, for replacement.

3.2.2 Agency System Perspective for Using Worker Presence Information

This operational concept describes how agency systems are involved with supporting the wearable sensors and use the data that is collected by wearable sensors.

3.2.2.1 **Software application to create geofenced areas.** Before worker presence sensors are used, construction contractors or agency staff may access a software application through a web portal on a desktop application or mobile device to make one or more geofenced areas to describe a work zone (e.g., a 10-mile work zone for a freeway pavement rehabilitation project may be divided into six geofenced areas to understand the specific locations of workers within a work zone, whereas a 1/2-mile long work zone for a culvert replacement project may comprise a single geofenced area). This software application connects with agency systems and may be integrated with work zone ITS devices in the field (e.g., digital speed limit signs, variable speed limit (VSL) system, or portable dynamic message sign (PDMS)) or back office agency systems (e.g., traveler information system, work zone data archive). Additionally, capabilities may be needed to remotely and/or automatically deactivate use of the worker presence sensor for circumstances when the worker leaves the work zone or is no longer conducting work activities (e.g., is driving through the work zone or leaves the work zone for lunch); this remote capability is preferred at agency systems rather than be a responsibility of the worker.

3.2.2.2 **Ingesting data in near real-time.** Agency systems ingest worker presence data as it becomes available (e.g., via a third-party construction contractor or vendor web portal that is hosted on a remote server via wired communications, via local communications within the work zone, etc.). Worker presence data is provided in an agency-specified data format, likely the Connected Work Zone standard (or the Work Zone Data Exchange specification version being used by the agency) to facilitate initial activities for integration. Worker presence data becomes available in near real time (e.g., around 1 minute of being generated by the worker presence sensor; note that higher reporting frequency may be possible but would increase the power consumed by the sensor). The worker presence data received by agency systems may already be processed, filtered (e.g., for privacy purposes), aggregated from multiple sensors, or formatted to a data specification.

3.2.2.3 **Field device agency system real-time use of data.** Some agency systems are work zone ITS devices located in the field and receive worker presence data (e.g., via local, short-range communications or via cellular communications). Worker presence data (e.g., workers present: yes or no) may be used to automatically adjust the device display. For instance, when worker presence data indicates that workers are present, work zone digital speed limit signs (or VSL signs) may automatically change to a pre-configured reduced speed or PDMS may automatically display a pre-configured message like “CAUTION! WORKERS PRESENT”. Work zones with more than one geofenced area may have work zone ITS field devices at the upstream edge of these geofenced areas such that the reduced speed limit or PDMS message is only displayed for the geofenced area where workers are present.

3.2.2.4 **Back office agency system real-time use of data.** Some agency systems are back office systems, such as advanced traffic management systems (ATMS), road condition reporting systems (RCRS), or traveler information systems. One or more of these back office agency systems may receive worker presence data at a pre-configured frequency (e.g., in some cases, one back office agency system may ingest and process the worker presence data and share it with other back office agency systems; alternatively, multiple back office agency systems could ingest and process the worker presence data separately). Back office agency systems may use worker presence data in a variety of ways, including:

- *Creation of a new work zone event* when workers are present in an area with no existing event.
- *Update to an existing work zone event* to change a planned work zone event to a verified, active work zone event when workers are present.

- *Update (or closure) of an existing work zone event* to a closed, planned, or inactive work zone event when workers are no longer present.

In the long term, while automatic creation and updates to work zone events is desired, it is likely that manual validation will still be needed from the field even with worker presence data. For instance, worker presence data provided from either a sensor that is "always on" (e.g., including when charging) or one with an on/off switch both have challenges for automatic event creation and updates.

A variety of users may access back office agency systems in real-time to use worker presence data, including:

- *Transportation management center (TMC) staff* to support operations and messaging (e.g., via dynamic message signs (DMS), to communicate with field staff like incident response team, etc.).
- *Public information officers* to support messaging to the traveling public (e.g., via social media or traveler information website).
- *The traveling public and third-party traveler information providers* to inform drivers and support navigation around or through active work zones (e.g., via connected vehicle in-vehicle or mobile device displays from providers like Stellantis, DriveWyze, or Waze). This information may be consumed directly from agency traveler information websites or mobile applications, or via public data feeds, such as a WZDx-compliant data feed.

