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ENTER PRISE

State of the Art of Roadway Sensors Phase 1

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. This 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. This effort considered sensors to be innovative if they are not widely used, either by being new to the transportation sector or not widely used by transportation agencies. 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.

Over 100 innovative sensors were identified through a literature review, web search for industry products, and a survey of DOT practitioners. Identified sensors included those used within the transportation sector and other sectors including the defense, forestry, environmental, warehousing, and port sectors. Analysis of identified sensors included organization by possible use case areas (e.g., road weather, work zones, worker safety, asset condition, parking availability, bicycle and pedestrian detection) and prioritization based on possible relevance and interest to department of transportation's (DOTs). Use cases of prioritized sensors document the data collected, deployment and operational considerations, applications, and identified sensor vendors.

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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

For this Phase 1 effort, this ENTERPRISE Pooled Fund Study project identified over 100 innovative sensors through a literature review, web search for industry products, and a survey of DOT practitioners. Identified sensors included those used within the transportation sector and other sectors including the defense, forestry, environmental, warehousing, and port sectors. Analysis of identified sensors included organization by possible use case areas (e.g., road weather, work zones, worker safety, asset condition, parking availability, and bicycle and pedestrian detection) and prioritization based on possible relevance and interest to DOTs.

ENTERPRISE members selected data types for the development of five use cases to document available information regarding deployment, operations, and maintenance considerations:

- Use Case #1: Start/End Location and Time of Work Zone Lane Closure (Work Zone Event Data)
- Use Case #2: Worker Presence (Worker Safety and Work Zone Event Data)
- Use Case #3: Work Zone Intrusion Detection (Worker Safety Data)
- Use Case #4: Detecting Threats to Fiber (Asset Condition Data)
- Use Case #5: Precipitation and Runoff Rate Sensors (Road Weather Data)

Information from these use cases will be used to further prioritize and select sensors to advance in a Phase 2 effort.

Chapter 1: Introduction

This project identified and described a wide variety of sensors with possible applications in the transportation industry.

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. 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 effort considered sensors to be innovative if they are not widely used, either by being new to the transportation sector or not widely used by transportation agencies. 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.

1.1 Project Background and Summary

This effort, as scoped, was different than how a typical research project is conducted. Rather than start with one (or a small number of) challenges, the initial research was a broad assessment of new sensors used in transportation and other industries that might aid in transportation operations and maintenance. For this reason, more commonly used sensors (e.g., road weather information system (RWIS) sensor technologies, loops, or radar traffic detection) were not reviewed. Rather, the research approach was to cast a wide net and seek as many sensors as could be found, then narrow in on which are of most interest, and finally to define use cases for how the new or innovative sensors could address department of transportation (DOT) challenges (or gaps in existing sensors).

Accordingly, this effort began by broadly scanning for many different types of innovative sensors with over 100 innovative sensors identified through a literature review, web search for industry products, and a survey of DOT practitioners. Identified sensors included those used within the transportation sector and other sectors including the defense, forestry, environmental, warehousing, and port sectors.

Next, a variety of activities took place to help narrow down the list of sensors to prioritize and select those of greatest interest. Analysis of identified sensors included organization by possible use case areas (e.g., road weather, work zones, worker safety, asset condition, parking availability, and bicycle and pedestrian detection) and prioritization based on possible relevance and interest to DOTs. This effort concluded with the development of five use cases on prioritized data elements that are provided by select sensors. Each use case documents the data collected, deployment and operational considerations, applications, and identified sensor vendors.

A Phase 2 effort as a follow up to this project will select sensors of interest from these five use cases for the development of systems engineering documentation that can then be used by an ENTERPRISE member agency interested in deploying and testing that innovative sensor. See Figure 1-1.

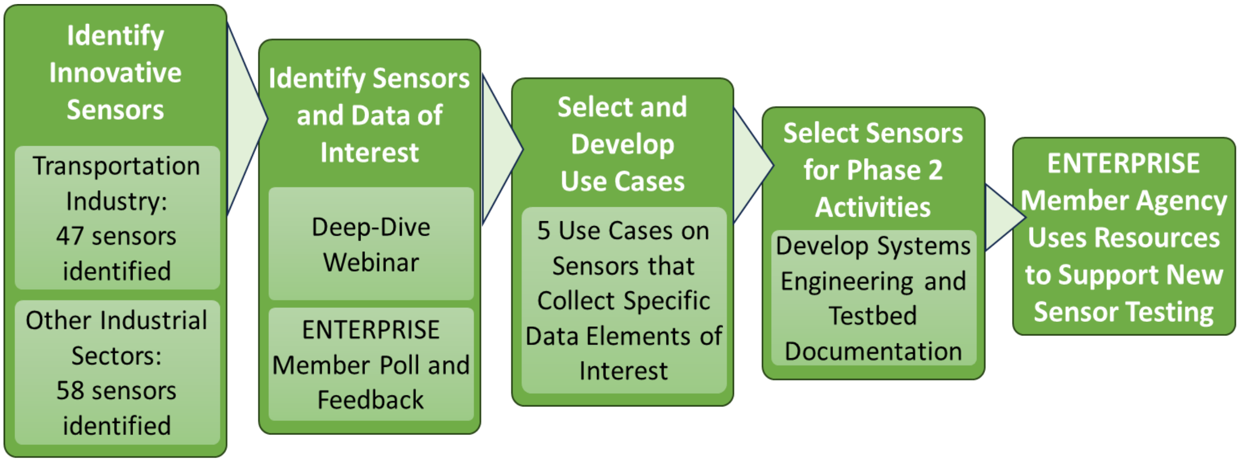

Figure 1-1 Process to Identify, Select, and Develop Phase 1 Use Cases to Select Sensors for Phase 2 Systems Engineering and Testbed Documentation

1.2 Report Organization

This report includes the following sections:

- Chapter 2: Project Approach – Describes the research approach and how information was gathered, as well as a high-level overview of various types of sensors identified from the literature review, web search of industry products, and survey of DOT practitioners. This includes innovative sensors used within the transportation sector and other industries and an analysis of potential applications, relevance to agencies, and potential drawbacks.
- Chapter 3: Use Cases – Presents five use cases of select sensors of interest to the ENTERPRISE members:
    - Use Case #1: Start/End Location and Time of Work Zone Lane Closure (Work Zone Event Data)
    - Use Case #2: Worker Presence (Worker Safety and Work Zone Event Data)
    - Use Case #3: Work Zone Intrusion Detection (Worker Safety Data)
    - Use Case #4: Detecting Threats to Fiber (Asset Condition Data)
    - Use Case #5: Precipitation and Runoff Rate Sensors (Road Weather Data)
- Chapter 4: Summary and Next Steps – Summarizes key project findings and next steps that will be accomplished in a Phase 2 effort as a follow on to this project.
- Appendix A: Agency Staff Survey – Provides screenshots of the survey that was developed to identify which state DOTs have recently deployed new or innovative sensors.
- Appendix B: High-Level Analysis of Identified Sensors – Tables with information from a high-level analysis of identified sensors from non-transportation sectors and the transportation sectors.

