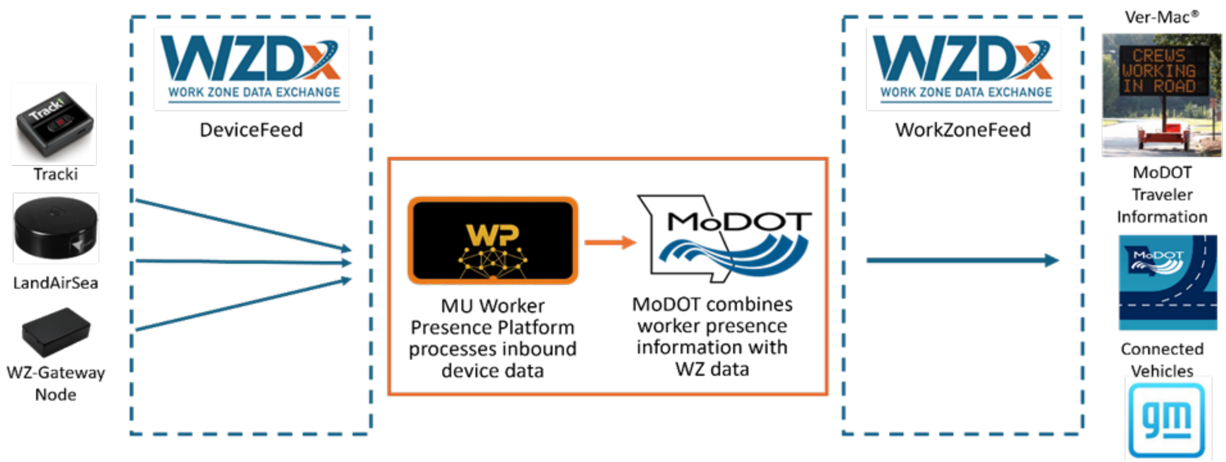
# Accurate Collection and Reporting of Worker Presence in Work Zones




| March 2026 | Project number TR202515 |
|---|---|
| Final Report | MoDOT Research Report number cmr 26-006 |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# TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.<br>cmr 26-006</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle<br>Accurate Collection and Reporting of Worker Presence in Work Zones</td><td>5. Report Date<br>March 2026<br>Published: March 2026</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)<br>Zhu Qing, PhD, PE<br>Yaw Adu-Gyamfi, PhD<br>Praveen Edara, PhD, PE, PTOE<br>Carlos Sun, PhD, PE, JD<br>Henry Brown, MS, PE<br>Ho Jun Baek, MS<br>Mark Amo-Boateng, PhD</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address<br>Department of Civil and Environmental Engineering<br>University of Missouri-Columbia<br>E2509 Lafferre Hall<br>Columbia, MO 65201</td><td>10. Work Unit No.</td></tr>
<tr><td>11. Contract or Grant No.<br>MoDOT project # TR202515</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address<br>Missouri Department of Transportation (SPR-B)<br>Construction and Materials Division<br>P.O. Box 270<br>Jefferson City, MO 65102</td><td>13. Type of Report and Period Covered<br>Final Report (October 2024-March 2026)</td></tr>
<tr><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes<br>Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at https://www.modot.org/research-publications.</td></tr>
<tr><td colspan="3">16. Abstract<br>Highway work zones remain high-risk environments due to the close interaction between workers, live traffic, and heavy equipment. While platforms like the Work Zone Data Exchange (WZDx) and DOT traveler information maps provide location and traffic impact data, real-time, verified information regarding actual worker presence is often unavailable. This data gap limits the effectiveness of smart work zone deployments and emerging connected vehicle applications. This study evaluated device-based location technologies for highway work zone applications by comparing Global Navigation Satellite System (GNSS) and Bluetooth Low Energy (BLE) approaches. Results indicated that BLE devices relying on crowdsourced networks produced inconsistent reporting and large location errors, particularly in rural areas, while GNSS devices provided more stable and temporally consistent data but involved tradeoffs related to cost, battery life, and data accessibility. To address these limitations, the research developed the WZ-Gateway Node, an open-source prototype that utilizes shared communication to reduce recurring costs. Complementing the hardware, the MU Worker Presence Platform was developed to process device-level data into validated worker presence attributes. By applying spatial buffering and activity classification logic, the platform filters false positive s and protects worker privacy while accurately associating field activity with work zone characteristics. Field evaluations confirmed the platform's ability to generate WZDx-compliant feeds with real-time, verified worker presence information. These findings offer a practical roadmap for Missouri DOT and other transportation agencies to enhance traveler safety, smart work zone operations, and connected vehicle applications by basing worker presence alerts on actual field conditions.</td></tr>
<tr><td colspan="2">17. Key Words<br>Work zone safety; Worker presence; Work zone data exchange</td><td>18. Distribution Statement<br>No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.</td></tr>
<tr><td>19. Security Classif. (of this report)<br>Unclassified.</td><td>20. Security Classif. (of this page)<br>Unclassified.</td><td>21. No. of Pages<br>58<br><br>22. Price</td></tr>
</table>