3.2.2.5 **Back office agency system use of archived data.** One or more back office agency systems (or a vendor system) may archive worker presence data for it to be available on demand. This data may be used by a variety of users for a number of process improvement purposes. Archived worker presence data will likely be of greater value when combined with agency datasets that provide additional detail about the work zone, such as whether positive protection barrier was present and the posted speed limit and/or digital speed limit display. Possible users of the archived data include:

- *Law enforcement.* In some instances, the posted speed limit in a work zone may depend on worker presence (e.g., static signing that posts a reduced speed limit "when workers present", digital speed limit signs, or a VSL system programmed to display lower speed limits when workers are present). In these instances, law enforcement issue citations for a reduced speed limit when workers are present. It may be possible for law enforcement officers to use worker presence data to verify contested citations that a work zone was active when the citation was issued.
- *Contract managers.* Agency staff may use archived worker presence data for a number of construction and maintenance contract monitoring purposes, such as agency documentation, payment, and to confirm work was performed during allowable work hours.

- *Evaluators and researchers.* Agency staff and others may use archived worker presence data to inform work zone exposure data to enhance analyses related to work zone safety and mobility.

3.3 Model System Requirements

The model system requirements below are intended to serve the operational concepts described above. The requirements are grouped within one of three categories: data generation, communications, and use of the sensor. Each requirement traces back to a need that is defined in section 3.1, which is indicated in parenthesis.

3.3.1 Data Generation Requirements

Requirement #1. **Location Data:** A wearable sensor shall reliably generate accurate location data about its position (e.g., lat/long) to within +/- TBD feet. Note that precise location for worker presence data may not be needed depending on how the data is intended to be used, the geofenced area created, and other factors; as such, the location accuracy should be based on specific agency needs for the intended use, and relative availability and costs of worker presence sensors with varying location accuracies (Need #1)

Requirement #2. **Unique ID:** A wearable sensor shall generate a unique sensor ID with each data entry (e.g., for the device to support asset management or other specific use cases). (Need #1)

Requirement #3. **Near Real-Time Data Generation:** A wearable sensor shall generate data in near real-time at TBD second intervals. Note that one-minute intervals are common for connected work zone devices; higher frequency data generation consumes additional power from the sensor than lower frequency data generation. (Need #1)

Requirement #4. **Data Format:** A wearable sensor shall generate data in the latest version of the Connected Work Zone data standard format (or the version of this standard or the Work Zone Data Exchange specification being used by the procuring agency or contractor) for users (e.g., either agency or contractor staff or systems) to easily access and ingest. Note: the data from a wearable sensor may first be processed by vendor software systems and provided to agency or contractor staff or systems via a third-party server. (Need #1)

Requirement #5. **Privacy:** A wearable sensor shall be configurable to allow for privacy of specific users, as deemed appropriate by the managing entity. (Need #4)

3.3.2 Communications Requirements

Requirement #6. **Wireless Communications:** A wearable sensor shall be capable of sending data over the air via a reliable communications mechanism (e.g., local communications within the work zone, or network communications). (Need #2)

Requirement #7. **Communications Distance:** A wearable sensor shall be capable of consistently sending data to agency or contractor systems regardless of the location of the worker within the work zone (e.g., the sensor may be part of a system that utilizes local communications from anywhere at the work zone, or network communications). (Need #2)

Requirement #8. **Near Real-Time Data Communications:** A wearable sensor shall communicate data in as it is generated at TBD second intervals (i.e., see data generation requirement for near real-time data). Note that a higher reporting frequency will consume additional power and communications. Repetitive data is not needed (e.g., if the location remains unchanged within +/- TBD feet), which may allow ongoing worker presence to be confirmed in near real-time while reducing consumed power and data communications. (Need #2)