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 Information Gathering

This project used a multi-pronged approach to identify innovative roadway sensors:

1. Detailed literature search
2. Web search of industry products
3. SurveyMonkey to transportation agency practitioners
4. Input from ENTERPRISE pooled fund study members

The literature search and web search were intended to cast a "wide net" and initially document different types of sensors that are commercially available. Both searches used key terms to identify different sensors collecting specific types of data (e.g., what is the sensor measuring) and identify sensors used by different industries. The literature and web searches identified sensors used with the following industries and sectors:

- Transportation
- Warehousing
- Forestry
- Ski Resort
- Tourism
- Water Resources
- Airports, Seaports, and Multimodal Hubs
- Defense

The literature and web searches also used key terms related to the six general sensor application categories that are in **bold** below, in order to identify the more specific sensor types that are relevant to transportation agency practitioners, including:

- **Road weather**
    - Wind speed and direction
    - Relative visibility for fog or dust
    - Pavement friction
    - Water levels

  - Pavement temperature
  - Air temperature
  - Relative humidity
  - Barometric pressure
- **Work zone**
  - Work zone location
  - Device location (e.g., sign or device)
  - Device status (e.g., powered on , correct position, stuck, blown over)
  - Back of queue location
- **Worker safety**
  - Wearable devices
  - Intrusion alarm / equipment proximity
- **Parking availability**
- **Bicycle / pedestrian detection**
  - Volume counts
  - Real-time detection for visual or vehicle warnings
- **Asset condition**
  - Pavement condition (e.g., potholes)
  - Bridge structural integrity
  - Sign structure integrity (e.g., mast arm)
  - Crash cushion or guardrail integrity (e.g., whether it has been struck)

Note that a related ENTERPRISE effort entitled "New Methods of Traffic Data Collection" occurring concurrently with this effort documented innovative roadway sensors that collect traffic data like speeds and volumes; as a result, sensors to collect these data were excluded. Additionally, sensors that rely on cameras, video analytics, and software processing were excluded from consideration.

Questions were also developed and sent to agency practitioners via a SurveyMonkey. The survey was developed and distributed in conjunction with the aforementioned ENTERPRISE effort entitled "New Methods of Traffic Data Collection". The section of the SurveyMonkey pertaining to this project asked a series of questions, one for each of the bulleted categories listed above and with each sub-bullet presented above as an option to select alongside an "other" option for respondents to select all that apply to them. Appendix A includes screenshots of the survey questions distributed.

2.2 Identified Sensors, Analysis, and Preliminary Selection

This section summarizes a high-level overview of various types of sensors identified from the literature review, web search of industry products, and survey of DOT practitioners. This includes innovative sensors used within the transportation sector and other industries.

In total, the literature review, web search of industry products, and survey of DOT practitioners identified over 100 sensors, as summarized in Table 2-1 below. The sensors were analyzed to identify potential transportation applications, relevance to agencies, and potential drawbacks. Note that some sensors are applicable to multiple data types; for instance, many sensors can be applied to both bicycle detection and pedestrian detection. Additionally, Appendix B presents the full list of identified sensors with descriptions and links for more information.

Table 2-1 Number of Identified Sensors

Data Type Collected	Transportation Sector	Other Sectors
Road Weather	10	13
Asset Condition	8	4
Work Zone Event Data	5	6
Worker Safety	8	9
Parking Availability	4	0
Bicycle Detection	11	3
Pedestrian Detection	10	2
Other	0	26
TOTAL*	**47**	**58**

*Note that the total is not the sum as some identified sensors collect multiple data types

During an ENTERPRISE Board Meeting, participants were asked to rank their interest in the various sensor categories as part of a Mentimeter poll. The findings, presented in Figure 2-1 and Table 2-2 below. Representatives from each ENTERPRISE member agency were present, and the findings show that data collected by each sensor type are of interest to various members. For instance, while sensors that collect work zone event data were of greatest interest overall, at least one member selected the next three highest ranked sensor types as their highest priority.

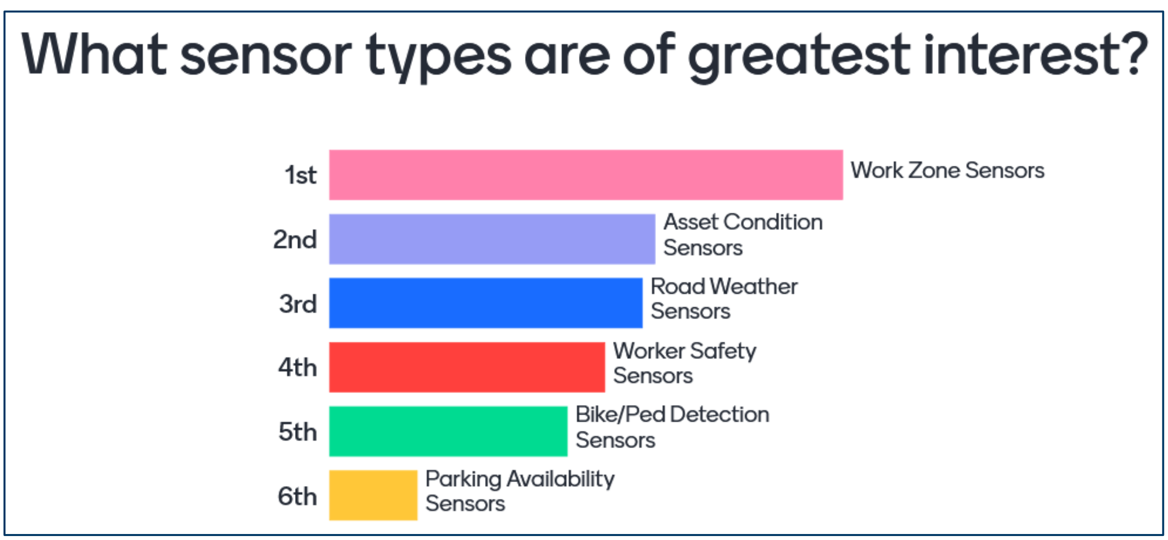

Figure 2-1 Mentimeter Poll: ENTERPRISE Board Members Interests in Each General Sensor Type

Table 2-2 ENTERPRISE Board Members Sensor Type Rankings

Responder	Parking Availability Sensors	Worker Safety Sensors	Bike/Ped Detection Sensors	Asset Condition Sensors	Work Zone Sensors	Road Weather Sensors
1		3	1		2	
2	5	1	6	4	2	3
3				3	2	1
4	3	5	6	1	4	2
5		4	3	1	2	
6			4	3	1	2
7	6	5	3	4	1	2
8		2			1	

Next, an in-depth webinar was conducted on August 23, 2023 for ENTERPRISE member agencies to hear a detailed report of the identified sensors and provide feedback about those of greatest interest. This information was also distributed to ENTERPRISE members via email to provide an opportunity to offer feedback offline. Staff from six different ENTERPRISE member agencies attended this webinar and identified eight sensors or sensor types of interest, and also provided feedback about identified (or other) sensors that had been tested at their agencies. Additional discussion with the full ENTERPRISE Board refined and confirmed the list of sensors that should be prioritized for gathering more information and development of the following use cases, which are presented in detail in the next section (in no particular order):

- Start/End Location and Time of Work Zone or 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)

Note that several sensors identified to be of interest during the deep-dive webinar were either consolidated with other use cases or removed. Specifically:

- The work zone “move over law system” (Worker Safety Data) was identified as still under development and not yet commercially available, and was merged with work zone intrusion detection and alarms.

- Near miss incident detection in a work zone (Work Zone Event Data) was identified as an item of interest, however this generally relies on manual reporting and software applications, given the many types of near miss incidents that could occur in a work zone, and was merged with work zone intrusion detection and alarms.

- Salinity gauges to detect salt penetration in bridge decks (Asset Condition Data) was identified to be of interest during the deep-dive webinar but was removed from consideration given its lack of use as part of operations, like the sensors in other use cases.

- Non-intrusive sensors to support the collection of Parking Availability Data for truck parking applications (e.g., rest area parking availability for commercial motor vehicles) were identified to be of interest during the deep-dive webinar. However, additional research did not identify specific innovative sensors that have not already been tested and documented through various efforts (including those conducted by ENTERPRISE member agencies), such as the:
    - Mid America Association of State Transportation Officials (MAASTO) Regional Truck Parking Information Management System (TPIMS) effort, and
    - FHWA National Coalition on Truck Parking: Technology and Data Working Group - Truck Parking Availability Detection and Information Dissemination resource.