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# Accurate Collection and Reporting of Worker Presence in Work Zones


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*Prepared for*
Missouri Department of Transportation

March 2026

Final Report

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## Acknowledgments

The authors would like to thank the Missouri Department of Transportation (MoDOT) and the Missouri Work Zone Safety Center of Excellence (MOWZES) for sponsoring this research. The authors also thank the members of the Technical Advisory Committee (Eric Kopinski, Dan Oesch, Liz Prestwood, Spencer Robinson, Garrett Depue, Owen Hasson, and Jennifer Harper) for their guidance and valuable input. Special thanks are extended to Project Manager Scott Breeding and MoDOT engineers Andrew Bertels and Corey Burton for their coordination and assistance with field data collection.

# Executive Summary

Highway work zones remain among the most complex work environments due to the close interaction between workers, live traffic, and heavy equipment. While Missouri Department of Transportation (MoDOT) shares work zone locations and traffic impacts through the traveler information systems and the Work Zone Data Exchange (WZDx), worker presence data is not actively captured. The lack of accurate and timely worker presence data prevents drivers from being informed when workers are active, thereby limiting the effectiveness of traveler alerts, Smart Work Zone (SWZ) messaging, and emerging connected vehicle applications. To address this gap, this research evaluated device-based location technologies and investigated practical, scalable methods for enabling real-time worker presence information in Missouri highway work zones.

A structured technology assessment compared Global Navigation Satellite System (GNSS)-based devices and Bluetooth Low Energy (BLE)-based devices across controlled urban and rural environments, as well as under smartphone-restricted conditions. Field testing demonstrated that BLE-based devices relying on crowdsourced smartphone networks, such as Apple AirTag and Tile Pro, exhibited some limitations. These devices produced intermittent reporting, large location errors, and data loss when nearby smartphones were unavailable to detect and relay Bluetooth signals, as well as when nearby smartphones lacked cellular connectivity to forward detection to backend servers. These conditions occurred most frequently in rural environments, resulting in unreliable and discontinuous location reporting. GNSS-based devices provided substantially more reliable and temporally consistent location data. However, the evaluation revealed important tradeoffs among commercial GNSS devices related to cost, battery life, wearability, and access to raw data. Fleet-oriented devices offered durability and long battery life but were often too large for routine worker-worn use. Smaller wearable devices improved practicality but required more frequent charging and relied on proprietary data platforms.

To address these limitations, the research team also developed and tested a prototype device, the WZ-Gateway Node, designed to support scalable worker presence detection. The prototype uses a shared Wi-Fi-based communication architecture rather than individual cellular subscriptions, significantly reducing recurring communication costs when deploying multiple devices. Built on open-source hardware and software, the WZ-Gateway Node provides full access to raw, time-stamped location and speed data, enabling transparent processing and future system refinement. Preliminary testing demonstrated that the prototype device could support reliable worker presence detection while maintaining flexibility for cost control and system evolution.

Building on individual device evaluations, the research developed the MU Worker Presence Platform, a centralized system that aggregates data to detect active work zones for safety alerts and traveler information. By focusing on the collective presence of personnel within work zones rather than tracking individual movement paths, the platform provides critical site-level insights while protecting worker privacy and avoiding the retention of individual location histories. As shown in Figure E-1, the platform ingests device-based location data, associates it with authoritative MoDOT work zone geometries, and derives worker presence as a dynamic work

zone attribute. Spatial buffering and speed-based activity classification logic are applied to distinguish active work from pass-through or commuting movements, reducing false-positive alerts and preserving worker privacy. The platform architecture was also designed to support MoDOT-led implementation and future expansion, with the potential to incorporate additional operational functions, including traffic incident management, project management, and work zone intrusion monitoring, as agency needs evolve.