Requirement #9. **Security:** A wearable sensor shall provide worker presence data in a way that is secured and can be trusted. (Need #5)

3.3.3 Use of the Sensor Requirements

Requirement #10. **Ease of Use:** A wearable sensor shall be easy to use such that field staff are able to conduct their primary work tasks without interruption and minimal inconvenience. Specifically, the sensor should be compact, lightweight, wireless, able to be placed in an area that does not hinder worker movement or activity. (Need #3)

Requirement #11. **Sensor Placement:** A wearable sensor shall be attached to worker clothing or protective wear in a way that is secured (i.e., not be lost). (Need #3)

Requirement #12. **Worker Access:** A wearable sensor shall be easy for field staff to access and charge with minimal additional effort. (Need #3)

Requirement #13. **Power:** A wearable sensor shall be capable of remaining powered on through extended work shifts (i.e., over 12 hours) without being removed for charging. (Need #3)

Requirement #14. **Use in Harsh Conditions:** A wearable sensor shall be sufficiently ruggedized for heavy wear and tear given the working conditions, as well as outdoor use, including cold and warm temperatures and wet conditions. (Need #1, Need #6)

Requirement #15. Maintenance Lifecycle: A wearable sensor shall be reliable over the vendor-specified lifecycle, with infrequent outages or maintenance needs (e.g., change a battery or other component) occurring no more than TBD times per year. (Need #3, Need #6)

Requirement #16. Product Guide: A wearable sensor shall include a "product guide" that includes instructions that can be used to derive a regular maintenance schedule to ensure ongoing wearable sensor functionality (e.g., cleaning, battery replacement, calibration). This guide may also include other relevant information like lifecycle information, warranty information, and how to configure the sensor to protect privacy. (Need #3, Need #4)

Chapter 4: Model Evaluation Approach

This chapter presents a model evaluation approach for agencies to follow as they deploy and operate a wearable sensor. A variety of uses were presented in the Operational Concepts that may warrant additional questions beyond those presented in the sections below. However, to comprehensively validate the functionality and usefulness of a wearable sensor, it would be valuable for one or more agencies to deploy wearable sensors in various scenarios and consistently evaluate their performance. These scenarios may vary based on:

- Duration (e.g., multiple months, multiple hours);
- Distance (e.g., small area, long distance with multiple geofenced segments);
- Roadway type (e.g., Interstate, undivided highway);
- Cellular coverage (e.g., including a more rural area with limited cellular coverage);
- Adjacent work zone devices to validate worker presence in the area (e.g., CCTV, smart arrow boards, maintenance vehicles with location data, smart cones);
- Use of worker presence data (e.g., in the field on digital speed limit signs or portable dynamic message signs, traveler information);
- Worker protection (e.g., barrier-separated work zones, work zones with no barrier).

Collectively, use of wearable sensors in different types of work zones over time will help to create a more comprehensive picture to identify uses that improve worker safety and reduce vehicle speeds, and generally improve work zone safety and mobility. However, determining the effects of wearable sensors in work zones will be extremely challenging in the near term given variables that make each work zone unique (e.g., roadway geometric constraints, the type and time of work activities performed). Additionally, it may take time for drivers to trust the displays and traveler information regarding worker presence that are used to encourage reduced travel speeds or activate lower speed limits in work zones, thereby improving safety. As such, this model evaluation approach largely focuses on functional performance of the wearable sensor. As wearable sensors are more widely deployed by one or more agencies, examination of potential safety impacts to workers and the traveling public may be possible.

A combination of qualitative and quantitative data will be needed to evaluate the wearable sensor, including the following, which are described in more detail below:

- Agency Office / Transportation Management Staff Survey (Qualitative)
- Worker Survey (Qualitative)
- Worker Presence Data (Quantitative)
- Additional Work Zone Data (Quantitative)

While the qualitative data sources may sufficiently address all requirements at a higher level, examination of quantitative data can help confirm observations, validate the evaluation, and potentially identify irregularities in the reported worker presence data.