Chapter 3: Use Cases

Various sensors that were identified as being of particular interest to ENTERPRISE members are described in greater detail in the following five use cases.

- Use Case #1: Start/End Location and Time of Work Zone Lane Closure (Work Zone Event Data)
- Use Case #2: Worker Presence (Worker Safety and Work Zone Event Data)
- Use Case #3: Work Zone Intrusion Detection (Worker Safety Data)
- Use Case #4: Detecting Threats to Fiber (Asset Condition Data)
- Use Case #5: Precipitation and Runoff Rate Sensors (Road Weather Data)

3.1 Use Case #1: Start/End Location and Time of Work Zone Lane Closure

Category: Work Zone Event Data

Data Collected: Collect and broadcast real-time data regarding device location for work zone start or end location depending on device placement at the taper or elsewhere within the work zone, as well as the time the work zone is active based on when the device is placed and activated. Other data collected could include impact alerts (e.g., if the device is struck by vehicle), device status (e.g., arrow board display), and sensor battery status alerts.

Deployment and Operation: Several types of connected work zone devices exist that incorporate sensors to report data about an active work zone and/or lane closure.

- *Pi-lit Sequential Warning Lights* are a series of cones that are portable and equipped with situational awareness to automatically synch blinking lights when they are placed in a row in order to guide merging traffic at a lane closure. One or more cones can include capabilities to collect and broadcast additional data described above. These devices have been tested by both Iowa and Michigan. See Figure 3-1.

Figure 3-1 Pi-lit Sequential Warning Lights (Source: Iowa DOT)

- *ConnectedTech Products by iCone* are sensors that are incorporated onto work zone barrels or cones, respectively called an iBarrel or iPin, and broadcast location information where deployed in a work zone. iBarrels include additional capabilities to collect and broadcast traffic speed data. See Figure 3-2.

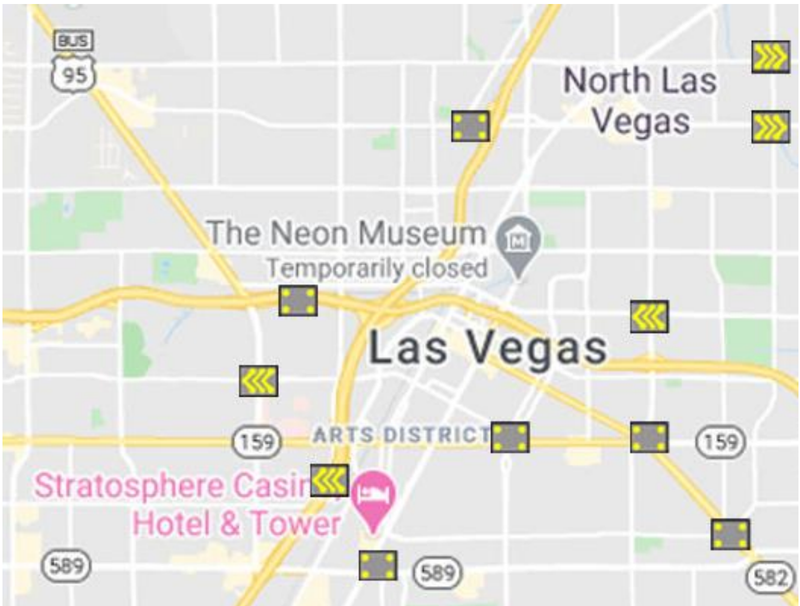

Figure 3-2 Location and Device Status of ConnectedTech Smart Arrow Boards Deployed in Las Vegas Displayed on a Map (Source: ConnectedTech)

- *Smart Arrow Boards* are work zone arrow boards deployed at the beginning of a lane closure that are equipped with additional sensors that broadcast the arrow board location (e.g., at the beginning of a lane closure), as well as the arrow board display when powered on (e.g., left or right arrow, or blinking lights indicating a lane is not closed). These sensors may be attached to either stationary arrow boards or arrow board trucks for mobile work zones. These devices are required on all Iowa DOT projects with a lane closure, and have also been used in other states including Nevada and Minnesota.

Given the nature of the temporary traffic control device that these sensors are attached to, there are no impacts to pavement or other infrastructure. However, from a maintenance standpoint, there is a relatively higher probability of one or more devices being struck by vehicles given their placement at a lane taper.

Devices are often included to be provided as part of construction contracts with communications and data formatting requirements for reporting the data in a way that is easily integrated with the agency advanced transportation management system (ATMS). These devices often report to a third-party vendor server where the device data is processed and formatted before being pulled by agency systems, thereby facilitating the integration of subsequent devices.

These sensors are often deployed as part of larger smart work zone systems and therefore included with other work zone intelligent transportation system (ITS) devices. Example documents developed by state DOTs to detail specifications and requirements for communications, integration, data provision, and security include the following:

- Iowa DOT has included smart arrow boards as part of their General Supplemental Specifications for Highway and Bridge Construction (a summary of information in this larger document that pertains to smart arrow boards can be found at this link).
- This Colorado DOT example includes specifications for these devices, illustrating that these devices are often procured in a similar manner to other work zone ITS.
- Both the Massachusetts DOT Smart Work Zone Standard Operating Procedures and Connecticut DOT Smart Work Zone Guide describe specifications and requirements for deploying, integrating, and operating these types of connected work zone devices.

Application: The automatic broadcast of device location provides situational awareness of where the work zone is located and when the lane closure is active (e.g., the connected work zone device is powered on and stationary). Data from this type of sensor may be used to support or populate data for a Work Zone Data Exchange (WZDx) feed for real-time traveler information, increase agency situational awareness of work zone activities, and be archived to support contract monitoring activities, better understand work zone exposure, and verify work zone-related crash reports. Some vendors also work directly with third-party providers (e.g., Waze) to populate work zone information in their traveler information platforms.

Identified Sensor Technology Vendors and Web Links:

- Pi-Lit Sequential Warning Lights: https://pi-lit.com/product/sequential-cone-top-lamps
- ConnectedTech Products by iCone: https://www.iconeproducts.com/all-products
- Smart Arrow Board kit by ConnectedTech: https://www.iconeproducts.com/connected-tech-arrow-board-kit
- Smart Arrow Board by Ver-Mac: https://ver-mac.com/en/products/series/serie/arrowboards/product/smart-arrowboard/99/

3.2 Use Case #2: Worker Presence

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 3-3, 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 3-3 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", as 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 variable speed limit (VSL) 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.

3.3 Use Case #3: Work Zone Intrusion Detection

Category: Worker Safety Data

Data Collected: Sensors are placed near or around an active work zone boundary to detect the presence of vehicles driven by the traveling public that are at risk of entering the work zone and endangering workers. These sensors are typically connected systems on the ground or carried by workers that provide alerts in the form of visual, audible, and/or haptic alarms to either the workers, the driver of the vehicle, or both. Data logged from these devices could be used to supplement a log of near-miss incidents in work zones.

Deployment and Operation: A work zone intrusion detection system involves the placement of one or more devices at the beginning of a lane closure or lane taper. These systems vary in how they detect approaching vehicles that pose a threat, as well as how and to whom alarms are issued. Similar systems may be attached directly to vehicles (e.g., maintenance vehicles or law enforcement) that are placed at the upstream end of an incident or work zone. As such, the work zone intrusion detection system will include some combination of the following components:

- Device(s) for detection: one system uses a pneumatic tube placed across the closed lane, another relies on sensors placed on cones to detect motion after being struck by an errant vehicle, and a third uses radar. Processing capabilities generally occur at this device for issuing an alert.
- Device to alert drivers: visual (e.g., flashing lights) and/or audio alarms directed at approaching vehicles that potentially escalate in intensity as the threat increases to encourage the driver to change lanes or reduce speed.
- Device to alert all workers at the work site: audio and/or visual alarms closer to the active work site and directed at workers to alert them of the need to move away from an approaching threat.
- Personal devices carried or worn by workers: haptic (e.g., vibrations) and/or audio alarms provided directly to workers that are carrying or wearing the device.