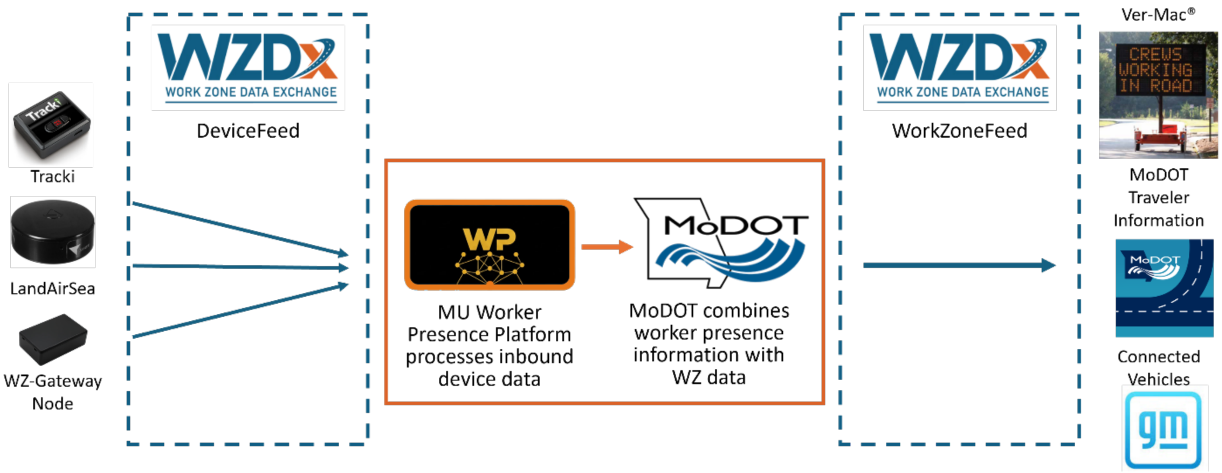


**Figure E-1. MU Worker Presence Platform and WZDx Integration Plan**

Field evaluations demonstrated that the platform can reliably generate real-time worker presence information with low latency and strong scalability. System robustness testing confirmed the ability to process data from hundreds of simultaneous devices without degradation in performance. By publishing worker presence as a WorkZoneFeed attribute rather than a DeviceFeed, the approach aligns with WZDx principles and MoDOT policy by providing actionable information while protecting privacy by not sharing raw or personally-identifiable data.

The results of this study provide a practical roadmap for MoDOT to enhance traveler information systems, smart work zone messaging, and connected vehicle warnings based on verified near real-time work zone conditions. The framework supports condition-based Changeable Message Sign (CMS) control, improved traveler awareness, and future infrastructure-to-vehicle (I2V) applications. While additional pilot deployments and worker feedback are recommended to refine operational parameters, the research demonstrates that worker presence verification can be implemented using scalable, privacy-secure, agency-controlled solutions without reliance on consumer smartphones or proprietary ecosystems.

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# List of Abbreviations and Acronyms

| | |
|---|---|
| API | Application Programming Interface |
| BIM | Building Information Modeling |
| BLE | Bluetooth Low Energy |
| CMS | Changeable Message Sign |
| COTS | Commercial Off-the-Shelf |
| DOT | Department of Transportation |
| FHWA | Federal Highway Administration |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| IP | Ingress Protection |
| LiDAR | Light Detection and Ranging |
| LoRaWAN | Long Range Wide Area Network |
| LTE | Long-Term Evolution |
| mAh | Milliampere-hour |
| MoDOT | Missouri Department of Transportation |
| PPE | Personal Protective Equipment |
| RFID | Radio Frequency Identification |
| RMSE | Root Mean Square Error |
| ROW | Right-of-Way |
| RTK | Real-Time Kinematic |
| SIM | Subscriber Identity Module |
| SWZ | Smart Work Zone |
| URL | Uniform Resource Locator |
| UTC | Coordinated Universal Time |
| UWB | Ultra-Wideband |
| V2X | Vehicle-to-Everything |
| WZDx | Work Zone Data Exchange |

# 1. Introduction

The Missouri Department of Transportation (MoDOT) is advancing a series of major corridor improvement initiatives to improve the state's highway system. Among these efforts, the Improve I-70 Program represents one of the most significant long-term investments in Missouri's transportation infrastructure. The program focuses on reconstructing and expanding I-70 across the state, including the addition of a third lane in each direction, pavement and bridge reconstruction, and upgrades to interchanges and supporting infrastructure. As construction progresses across multiple segments and phases, the Improve I-70 Program is expected to introduce extensive and long-duration work zones along one of Missouri's most heavily traveled freight and commuter corridors.