4.1 Agency Office / Transportation Management Staff Survey

The following questions would be appropriate for agency staff who routinely access and use the worker presence data received from wearable sensors in order to support work zone monitoring and operations by creating and updating work zone events. Ideally, additional work zone intelligent transportation systems (ITS) would be available to validate the worker presence data, however validating worker presence by directly communicating with field staff about worker location could also work. While closed-circuit television (CCTV) cameras in the work zone would be preferred for validating specific worker locations, other devices like connected arrow boards or maintenance vehicles equipped with location sensors may adequately validate worker locations at maintenance work zones that are shorter in duration and length.

Please answer the following questions as you observed the worker presence data reported from the wearable sensor (i.e., these are not intended to be comprehensive).

1. Did the wearable sensor report workers being present when and where there were none? (Requirements #1, #6, #7)
    - If yes, did you determine why this occurred and modify practices in any way? (e.g., due to wireless communications issues or the location of workers within the work zone) Please explain.
    - How often did this occur?
2. Did the wearable sensor fail to report workers being present in a location when and where workers with wearable sensors were present? (Requirements #1, #6, #7)
    - If yes, did you determine why this occurred and modify practices in any way? (e.g., due to wireless communications issues or the location of workers within the work zone) Please explain.
    - How often did this occur?
3. Did the wearable sensor reliably update worker location as the wearer moved anywhere within the work zone? (Requirements #1, #7)
4. Did the wearable sensor generate a unique sensor ID with each data entry? (Requirement #2)
5. Did the wearable sensor generate data in near real-time at TBD second intervals? (Requirement #3)
6. Did the wearable sensor generate data in the latest version of the Connected Work Zone data standard format (or the version of this standard or the Work Zone Data Exchange specification being used by the procuring agency or contractor) for easy access and ingest? (Requirement #4)
7. Was the wearable sensor configurable to allow for privacy of specific users, as deemed appropriate by the managing entity? (Requirement #5)
8. Did the wearable sensor communicate data at TBD second intervals (except repetitive data)? (Requirement #8)

9. Did the wearable sensor provide worker presence data in a way that was secured and able to be trusted? (Requirement #9)
10. Did the wearable sensor appear to remain operational when harsh conditions were present, including hot, cold, and/or wet conditions? (Requirement #14)

4.2 Worker Survey

The following questions would be appropriate for workers who routinely wore and maintained the wearable sensor in order to confirm the ease of use and functionality of the units under various conditions.

Please answer the following questions based on your experience using and maintaining the wearable sensor.

1. Was the wearable sensor easy to use (e.g., you were able to conduct your primary work tasks without interruption and minimal inconvenience)? (Requirement #10)
2. Was the wearable sensor sufficiently compact, lightweight, wireless, and able to be placed in an area that did not hinder movement or activity? (Requirement #10)
3. Did the wearable sensor sufficiently attach to clothing or protective wear in a way that it was secured (i.e., not be lost)? (Requirement #11)
4. Was the wearable sensor easy to access and charge with minimal additional effort? (Requirement #12)
5. Was the wearable sensor capable of remaining powered on through extended work shifts (i.e., over 12 hours) without being removed for charging? (Requirement #13)
6. Did the wearable sensor appear to remain operational in harsh conditions, including hot, cold, and/or wet conditions? (Requirement #14)
7. Has the wearable sensor required a battery replacement or other significant maintenance? (Requirement #15)
8. Was the wearable sensor regular maintenance schedule readily available in a product guide? (Requirement #16)
9. Was the wearable sensor routine maintenance easy to understand and perform? (Requirement #16)

4.3 Worker Presence Data

The following questions can be addressed by examining all or a subset of the worker presence data.