Given the nature of temporary traffic control devices, there are no impacts to pavement or other infrastructure. However, from a maintenance standpoint, there is a relatively higher probability of one or more devices that are deployed as part of a work zone intrusion alarm system being struck by vehicles given their placement at a lane closure.

Unlike other connected work zone devices, these devices only require local wireless communications on-site to generate an alarm on the personal devices based on a threat detected by the sensor, if personal devices are included. In general, work zone intrusion alarms are not used to archive data or integrated with other agency systems. These sensors are often deployed as part of larger smart work zone systems and therefore included with other work zone ITS devices.

It should be noted that a number of evaluations have taken place, which have shown shortcomings with various types of work zone intrusion detection systems. For example, alarm activation does not always occur as expected, the available time between an alarm and imminent danger to workers may not be greater than the worker reaction time needed to move out of harm’s way due to delayed alarm activation, and false alarms are possible.

Application: A variety of work zone intrusion system technologies, such as those shown in Figure 3-4, have been tested and used in various places around the country. These systems are generally placed at the upstream lane taper for a lane closure to provide visual or audio alerts to either approaching vehicles, workers, or both, and some include personal devices carried by workers that also provide vibration and/or audio alarms. Evaluations conducted on various available work zone intrusion systems have summarized the relative benefits and costs, and specific work zone applications for which each type is best suited (e.g., based on work zone duration, fixed or mobile work zone, and speed limit).

Figure 3-4 Examples of Different Work Zone Intrusion Alarm Technologies (Source: FHWA)

Additionally, automated vehicle-mounted sensor and alarm technologies are under development in Virginia and Iowa that would similarly function to use camera and/or radar sensors mounted on a vehicle (e.g., maintenance vehicle, truck-mounted attenuator, safety service patrol, law enforcement, first responders) to detect approaching vehicles and issue a visual and/or audio warning if they do not reduce speeds or change lanes, as necessary.

Identified Sensor Technology Vendors and Web Links:

- TAPCO Worker Alert System (site and personnel alarms): https://www.tapconet.com/product/worker-alert-system.
- CRH Americas AWARE System (site and personnel alarms): link not available.
- Highway Resource Solutions Intellicone (site alarm only, currently only available in the United Kingdom): https://www.highwayresource.co.uk/digital-services/intellicone-incursion-prevention-warning
- Automated Audible Warning System (currently being developed and tested by Iowa State University and Iowa DOT): https://intrans.iastate.edu/research/in-progress/audible-attenuator.
- Move Over Law System (currently being developed and tested by VTTI and Virginia DOT): https://rosap.ntl.bts.gov/view/dot/67373.

- Several recent efforts have evaluated and documented available work zone intrusion alert technologies:
    - Federal Highway Administration, 2023: "Improving Work Zone Safety with Intrusion Alarms."
    - National Cooperative Highway Research Program, 2022: "Guide to Alternative Technologies for Preventing and Mitigating Vehicle Intrusions into Highway Work Zones."
    - Tennessee Department of Transportation, 2021: "Work Zone Alert Systems."
    - Caltrans, 2019: "Evaluation of Work Zone Intrusion Alarms."

3.4 Use Case #4: Detecting Threats to Fiber

Category: Asset Condition Data

Data Collected: Sensors are attached to fiber optic cables to detect variations in light within the fiber that are caused by vibrations in the soil. These light wave patterns are processed to identify the cause of vibrations within ~50 meters, and can be translated into a variety of data for different transportation applications depending on the proximity of the fiber to the roadway. Specifically, data can be used to identify threats to the valuable fiber asset itself (e.g., unauthorized digging). Other possible data that may be available include average traffic speeds every second per 50 meter segments and travel times; identification of rockfalls, avalanches, congestion, and queuing conditions; and traffic volumes and flow rates.

Deployment and Operation: The deployment of this sensor is simple and fast at a back office location, without any disruptions to traffic. However, several factors may impact the success of operations beyond fiber asset condition monitoring due to varying data sensitivities for detection. The fiber placement location, type of fiber, and type of fill are all critical to successful use of this sensor technology for some applications. For instance, traffic monitoring capabilities require presence of fiber immediately adjacent to roadway (e.g., capabilities will not be as sensitive if the fiber is installed adjacent to a distant right-of-way fence). Additionally, the placement of fiber within the conduit can impact data sensitivity, as illustrated in Figure 3-5.

Figure 3-5 Examples of Different Work Zone Intrusion Alarm Technologies (Source: FHWA)

After installing the sensor, calibration may take time but is critical to accurately understand how to interpret the data about what is occurring and then inform the development of policy to generate automated alerts. Figure 3-6 illustrates an example of the output data, referred to as a "waterfall diagram", in Utah from distributed acoustic sensing that can be used to collect traffic speed and volume information, and also detect other types of impact events like rockfalls, avalanches, and crashes. This data is collected at the agency back office, reducing concerns about security issues or data communications from a remote location.