Highway work zones associated with large-scale corridor reconstruction projects present complex safety challenges for motorists and workers alike. Work zones increase drivers' cognitive workload, elevate their stress, and heighten the risk of driver error. At the same time, these conditions often require construction workers to operate in close proximity to live traffic. National crash statistics indicate that work zone safety remains a critical concern. Work zone fatalities and injuries have increased steadily over the past decade, with 857 fatalities and approximately 44,000 injuries occurring in work zones in 2020 alone (National Work Zone Safety Information Clearinghouse 2024). Work zone fatal crashes are disproportionately concentrated on high-speed, high-volume roadways, involve commercial motor vehicles at significantly higher rates than non-work zone crashes, and are more frequently associated with distracted driving and speeding (ARTBA 2024).

One promising approach to addressing these safety challenges is the accurate detection and reporting of worker presence within highway work zones. Knowing the real-time location of workers can enhance safety by improving situational awareness for motorists, connected vehicle applications, and work zone intrusion detection systems. Worker presence information is also a key element of emerging work zone data exchange (WZDx) efforts, which aim to provide timely and standardized information to road users and traffic management systems. In addition, accurate worker location data can support faster emergency response following incidents and improve operational efficiency by enabling better coordination of personnel and work activities.

Traditional methods for determining worker presence, such as manual check-ins or visual supervision, are often inadequate for large or dynamic work zones. Recent advances in location and sensing technologies—including Global Positioning System (GPS)-based systems, Ultra-Wideband (UWB), Radio Frequency Identification (RFID), Bluetooth Low Energy (BLE), and camera-based systems—have demonstrated the ability to track and report the real-time location of workers in building construction and industrial environments. However, highway construction and maintenance differ fundamentally from building construction sites. Highway work zones typically involve longer linear footprints, mobile or short-duration operations, frequent layout changes, and continuous interaction among workers, construction vehicles, and live traffic. In addition, rural highway environments may lack reliable cellular or internet connectivity, limiting the feasibility of technologies that depend on continuous high-bandwidth communication. As a result, worker presence technologies developed for controlled or fixed-site environments cannot be directly applied to highway work zones without careful evaluation and adaptation.

In this project, worker presence determination and reporting technologies were investigated under real-world highway work zone conditions representative of large-scale interstate construction. The research also explored how worker presence data can be leveraged to enhance work zone awareness and improve safety outcomes.

# 2. Literature Review

The need to detect the presence of workers in highway work zones is increasing, as such detection plays a critical role in enhancing safety by improving driver awareness, reducing emergency response times, and enabling real-time work zone management. However, highway construction site environments often pose challenges for locating workers and transmitting data to a central platform, primarily due to situational constraints. In light of these challenges, this section reviews various technologies for worker detection and location reporting, with an emphasis on their applicability to highway work zone environments. The review also highlights recent Department of Transportation (DOT) pilot deployments and data integration efforts that inform the design and evaluation of worker presence tracking systems suitable for large-scale, real-world highway applications.

## 2.1 Vision-Based Technology

Vision-based systems establish a monitored area using fixed sensors such as cameras or Light Detection and Ranging (LiDAR) units positioned around a work zone. These systems can detect workers, vehicles, and equipment without requiring individuals to carry tracking devices, making them suitable for identifying untagged or uncooperative entities. In addition to spatial coordinates, vision-based systems provide contextual imagery that can support situational awareness and incident verification.

Brilakis (2011) introduced a camera-based method that detects and tracks multiple objects, including workers and equipment, by processing 2D frames from multiple cameras and converting them into 3D spatial positions using centroid computation and epipolar geometry. The approach relies on comparing sequential image frames to identify new entities and track their movements. However, such systems require clear line-of-sight and are vulnerable to occlusion caused by equipment, vehicles, or temporary barriers.

To mitigate occlusion effects, Park (2016) proposed a hybrid detection and tracking approach that combines object detection with frame-by-frame tracking, achieving near real-time performance with processing times between 0.05 and 0.15 seconds per frame. In connected vehicle environments, Cui et al. (2023) developed a vision-based work zone alert system that integrates calibrated monocular video with GPS alignment to generate safety messages for approaching vehicles while meeting latency requirements for timely warnings.