1. Did the wearable sensor generate a unique sensor ID with each data entry? (Requirement #2)
2. Based on the timestamp, did the wearable sensor generate data in near real-time at TBD second intervals? (Requirement #3)

3. Based on timestamp within agency systems, If available, did the wearable sensor communicate data at TBD second intervals (except repetitive data)? (Requirement #8)
4. Did the wearable sensor generate complete data in the latest version of the Connected Work Zone data standard format (or the version of this standard or the Work Zone Data Exchange specification being used by the agency)? (Requirement #4)
5. Did the wearable sensor allow for privacy of specific users, as configured? (Requirement #5)
6. *(If no additional work zone data is available)* Did the wearable sensor report and update worker location in an expected manner? (e.g., were locations and movements as expected and without erratic location changes or missing data points?) (Requirement #7)

4.4 Additional Work Zone Data

The availability of additional agency work zone data and observations will support further validation of the worker presence data generated from the wearable sensor.

1. Based on work zone event data and/or work zone device data, did the wearable sensor report workers being present when and where there were none? (Requirements #1, #6, #7)
    - If yes, did you determine why this occurred and modify practices in any way? (e.g., due to wireless communications issues or the location of workers within the work zone) Please explain.
    - How often did this occur?
2. Based on work zone event data and/or work zone device data, did the wearable sensor fail to report workers being present in a location when and where workers with wearable sensors were present? (Requirements #1, #6, #7)
    - If yes, did you determine why this occurred and modify practices in any way? (e.g., due to wireless communications issues or the location of workers within the work zone) Please explain.
    - How often did this occur?
3. Based on observations in the field or via CCTV footage or other smart devices, did worker presence sensors accurately report when workers arrived / entered or left a geofenced work area within the timeframes defined by the vendor specifications? Note: deployers should follow any vendor recommendations for setup and initial testing/validation for each work zone. (Requirements #1, #6, #7)
4. Based on observations in the field or via CCTV footage, did the wearable sensor reliably update worker location as the wearer moved anywhere within the work zone? (Requirements #1, #7)
5. If the work zone is geofenced into different zones (i.e., for digital speed limits), based on observations in the field or via CCTV footage, did the wearable sensor reliably activate the correct zones based on the specific worker location as the wearer moved between zones within the work zone? (Requirement #1)

6. Based on available weather data, did the wearable sensor appear to remain operational when harsh conditions were present, including hot, cold, and/or wet conditions? (Requirement #14)
7. Work zone characteristics should be documented or available for a more comprehensive analysis in the long term, including the presence of positive protection and how wearable sensors are used (e.g., to activate digital speed limits or VSLs). Analyses may examine travel speeds through the work zone, worker safety and near-miss incidents, and crashes. This data may be examined versus similar work zones that did not have wearable sensors to report worker presence.

Chapter 5: Project Summary and Implementation

This Phase 2 ENTERPRISE Pooled Fund Study project built on the work of a Phase 1 effort that initially identified over 100 innovative sensors of possible interest. ENTERPRISE members feedback in Phase 1 resulted in development of five use cases to document available information regarding deployment, operations, and maintenance considerations for data types of greatest interest.

In this Phase 2 effort, these five use cases were the basis to further prioritize and select a wearable presence sensor for the development of additional documentation to support deployment and evaluation. Specifically, this effort developed a high-level system engineering approach that defined the needs addressed, operational concepts, and preliminary requirements, with a goal of having a scientific-based description of the use of the select roadway sensors that can be presented internally by member agencies. Additional documentation included recommendations for a model evaluation approach to examine common attributes of deployment (e.g., placement, security, communications) such that the individual deployments consistently evaluate the performance of the wearable sensor.

5.1 Implementation

The research resulted in several resources that ENTERPRISE member agencies can use to help in considering, procuring, implementing, and evaluating the use of worker presence sensors. This includes:

- A description of existing deployments using a wearable worker presence sensor (Chapter 2).
- High-level concept of operations and system requirements with user needs to be addressed and operational concepts from both worker and agency systems perspectives (Chapter 3).
- A model evaluation approach (Chapter 4).