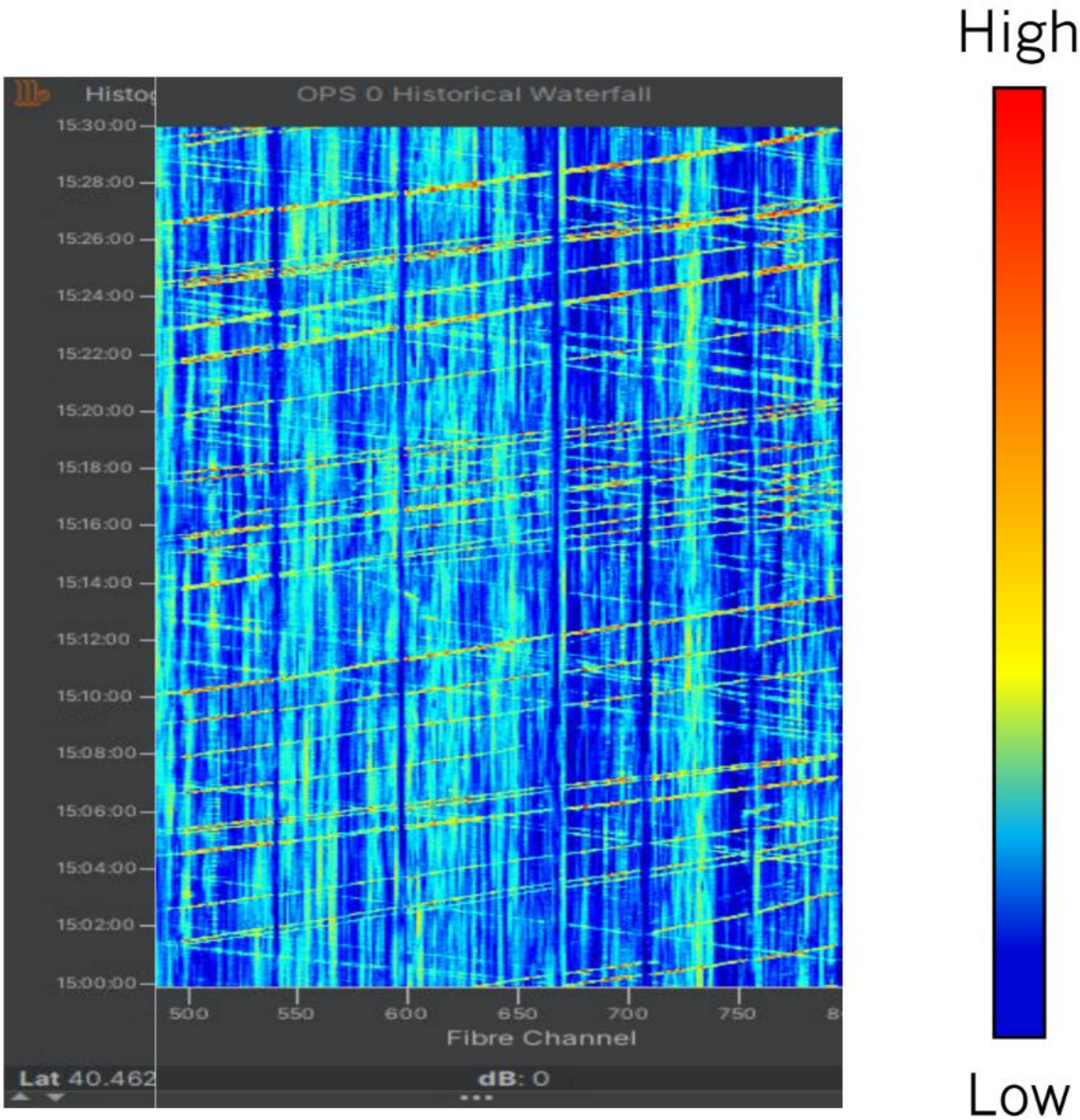

Figure 3-6 Distributed acoustic sensing generates "waterfall diagrams" from summed energy of detected vibration data across the length of the fiber over time, color coded for display from high to low, which are used to understand traffic volumes and speeds in Utah (Source: Utah DOT webinar)

In general, distributed acoustic sensing to date has been used by transportation agencies to augment existing data that is collected to enhance situational awareness, rather than replace those data sources. Also, distributed acoustic sensing has only been implemented in limited demonstration or pilot efforts by a few state transportation agencies. Broader procurement documentation, specifications, or requirements have not been identified.

Application: Distributed acoustic sensing can increase agency situational awareness of threats to the fiber optic cable to monitor this asset. Depending on fiber placement it may also be possible sense impact events like crashes or avalanches or collect traffic speed and volume data, all within 50 meter segments. Several states have used distributed acoustic sensing for various applications:

- Georgia DOT piloted an OptaSense solution on I-20 in Atlanta in 2020 to collect traffic speed and traffic count data (case study available: https://www.optasense.com/case-study-optasense-traffic-monitoring-solution-deployed-on-interstate-20-atlanta).
- North Dakota DOT successfully piloted OptaSense on a 4.5-mile section of I-29 highway in Fargo in 2016 to enable traffic monitoring capabilities (case study available: https://www.optasense.com/case-study-optasense-traffic-monitoring-solution-deployed-on-us-highway).
- Ohio DOT uses distributed acoustic sensing with vendor Terrasound to detect disturbances that could harm fiber.
- Utah DOT worked with their vendor, OptaSense, to pilot this approach on a road impacted by rock falls and avalanches to detect these incidents, in addition to other disturbances (webinar available at: https://youtu.be/R2a-V1QSieg).

Identified Sensor Technology Vendors and Web Links:

- OptaSense: https://www.optasense.com/transportation/traffic-monitoring
- Terrasound: https://www.terrasound.us
- Note that while other vendors offer distributed acoustic sensing, no others have been identified that support transportation applications, which require different types of calibration.

3.5 Use Case #5: Precipitation and Runoff Rate Sensors

Category: Road Weather Data

Data Collected: Environmental sensor stations (ESS) types that collect precipitation and runoff rate data are generally deployed at a fixed location with other ESS that collect other road weather data as part of a road weather information system (RWIS). Sensors that collect precipitation rate and/or runoff rate data may also be capable of collecting other road weather data, such as precipitation type, visibility, road surface condition, water film level, and residual salt content.

Deployment and Operation: Various types of sensors are available to collect data on precipitation rate or water film level, which are non-intrusively deployed on RWIS, such as the one in Figure 3-7. These sensors would likely be deployed at new or existing RWIS sites. Given the extended timeframe that RWIS have been routinely deployed by agencies, the processes for procuring, deploying, operating, and maintaining RWIS are generally mature and understood, as are the solutions for addressing security challenges and communicating and integrating the RWIS data with agency systems. Examples of specifications for procuring RWIS include those at the following links that are available from Colorado DOT, Florida DOT, New York State DOT (example 1 and example 2), and Texas DOT. In some cases, sensors may be embedded in pavement to directly collect runoff rates and other data types, which would inherently incur additional maintenance considerations and ruggedization requirements for plowing, re-paving, and salt corrosion, for example.

Figure 3-7 Typical road weather information system deployment (Source: Campbell Scientific)

Application: RWIS data are often made publicly available for use by the traveling public on agency traveler information websites, as well as by National Weather Service, news media, and private-sector weather providers to help understand real-time weather conditions and generate forecasts and public messaging. Additionally, RWIS data are frequently used by many transportation agencies to support a variety of decisions, including but not limited to those described below:

- Winter maintenance decisions regarding road treatment, plow routing, and staffing. Agency staff may make these decisions directly or use RWIS data as input to automated maintenance decision support systems (MDSS) to more efficiently allocate resources to treat roads appropriately in a more timely manner for increased safety and mobility, while also reducing agency costs. For more information about state uses and applications of MDSS, see: https://mdss.dtn.com.

- Variable speed limits (VSLs) may be based on real-time road weather conditions and set using a combination of real-time travel speed data and data from RWIS that determines visibility or road surface conditions. Utah and Wyoming are examples of states that use VSLs during winter weather conditions.

- Road closures or warning systems are implemented in a variety of states and may be triggered manually or automatically based on RWIS data regarding road surface conditions caused by high water levels, low visibility, or winter weather conditions, for example.

Identified Sensor Technology Vendors and Web Links:

- Campbell Scientific RWIS: https://www.campbellsci.com/rwis
    - CS125 Present Weather Sensor (data on visibility, precipitation rate, and precipitation type): https://www.campbellsci.com/present-weather
    - Lufft Intelligent Road Sensor (data on road temperature and up to two more subsurface temperature measurements, residual salt content and calculation of freezing temperature, road surface condition, and water film level)
- Vaisala Road Weather Station RWS200: https://www.vaisala.com/sites/default/files/documents/WEA-GT-ProductSpotlight-RWS200-B212061EN-B.pdf
    - Present Weather and Visibility Sensors PWD (data on visibility, precipitation type, precipitation accumulation/intensity) https://www.vaisala.com/en/products/weather-environmental-sensors/present-weather-detectors-visbility-sensors-pwd-series
- High Sierra Electronics Road Weather Sensors: https://hsierra.com/products/sensors/road-weather-sensors
    - Intelligent Road Sensor Model 5422 (in-pavement sensor provides data on road surface temperature, water film height, freeze point temperature, chemical concentration, road condition): https://hsierra.com/product/intelligent-road-sensor-model-5422
    - Present Weather Sensor Model 5438 (data on visibility, present weather, and precipitation measurements): https://hsierra.com/product/present-weather-sensor-model-5538-00
    - Present Weather and Visibility Model 5432 (data on precipitation and visibility): https://hsierra.com/product/present-weather-visibility-model-5432
- Additionally, the Aurora Pooled Fund Study conducts research to advance RWIS: https://aurora-program.org.

Chapter 4: Summary and Next Steps

For this Phase 1 effort, this ENTERPRISE Pooled Fund Study project identified over 100 innovative sensors through a literature review, web search for industry products, and a survey of DOT practitioners. Identified sensors included those used within the transportation sector and other sectors including the defense, forestry, environmental, warehousing, and port sectors. Analysis of identified sensors included organization by possible use case areas (e.g., road weather, work zones, worker safety, asset condition, parking availability, and bicycle and pedestrian detection) and prioritization based on possible relevance and interest to DOTs.