More recently, Wu et al. (2023) evaluated roadside-mounted 360-degree LiDAR sensors for detecting vehicle intrusions into work zones and issuing alerts to workers. Field testing demonstrated high vehicle detection accuracy (99.5%), but system performance degraded when multiple vehicles appeared simultaneously due to increased computational demand and processing latency.

Despite their accuracy and rich data output, vision-based systems face practical limitations for highway deployment. Fixed sensor placement, calibration requirements, high computational demands, and reliance on reliable high-bandwidth communication infrastructure limit their feasibility for large-scale, mobile, or short-duration highway work zones.

## 2.2 Radio-Frequency-Based Technology

Radio-frequency-based tracking systems, including BLE, RFID, and UWB, are among the most commonly explored technologies for real-time location tracking in construction and work zone environments. These technologies are generally well suited for wearable applications due to their compact size, light weight, and low power consumption. However, each exhibits distinct tradeoffs in terms of accuracy, scalability, infrastructure requirements, and communication reliability.

BLE is a short-range radio communication technology that enables proximity-based positioning. Cho (2024) developed a BLE-based worker safety management system by integrating BLE modules into safety vests and deploying beacons throughout the work zone. The system estimated worker position using distance and angle measurements relative to fixed beacons. Laboratory testing demonstrated high accuracy at short ranges, with a root mean square error (RMSE) of 0.257 m (standard deviation: 0.724 m) for distance and 10.03° (standard deviation: 2.16°) for angle at a 2.5 m range. However, performance degraded significantly as distance increased; at 12.5 m, the RMSE increased to 1.531 m (standard deviation: 3.071 m) for distance and 23.92° (standard deviation: 9.50°) for angle. As shown in Figure 2-1, these findings highlight the high sensitivity of BLE-based systems to signal attenuation and the critical importance of beacon density.

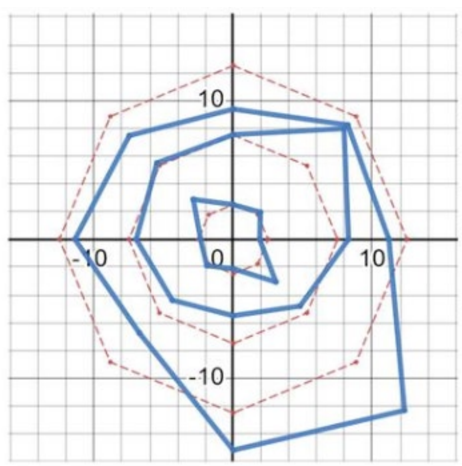


**Figure 2-1. Comparison of Reported BLE Positions (blue) and Ground-Truth Positions (red) Illustrating Distance-Dependent Error**

Field testing of the BLE system showed a reaction time of approximately 2.2 seconds when a vehicle approached at 5 mph, demonstrating responsiveness for short-range alerts. A web-based interface was also developed to visualize real-time worker positions and alert logs. BLE offers advantages in terms of low power consumption (reported 48-hour battery life per charge), compact form factor, and ease of integration into wearable PPE. However, its reliability depends heavily on beacon density, signal stability, and proximity. Performance degradation at longer ranges and in complex environments raises concerns about scalability and robustness in large highway work zones, particularly where workers and vehicles move rapidly and unpredictably.

RFID systems communicate using electromagnetic fields between tags and readers. A key strength of RFID is its ability to track large numbers of entities simultaneously—often up to 1,000 tags per reader—without requiring line-of-sight. Passive RFID tags operate without batteries, making them lightweight, inexpensive, and maintenance-free. Costin et al. (2015) proposed an RFID- and Building Information Modeling (BIM)-integrated work zone management system deployed on a 900,000-square-foot construction site. The system used 80 RFID readers to track 1,200 workers from 125 contractors, generating time-stamped location data that supported safety compliance monitoring and movement analysis.

Despite these advantages, RFID systems have limited communication range. Bansal et al. (2023) reported a maximum effective read range of 5.9 m when tags were mounted on metal objects attached to safety helmets. As a result, maintaining continuous coverage requires dense reader deployment and wired or wireless backhaul connectivity, which poses significant challenges for highway work zones with long linear extents and frequent layout changes.