Transportation agencies can implement the results of this research in several ways. Recommended implementation steps could include the following actions:

1. Distribute the report to agency construction and maintenance decision makers and field staff, including construction contractors, at ENTERPRISE agencies.
2. Support the agency procurement of wearable sensors by adapting the model concept and requirements to an agency specification.
3. Support an evaluation of wearable sensors that are used in agency work zones.
4. Learn from other agency experiences documented in these research findings, consider procuring wearable sensors, and conducting a follow-up ENTERPRISE project for an evaluation.

Overall, the research conducted for this project can support ENTERPRISE member agencies’ decisions for procuring and evaluating an innovative wearable sensor to generate worker presence data and support improved, validated work zone event data for enhanced traveler information and other work zone management purposes.

References

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Virginia Tech Transportation Institute. *Smart Work Zone System.* 2022. Accessed July 2023: https://rosap.ntl.bts.gov/view/dot/67373/dot_67373_DS1.pdf.

Appendix A: Worker Presence Use Case

Category: Work Zone Event Data

Data Collected: Wearable devices are available that broadcast real-time location data from workers at a work zone to indicate worker presence. These devices can work in conjunction with other smart work zone devices that define a geo-fenced "safe area" and are capable of processing and broadcasting information to provide alerts:

- To connected vehicles approaching the work zone,
- To workers if they are leaving the safe area, and
- To workers if the area is at risk from an encroaching connected vehicle.

Alternatively, a surrogate measure for worker presence is possible by equipping maintenance vehicles with automatic vehicle location (AVL) / global positioning systems (GPS) and sensors to broadcast location and/or data about flashing or warning lights being activated. This maintenance vehicle data can be used to infer worker presence for an active work zone, potentially in conjunction connected work zone device data (as described in use case #1 above) and/or by cross-checking maintenance vehicle data with planned work zone event data.

Deployment and Operation: The Worker Presence Connected Vest, shown in Figure A-1, has only recently become commercially available through a vendor. Previously, it was developed and tested in Virginia by the Virginia Tech Transportation Institute (VTTI). In that demonstration, it was deployed in conjunction with smart cones used to define a "safe area" for the work zone activities and a base station that would collect and process location data from the vest and cones, which was then used for broadcasting alerts to worker vests, when warranted, and information via both cellular communications to agency systems and also vehicle to everything (V2X) communications to passing connected vehicles.

Figure A-1 Worker Presence Connected Vest (Source: VerMac)

In general, the deployment and operation of a smart vest was designed to be lightweight, comfortable, and easy to use. VTTI designed initial smart vest hardware and electronics to be battery powered and have low power consumption for up to 20 hours of field operation. Alerts provided to workers are designed to be visual, auditory, and tactile. Additionally, the sensor is designed to be detached from a work zone vest to facilitate cleaning.

Because only one product is currently available from a single vendor, no example documentation of specifications or contracts have been identified.

Application: The broadcast of worker location can be used on-site to increase worker safety in several ways.

- The primary purpose of broadcasting data about workers being present in an active work zone is for agency traveler information websites and applications, as well as WZDx data feeds that can be used by third-party traveler information providers (Michigan and Minnesota) and V2X safety applications alerts and warnings (Virginia).
- Knowing the specific location of workers can also be used to provide alerts to them when they leave the "safe area" designated by other smart work zone devices as demonstrated with smart vests in Virginia.
- Michigan is using the VerMac Worker Presence Connected Vest to know when workers are present in a work zone and automatically trigger reduced speed displays on portable digital speed limit signs.
- Archived worker presence data can also be used to inform work zone exposure and support speed limit citations issued by law enforcement.

Identified Sensor Technology Vendors and Web Links:

- VerMac Worker Presence Connected Vest, based on the Smart Vest developed by VTTI: https://rosap.ntl.bts.gov/view/dot/67373.
- VTTI is currently conducing research and development on a Smart Helmet that could be worn by workers and be serve a similar function as the Smart Vest.