ENTERPRISE members selected data types for the development of five use cases to document available information regarding deployment, operations, and maintenance considerations:

- Use Case #1: Start/End Location and Time of Work Zone Lane Closure (Work Zone Event Data)
- Use Case #2: Worker Presence (Worker Safety and Work Zone Event Data)
- Use Case #3: Work Zone Intrusion Detection (Worker Safety Data)
- Use Case #4: Detecting Threats to Fiber (Asset Condition Data)
- Use Case #5: Precipitation and Runoff Rate Sensors (Road Weather Data)

Information from these use cases will be used to further prioritize and select sensors to advance in a Phase 2 effort. Specifically, the Phase 2 project will identify possible test bed approaches that one or more agencies may test in a future test bed environment, with recommendations for common attributes of deployment (e.g., placement, security, communications) such that the individual deployments all contribute to a universal virtual test bed. Additionally, this effort will develop a high-level system engineering approach that defines the needs addressed, operational concepts, and preliminary requirements, with a goal of having a scientific-based description of the use of the roadway sensors identified in Phase 1 that can be presented internally by member agencies within their organization.

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Appendix A
Agency Staff Survey

The screenshots below present the questions in a survey for this project that was combined with survey questions from a related ENTERPRISE project. This survey was distributed to ENTERPRISE Pooled Fund Study members and the AASHTO Committee on Transportation System Operations (CTSO) in June 2023.

ENTERPRISE

ENTERPRISE: Emerging Technologies

Roadway Sensors

Beyond roadway sensors, this effort is also considering new sensors that have recently been developed and are not widely used by transportation agencies, including those used in other industries that may have applications to transportation agencies. For the following questions, we are interested in understanding what new and innovative sensors that your agency may have recently deployed. Please consider sensors that may be new or innovative for transportation agencies in general (i.e., new for the industry, not just at your agency) and are either intrusive or non-intrusive sensors that collect data for agency planning, operations, and maintenance.

6. Has your agency deployed ROAD WEATHER data sensors for any of the following uses that are either new, innovative, or emerging within the transportation industry, including mobile sensors on agency fleet vehicles? Select all that apply.

- ☐ Wind speed and direction
- ☐ Relative visibility for fog or dust
- ☐ Pavement friction
- ☐ Water levels
- ☐ Pavement temperature
- ☐ Air temperature
- ☐ Relative humidity
- ☐ Barometric pressure
- ☐ No
- ☐ Unsure
- ☐ Other. Please describe.

Please provide brand names and brief descriptions.

7. Has your agency recently deployed ASSET CONDITION data sensors for any of the following uses that are either new, innovative, or emerging within the transportation industry? Select all that apply.

- ☐ Pavement condition (e.g., potholes)
- ☐ Bridge structural integrity
- ☐ Sign structure integrity (e.g., mast arms and gantries)
- ☐ Crash cushion or guardrail integrity (i.e., whether it has been struck)
- ☐ No
- ☐ Unsure
- ☐ Other. Please describe.
- ☐ None of the above

Please provide brand names and brief descriptions.

8. Has your agency recently deployed WORK ZONE data sensors for any of the following uses that are either new, innovative, or emerging within the transportation industry? Select all that apply.

- ☐ Worker presence
- ☐ Work zone location
- ☐ Traffic control device location (e.g., sign or device)
- ☐ Traffic control device status – powered on
- ☐ Traffic control device status – correct position, stuck, blown over, etc.
- ☐ Back of queue location
- ☐ No
- ☐ Unsure
- ☐ Other. Please describe.

Please provide brand names and brief descriptions.

9. Has your agency recently deployed PARKING AVAILABILITY data sensors that are either new, innovative, or emerging within the transportation industry?

- ◯ No
- ◯ Unsure
- ◯ Yes. Please provide brand names and a brief description.

10. Has your agency recently deployed (or authorized other entities to deploy) ORIGIN-DESTINATION data sensors (e.g., license plate readers) that are either new, innovative, or emerging within the transportation industry?

- ◯ No
- ◯ Unsure
- ◯ Yes. Please provide brand names and a brief description.

11. Has your agency recently deployed BICYCLE DETECTION data sensors that are either new, innovative, or emerging within the transportation industry?

- ◯ No
- ◯ Unsure
- ◯ Yes. Please provide brand names and a brief description.

12. Has your agency recently deployed PEDESTRIAN DETECTION data sensors that are either new, innovative, or emerging within the transportation industry?

- ◯ No
- ◯ Unsure
- ◯ Yes. Please provide brand names and a brief description.

13. Please provide any additional information that may be relevant on new, innovative, or emerging sensors for this research project to consider.

Appendix B
High-Level Analysis of Identified Sensors

Table B-1 and Table B-2 below present information from the high-level analysis of identified sensors from non-transportation sectors and the transportation sector, respectively. Each table includes:

- The type of sensor with a reference and link, as available, in the left-most column.
- The type of data collected by the sensor (e.g., road weather, asset condition, etc.)
- A description of the sensor in the right-most column.

Additionally, the table of sensors identified in non-transportation sectors also includes a column noting the sector that uses the sensor and a preliminary assessment of possible use cases for the identified sensors.

Table B-1 Identified Sensors Used In Non-Transportation Sectors

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Warehouse temperature	Warehouse	✓	✓							Monitor temperature in devices to avoid overheating (e.g., older walk-in DMS)	Wireless sensor, automatic data logging (-40 to 257F)
Water detection	Warehouse	✓								Flood warning systems; possibly not sufficiently ruggedized	Spot detection sensor to detect standing water
Humidity sensor	Warehouse	✓								Mold or moisture damage alerts; possibly not sufficiently ruggedized.	Measures relative humidity, temperature, and dew point
Snowvision Sensor	Ski	✓								Alerts for detecting conditions conductive to avalanches, road surface conditions	Fully automatic, remotely operated small-sized sensors that measure: Depth of snow cover up to 1.5 m or ice depth up to 0.5 m; snow temperature at any depth; snow density and snow water equivalent (SWE); microwave albedo of the snow; melting and freezing points; ice crust or water layer presence; snow structure
Snow depth and snow making sensors	Ski	✓								Alerts for detecting conditions conductive to avalanches, road surface conditions	Ultrasonic or radar sensor for depth; relative humidity. (Snow making also used for frost protection on construction projects.)

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Snow water equivalency sensor	Ski	✓								Detect road weather conditions, heavy snow weight conditions	Heated rain gauge or SWE sensor to document snow precipitation data
Water velocity, flow, and depth sensors	Water Resources	✓								Flood warning systems to issue alerts as water pipe or channel levels may flood roads or other infrastructure	Sensor mounted to bottom of pipe or channel to measure water level and velocity; also sensors for flumes and weirs
Water level monitoring sensors	Water Resources	✓								Flood warning systems to issue alerts as reservoir or lake levels may flood roads or other infrastructure	Sensors appropriate to measure ground water levels, as well as lakes, reservoirs, tanks, and wastewater applications
Water quality and turbidity sensors	Water Resources	✓								Environmental assessment (e.g., winter maintenance, road construction)	Many sensors and systems are available to monitor many water quality variables
Flow sensor	Defense	✓								Flood warning systems	Rugged sensor for harsh environments to measure flow
Humidity sensor	Defense	✓								Road weather conditions	Rugged sensor for harsh environments to measure humidity levels
Temperature	Defense	✓								Road weather conditions	Rugged sensor for harsh environments to measure temperature

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Ice detection	Defense	✓								Road weather conditions	Military aerospace application
Load sensor	Defense		✓							Structural health monitoring	Rugged sensor for harsh environments
Shock/vibration sensor	Defense		✓							Structural health monitoring	Rugged sensor for harsh environments
Torque sensor	Defense		✓							Structural health monitoring	Rugged sensor for harsh environments
Structural health monitoring sensor	Defense		✓							Structural health monitoring	Military air and ground vehicle applications
Position	Defense			✓	✓					Detecting road closure gate position; proximity of workers to equipment; presence of work activity	Measure binary, linear, or rotary position; also position of military ground equipment gears or turret, landing gears, and wing flaps
Dock laser line projector	Warehouse			✓						Possible work zone or winter application	Laser "lanes" lines that cannot be obscured by debris or snow
Laser measurement systems	Multimodal Port			✓						Work zone device or traffic control positions	Precise positioning of containers