UWB technology transmits signals over wide frequency bands, enabling higher positioning accuracy than BLE or RFID. Ahmed et al. (2020) reported UWB anchor coverage ranges of 20–100 m per station, substantially exceeding typical RFID ranges. Ochoa-de-Eribe-Landaberea et al. (2024) developed a UWB-based safety system using instrumented traffic cones as anchors to define virtual safety zones (safe, warning, and danger). UWB tags mounted on safety helmets communicated with these anchors to determine worker location and trigger alerts when entering hazardous areas. The system achieved a 98.9% warning accuracy under outdoor conditions, and anchor self-localization showed a maximum deviation of 0.441 m from true positions.

While UWB offers high accuracy and wireless operation, it still requires careful anchor placement. Industry guidance suggests anchor spacing of approximately 20 feet, which increases deployment complexity for large highway work zones. Moreover, UWB systems typically operate within a localized network and do not directly communicate with external systems such as connected vehicles, traffic management centers, or public traveler information platforms. Additional communication infrastructure (e.g., Ethernet, Wi-Fi, or Long Range Wide Area Network (LoRaWAN)) is required to bridge this gap, limiting scalability.

## 2.3 Global Navigation Satellite System (GNSS)-Based Technology

GNSS technology is one of the most widely adopted approaches for outdoor location tracking. GNSS devices typically achieve lane-level accuracy (approximately 4–5 m) under open-sky conditions (van Diggelen & Enge, 2015) and demonstrate high reliability, with reported availability exceeding 99.98% per hour. GNSS-based tracking is particularly attractive for highway applications due to its infrastructure-independent operation and broad geographic coverage.

Because GNSS devices calculate position through one-way satellite signal reception, they require supplemental communication technologies—such as cellular networks, Wi-Fi, LoRaWAN, or BLE—to transmit data to external platforms. Despite this limitation, GNSS-based systems have been widely adopted in fleet management, logistics, and asset tracking, demonstrating maturity and scalability.

Talledo Vilela et al. (2022) developed a Smart Work Zone system using GNSS-equipped safety vests and cones connected through a DigiMesh network. The system achieved self-localization accuracy of approximately 20 cm and supported intrusion detection using additional camera and radar sensors. Battery life was reported as 22 hours for vests and 20 hours for cones, highlighting the importance of power management for continuous operation.

GNSS-based tracking provides both location and speed data, enabling differentiation between active work activities and pass-through movements—an essential capability for minimizing false-positive worker presence indications in highway work zones. However, GNSS performance can degrade due to signal blockage, multipath effects, or limited communication connectivity, particularly in urban canyons or rural areas with sparse cellular coverage.

## 2.4 DOT Practice and Pilot Deployments

In addition to academic research, several state DOTs have conducted pilot deployments that provide practical insights into worker presence detection and work zone data management. This section reviews two representative DOT efforts. One focuses on high-precision worker tracking at the field level, while the other emphasizes automated verification and integration of work zone data, illustrating an approach for transforming device-based observations into reliable, system-level work zone information.

### 2.4.1 Virginia DOT: Smart Work Zone System

The Virginia Tech Transportation Institute, in partnership with the Virginia DOT, developed a Smart Work Zone System to improve worker localization and intrusion detection in active highway work zones (Talledo Vilela et al., 2022). The system consists of Smart Vests and Smart Cones equipped with Real-Time Kinematic (RTK) GNSS modules. Unlike standard GNSS devices, which typically provide lane-level accuracy, the RTK-enabled system achieves centimeter-level positioning accuracy. This level of precision allows worker locations to be tracked relative to exact work zone boundaries and equipment placement.

The system architecture relies on a local DigiMesh wireless network formed by the Smart Cones and a centralized base station. This network supports the creation of a dynamic geofence that defines safe and restricted areas within the work zone. The pilot demonstrated effectiveness in two primary safety applications. First, the Smart Vest provides vibration and visual alerts when a worker exits the predefined safe zone. Second, the base station communicates with connected vehicles through cellular vehicle-to-everything (V2X) technology to predict potential vehicle intrusion trajectories and issue advance warnings to workers.

While the Virginia DOT pilot demonstrated clear safety benefits associated with high-precision wearable tracking, it also revealed challenges related to scalability and deployment complexity. The system requires specialized RTK hardware, local base stations, and site-specific configuration. These requirements may limit feasibility for short-duration maintenance activities or for widespread deployment across multiple work zones operating simultaneously.

### 2.4.2 Iowa DOT: Automated Work Zone Data Integration

While Virginia prioritized field-level tracking precision, the Iowa DOT emphasized data reliability through automated verification. Knickerbocker et al. (2020) documented persistent discrepancies between scheduled work zone activities and actual field conditions, noting that manual entry errors often resulted in inaccurate timestamps. These inconsistencies undermine the credibility of information shared with travelers and downstream external systems.

To address this issue, Iowa DOT deployed Smart Arrow Boards equipped with GNSS receivers and cellular communication modules. Instead of relying on manual updates, the system automatically inferred lane closure status based on the operational state of the arrow boards, such as whether the board was actively displaying a directional message. This approach enabled automated verification of the spatial and temporal limits of lane closures directly from field devices.

The verified work zone information was integrated into the Work Zone Data Exchange and disseminated through Iowa DOT's 511 traveler information system, as well as shared with third-party navigation providers such as Waze and Google Maps. The Iowa DOT study concluded that replacing manual reporting with automated, field-based verification is essential for producing reliable work zone data that can support real-time traveler information and connected vehicle applications.

The reviewed literature demonstrates that while numerous technologies are capable of detecting or tracking worker locations with varying degrees of accuracy, most existing efforts focus on either device-level performance or site-specific deployments. Vision-based and high-precision radio-frequency systems offer strong accuracy but require substantial fixed infrastructure, limiting scalability for large, mobile highway work zones. GNSS-based approaches provide broader coverage and operational flexibility but introduce tradeoffs related to reporting latency, battery life, and data integration.

Importantly, prior studies and DOT pilot deployments emphasize location tracking as an end in itself, rather than as an intermediate input to operational decision-making. Fewer efforts address how worker location data can be systematically transformed into reliable, privacy-preserving, and actionable worker presence information that aligns with Work Zone Data Exchange practices and can be consumed by traveler information systems, Smart Work Zone platforms, and connected vehicle applications. This gap motivates the present study, which shifts the focus from individual tracking technologies to a platform-level approach that derives worker presence at the work zone level under realistic operational constraints.

# 3. Technology and Device Selection

This section describes the evaluation process used to identify worker presence device-based location technologies suitable for deployment in highway work zones and documents the rationale for selecting candidate devices for field testing. The evaluation was guided by the operational characteristics of Missouri highway work zones, which typically involve large linear footprints, sometimes mobile or intermittently active work operations, frequent changes in work zone configuration, and variable network connectivity.

## 3.1 Technology Screening and Selection Rationale

Based on the literature review and operational considerations, GNSS-based tracking and BLE-based tracking were identified as the most viable technologies for initial evaluation in highway work zones. This determination was driven by the need for infrastructure-light solutions that can be deployed rapidly without relying on fixed roadside installations or continuous line-of-sight. Vision-based systems, RFID, and UWB technologies can provide high positional accuracy in controlled environments; however, these systems typically require substantial fixed infrastructure, such as calibrated cameras, dense anchor placement, or wired communication networks. These requirements limit their feasibility for large-scale interstate construction projects, mobile maintenance operations, and short-term work zones. In contrast, GNSS- and BLE-based solutions rely primarily on portable or wearable devices and existing communication networks, allowing greater flexibility and lower deployment burden.

Although smartphone-based applications represent a technically feasible approach for location tracking in many transportation and logistics contexts, such approaches were intentionally excluded from this study based on MoDOT policy and guidance from subject matter experts. MoDOT discourages the use of personal smartphones by workers and contractors within active work zones due to safety and privacy considerations. Accordingly, this research focused exclusively on tracking solutions that operate independently of worker-owned or worker-operated mobile devices.

BLE-based tracking was included in the evaluation due to its low cost, compact size, and widespread availability in consumer and industrial devices. However, BLE was treated as a comparative or complementary technology rather than a primary candidate, given its known dependence on proximity-based communication and, in many cases, smartphone or crowdsourced network support. GNSS-based tracking was hypothesized to provide more consistent performance across diverse highway environments. However, overall system reliability depends on both satellite-based location determination and the availability of communication channels for data transmission. In rural highway work zones, GNSS positioning typically remains available, while cellular connectivity can be intermittent, making it necessary to evaluate positioning accuracy and communication reliability together. However, overall system reliability depends on both satellite-based location determination and the availability of communication channels for data transmission. In rural highway work zones, GNSS positioning typically remains available, while cellular connectivity can be intermittent, making it necessary to evaluate positioning accuracy and communication reliability together.