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Acoustic noise sensor	Defense			✓	✓					Identify work zone activity or monitor worker noise exposure	Rugged sensor for harsh environments to measure noise levels
Motion and occupancy sensor	Warehouse			✓	✓		✓	✓		Identify worker presence, protect workers from intrusions or equipment, detect bikes and peds. Possibly not sufficiently ruggedized.	Capture movement with passive infrared
Warehouse traffic sensor systems	Warehouse				✓		✓	✓		Protect workers from intrusions or equipment, detect bikes and peds. Possibly not sufficiently ruggedized.	Motion sensors that trigger LED lights to warn workers, including interactive LED warning signs
Exterior loading dock alarm	Warehouse				✓					Protect workers from intrusions or equipment.	Audible and visible warning for truck motion
Exterior traffic sensors	Warehouse				✓					Protect workers from intrusions or equipment.	Audible and visible warning for potential collision with workers
Safety switches and light curtains	Multimodal Port				✓					Protect workers from intrusions or equipment.	Safety systems

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Wearable and smart sensors	Defense			✓	✓					Identify worker presence, help protect workers from intrusions or equipment	Collect data and transmit signals for training and in-field purposes, to track a soldier location and vitals, communicate mission-critical information, train soldiers using augmented and virtual reality devices; can supplement GPS if jammed
Infrared sensors	Defense				✓					Identify worker presence, help protect workers from intrusions or equipment	To improve weapons ability and accuracy, including explosives detection systems, chemical warfare, missile systems, and target and weapon seeker (e.g., body heat through vegetation)
Safety and security sensors	Airport						✓	✓		Detect bikes or peds	Include intruder detection systems, monitoring runways and ramps for vehicles, and foreign object debris detection sensors
Motion sensor	Defense						✓	✓		Detect bikes or peds	Rugged sensor for harsh environments to detect motion
Vehicle counting / detection	Warehouse						✓				Tube counter for vehicle count/detection

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Wildlife sensors	Airport								✓	Warning systems and/or traveler info at frequent wildlife crossings	Wildlife detection and avian radar
Open / closed sensor	Warehouse								✓	Reversible lane gates	Door/window security monitor
Tilt detection sensor	Warehouse								✓	Reversible lane gates	Detect raising and lowering of garage doors
Dry contact sensor	Warehouse								✓	Reversible lane gates	Measures contact between two wires (seat switches, gate monitoring, etc.)
Open gate alarms	Warehouse								✓	Reversible lane gates	Audible and visible warning when gate is open
Low clearance alarms	Warehouse								✓	Height warning systems for bridge clearance	Audible and visible warning when low clearance detected
Rotating encoders, linear positioning systems, distance sensors	Multimodal Port								✓	Possible CAV use	Automated crane positioning
Sensors for automation of port vehicles	Multimodal Port								✓	Possible CAV use	

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Distance sensors	Multimodal Port								✓	Possible CAV use for vehicle platooning or maintenance vehicles	Use to maintain minimum distance between vehicles along same driveway, or generate protective area to detect fixed or moving obstacles
AC current meters	Warehouse								✓	Detect when field equipment (DMS, sensors, etc.) not working properly	Detect excess power consumption by equipment
Sensors for CO, CO2, Other Gases	Defense								✓	Air quality monitoring in tunnels	Rugged sensor for harsh environments to detect presence of gases
Overhead crane warning lights	Warehouse									Unknown	Show location of overhead hooks with LED lights
Tree and leaf sensors	Forestry									Unknown	In situ automatic dendrometers monitor tree stem circumference; sap flow probes measure transpiration; other sensors can measure leaf temperature at a single point or across a canopy
Soil water content sensors	Forestry									Unknown	Options include: time domain reflectometry (TDR), frequency domain reflectometry (FDR), and capacitance sensors

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
IR and laser-based gas analyzers	Forestry									Unknown	Measure soil gas emissions in the field of up to five greenhouse gases
Soil temperature	Forestry									Unknown	Typically deployed with meteorological stations
Explosives screening devices	Airport									Unknown	Monitors air chemistry and odors to identify potential threats
Micro-electro-mechanical systems (MEMS)	Defense									Unknown	Use as pressure sensors inside: aircraft, water-in-fuel sensors, and friend-or-foe identification; remote satellites to accumulate data, direct rockets, and improve security; and automotive applications
Active sensors	Defense									Unknown	Use external power source to send out a signal or wavelength of light to detect changes in the environment. Use for air defense, surveillance, navigation, search and rescue, weapon fire control, weapons-locating systems

Sensor Type with Reference Link	Sector	Data Type Collected by the Sensor								Assessment: Transportation Area / Possible Use Case	Sensor Description
		Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	Other		
Nanosensors	Defense									Unknown	Mechanical or chemical sensors collect data about particles at a nanoscale level for medical diagnostics, chemical detection, food and water quality, and improving clothing materials to make them stronger, lighter, and more adaptive
Level sensor	Defense									Unknown	Rugged sensor for harsh environments
Speed sensor	Defense									Unknown	Military vehicle applications
Cabin condition sensors	Defense									Unknown	Military air and ground vehicle applications
Kerosene leakage sensor	Defense									Unknown	Military ground vehicle application
Secure door close confirmation sensor	Defense									Unknown	Military application in marine environments
Fuel tank level sensor	Defense									Unknown	Military application in marine environments
Pressure sensor	Defense									Unknown	Rugged sensor for harsh environments to measure pressure

Table B-2 Identified Sensors Used In the Transportation Sector

Sensor Type with Reference Link	Data Type Collected by the Sensor							Sensor Description
	Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	
Smart Guardrail Sensor	✓	✓					✓	Identifies risk situations and alerts users and authorities of accidents and events, such as impact against the guardrail, vehicle speeds, passage of pedestrians on the road, weather conditions in the area, CO_2 levels. Designed for use on urban and interurban roads, includes internal sensors for external visibility, temperature and air quality sensors, radar, and thermal camera to detect risk situations; lights up and shows signs at preceding stretches to warn drivers of the situation
Lufft Intelligent Road Sensor	✓							Measures road temperature (with up to two additional subsurface temperature measurements), residual salt content and calculation of freezing temperature, road surface condition (dry, moist, wet, ice, snow), and water film level
PWS100 Present Weather Sensor	✓							Identifies many precipitation types, including drizzle, rain, snow, hail, and graupel. Designed for continuous, long-term, unattended operation in adverse conditions.
Vaisala Mobile Detector MD30	✓							Mobile sensor tracks road conditions and transmits road weather data — including road surface state, grip, relative humidity, dew point and road and air temperature — from plows or other vehicles. Supports local and systemwide treatment decisions.
Vaisala Surface Patrol Pavement Temperature Sensor DSP100	✓							Detect risk of freezing based on real-time road and air temperature observations. Offers basic live data for winter maintenance operators. The data can also be fed to external systems such as spreader controllers and AVL-systems
IceSight™ Road Surface Condition Sensor	✓							Non-intrusive sensor by High Sierra to measure road surface condition. Available for fixed or mobile vehicle mount.

Sensor Type with Reference Link	Data Type Collected by the Sensor							Sensor Description
	Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	
Surface Sentinel™ Temperature Sensor	✓							Non-intrusive sensor by High Sierra to measure air and surface temperature. Available for fixed or mobile vehicle mount
Creacom Visibility Sensor	✓							Sensor used by Texas DOT for fog detection on I-10. Reported from survey.
Eltec	✓							Bronze-housed sensor positioned at one or more high water detection points that links to flashing road beacons and can transmit messages. Used by Texas DOT.
Trafficalm	✓							"Water presence detector puck" sensor that can be placed at a high-level water mark on a signpost or pedestal post to activate high water warning with signs. Used by Texas DOT.
Distributed Acoustic Sensing: Source 1 and Source 2		✓						Sensor attached to fiber detects variations in light within the fiber that are impacted by vibrations in soil; installation techniques make a difference on sensitivity and fiber must be adjacent to roadside. This can detect crashes, traffic speeds, queue detection, traffic volumes, rockfalls, avalanches, and disturbances that could harm fiber. Used by Ohio DOT and Utah DOT. Requires presence of fiber immediately adjacent to roadway.
Strain Gauge Sensor		✓						Supports structural bridge monitoring and structural supports (e.g., mast arms) for signs, lighting, and signals. Uses either electrical resistivity or vibrating wire; available with connectivity.
Load Cell		✓						Supports structural bridge monitoring; uses either electrical resistivity or vibrating wire

Sensor Type with Reference Link	Data Type Collected by the Sensor							Sensor Description
	Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	
Displacement / Crack Meters		✓						Various sensors available to support monitoring for bridge structures, culverts, pavements, retaining walls, barriers, and sign structures. Sensors include Crack meters (vw and RDT), Strand meters (vw), Cable potentiometer (cpot), Linear variable displacement transducer (LVDT); available with connectivity
Inclination Sensor		✓						For retaining wall or slope monitoring. On-structure: Tiltmeter (vw, MEMS, electrolytic); In-ground: Inclinometer, embedded, MEMS); available with connectivity
Vibration / Acceleration Sensor		✓						Accelerometer (MEMs) used to support monitoring of bridges, signs, traffic signals, rock falls, and impact attenuators.
ConnectedTech Devices			✓					Smart pins, smart cones, smart arrow boards provide location data, and orientation and operational status of the device, as applicable. Temporary traffic signals, automated flagger assistance devices, and other devices may be available from other providers.
HAAS Alert Devices			✓					Device that connects to vehicle light bar or digitally links with warning lights, etc. to broadcast data about vehicle and worker presence.
Pi-lit Sequential Warning Lights			✓					Automatically synch to guide merging traffic at lane closure; can provide start/end location information, impact alerts, and battery status alerts
3M Impact Detection System			✓					Attaches to guardrail, cushions, and hard plastics to monitor impacts
Ver-Mac Sign Activation			✓					Attaches to sign; swipe to activate so it appears on a map to provide digital work zone information that is on the sign
Smart Vest				✓				Worn by workers to provide worker location; developed by VTTI. Also “Worker Presence Connected Vest” by Ver-Mac. Virginia notes a Smart Helmet is being developed

Sensor Type with Reference Link	Data Type Collected by the Sensor							Sensor Description
	Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	
Automated Audible Warning System				✓				Radar and camera on back of maintenance vehicle used to detect presence of encroaching vehicle and transmit audible warning
Equipment Proximity Unit				✓				Magnetic sensor attaches to equipment and integrates with local mesh to provide warnings to workers when they are close and equipment starts to move
Move Over Law System				✓				Sensors mounted on roadside vehicles for a warning solution for roadside workers based on trajectory of approaching vehicles
Downed Worker Device				✓				Worn by workers and used to detect worker fall or impact
Safety Proximity Sensors				✓				Detect objects nearby, or within a set radius, without physical contact up to a nominal range or sensor vicinity, and sends information to warning device or platforms. Includes infrared, radio frequencies, Bluetooth and specialized lasers
Fatigue Monitoring and Wearable Sensors				✓				Wearable technologies to monitor fatigue and other health issues; include electroencephalography (EEG) sensors to monitor brain activity relative to fatigue, monitoring for visual cues and microsleeps, and using sleep and activity data to calculate fatigue risk levels
Work Zone Intrusion Sensor				✓				Alarms or alerts linked to radar-, camera- or infrared-based hardware and accompanying analytical software to advise workers when unwanted vehicles or pedestrians enter a worksite
Vehicle Detection In-Pavement or Surface					✓			In-ground sensor monitors individual parking spaces and relays occupancy status; surface mounts are for “exposed sites” like thin surfaces and do not require drilling

Sensor Type with Reference Link	Data Type Collected by the Sensor							Sensor Description
	Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	
Vehicle Detection Overhead Identification					✓			Overhead indicator that monitors individual parking spaces, displays a light color to reflect occupancy status, and relays occupancy status (parking garage settings)
LiDAR Sensors					✓			Detects reflection when a car is present; only support close-range accuracy, require computation and cost heavily compared to other methods, but offer good accuracy and better frequency by scanning several times in a second.
In-Ground Vehicle Detection Sensors					✓			Most sophisticated for parking, and use different technologies and working principles: •Magnetometer-based sensors detect magnetic field distortion from the vehicle (e.g., iron). •Infrared sensors emit photons and sense their reflection, and can identify the distance of park cars by comparing photon's speed of propagation. •Ultrasonic sensors are similar to infrared, but they use ultrasound waves instead. •Radar sensors are similar but with radio waves; less susceptible to interference than IR or ultrasonic, can detect vehicles through snow, and can be tuned only to detect low clearance park occupancy. •Hybrid sensor with Radar and Magnetometer can offer the best sensitivity, accuracy, and range.
High-Resolution Thermal Sensor						✓	✓	Study sensor had 640 × 480 pixel resolution with 90 degree horizontal view, 69 degree vertical view, and 30 fps frame rate, rated for a detection distance of up to 100 ft. Can differentiate between pedestrians, bicycles, and vehicles.
Low-Resolution Thermal Sensor						✓	✓	Study sensor had 160 × 120 pixel resolution with 95 degree horizontal view and 9 fps frame rate; rated for detection distance of up to 40 ft for pedestrians and 65 ft for bicycles and vehicles. Can differentiate between pedestrians, bicycles, and vehicles.
Optical Sensor						✓	✓	Study sensor was 4K resolution, fish eye lens camera with a 182 degree horizontal view, 176 degree vertical view, and 15 fps frame rate. Can differentiate between pedestrians, bicycles, light vehicles, single-unit trucks, articulated trucks, and buses.

Sensor Type with Reference Link	Data Type Collected by the Sensor							Sensor Description
	Road Weather	Asset Condition	Work Zone Event Data	Worker Safety	Parking Availability	Bicycle Detection	Pedestrian Detection	
LiDAR Sensor						✓	✓	Tampa CV Pilot installed at crosswalks to collect high-resolution 3D representations of objects using pulsed laser light for bike and ped detection for creation of personal safety message (PSM).
Current by GE (Portland)						✓	✓	Provide accurate 24/7 count of vehicles, peds, and bikes, analyze vehicle speeds, identify areas of excessive speeding is prevalent, and identify demand and supply of parking spaces.
Sensol						✓	✓	Crosswalk system overlaid on road surface or directly inset; illuminates ped's exact location from below as ped steps on it. Detects and distinguishes pedestrians, vehicles, and bicycles.
TAPCO / FLIR						✓	✓	Thermal detection activation lights up Rectangular Rapid-Flashing Beacon (RFFB) when peds and bikes are present.
Loop Detector						✓		Inductance loops are relatively inexpensive and provide a high level of reliability for detection.
Microwave / Radar Detection						✓		Microwave radar detection is a good option for signalized intersections at which the installation of loops would not be practical and at which the installation of other common forms of detection, such as video, are determined to be problematic due to weather, low light, occlusion, or other factors.
Infrared Detection						✓		Infrared detection systems are commonly installed for intersections at which existing video detection systems have proven to be problematic due to various issues.
In-Ground Radar						✓		Advantageous for bike detection in situations in which other forms of detection have operational concerns (e.g., to detect bikes with low amounts of metal, or concerns with glare/visibility that can affect video detection)