## 3.2 Evaluation Framework and Selection Criteria

Candidate device-based location technologies and devices were evaluated using a comprehensive framework designed to reflect the operational realities of Missouri highway work zones. The evaluation framework therefore emphasized not only positional accuracy, but also the usefulness of the data produced, ease of deployment, and long-term operational feasibility for MoDOT applications. Four primary evaluation criteria were applied:

- **Accuracy and Connection Reliability**

This criterion assessed the consistency, stability, and continuity of reported location data across both urban and rural environments. Field tests compared device-reported coordinates against known geodetic positions and evaluated performance under varying levels of cellular and network coverage. Particular attention was given to signal loss, latency, and the ability of devices to maintain reporting during transitions between areas with strong and weak connectivity, as these conditions are common in Missouri highway work zones.

- **Data Content and Integration Capability**

Devices were evaluated based on the type, resolution, and completeness of data they could provide, as well as their suitability for integration into a centralized worker presence platform and for sharing through WZDx. In addition to geographic coordinates, the availability of operationally relevant attributes—such as speed, movement state, or timestamp granularity—was assessed. The evaluation also considered the availability of application programming interfaces (APIs), data export functionality, and compatibility with standard geospatial data formats required for automated processing and data sharing.

- **Operational Practicality**

Operational practicality assessed the feasibility of deploying and maintaining devices in active highway work zones without disrupting worker tasks or existing work practices. This included evaluation of device size, weight, attachment options, and durability, as well as the ability to mount devices on personal protective equipment (PPE) or portable work zone assets. Battery life was treated as a critical component of operational practicality, as devices must function continuously over extended work shifts or multiple days without frequent charging or battery replacement. Devices requiring minimal user interaction were favored to reduce worker burden and minimize distraction in safety-critical environments.

- **Cost-Effectiveness**

Cost-effectiveness was evaluated in terms of total cost of ownership rather than initial purchase price alone. This included initial hardware acquisition costs, recurring subscription or service fees, and anticipated maintenance or battery replacement costs over a multi-year deployment horizon. This criterion reflects the need for solutions that are financially sustainable for potential large-scale or long-term deployment by MoDOT across multiple projects and districts.

## 3.3 Candidate Devices

Based on the technology screening rationale described in Section 3.1 and the evaluation framework outlined in Section 3.2, five commercial off-the-shelf (COTS) location-enabled devices were selected for detailed evaluation. The selected devices represent two primary technology categories—GNSS-based tracking and BLE-based tracking—and were chosen to capture a range of communication architectures, data capabilities, and operational characteristics relevant to highway work zone deployment.

Three GNSS-based devices were selected to represent standalone location-reporting solutions capable of operating independently of worker-owned mobile devices. These devices—LandAirSea 54, Tracki, and Roadlytics—use satellite positioning for location determination and cellular networks for data transmission. GNSS-based devices were prioritized because they offer infrastructure-independent operation, broad geographic coverage, and the ability to provide both location and speed information, which is critical for distinguishing active workers from passing vehicles. The selected GNSS devices also vary in form factor, battery capacity, power-management strategies, and data access mechanisms, allowing for a comparative assessment of operational practicality and integration feasibility.

Two BLE-based devices, Apple AirTag and Tile Pro, were selected to represent widely available, low-cost proximity-based tracking technologies. These devices rely on Bluetooth communication and crowdsourced or smartphone-mediated networks to report location information. BLE devices were included to evaluate whether their low cost, small size, and minimal maintenance requirements could offset known limitations related to data completeness, connection reliability, and dependence on nearby mobile devices. Consistent with MoDOT policy, these devices were evaluated strictly as standalone trackers without assuming continuous access to worker smartphones.

The selection of these five devices was intended to balance practical feasibility with technical diversity. Devices were chosen to span a range of price points, battery designs (rechargeable versus replaceable), data access models (application dashboards versus programmable interfaces), and attachment options for personal protective equipment or work zone assets. This approach enabled the research team to assess not only raw tracking performance, but also the broader suitability of each device for potential deployment in Missouri highway work zones.

Detailed descriptions of each candidate device, including hardware specifications, communication mechanisms, and manufacturer-reported capabilities, are provided in Sections 3.3.1 through 3.3.5.

### 3.3.1 LandAirSea 54 GPS Tracker

The LandAirSea 54 is a commercial-grade GNSS tracking device originally designed for fleet and asset management applications (Figure 3-1). The device utilizes GNSS positioning combined with a 4G Long-Term Evolution (LTE) cellular connection to transmit real-time location data to a cloud-based platform. It carries an IP67 rating, indicating protection against dust ingress and temporary immersion in water, making it suitable for outdoor highway work zone environments.

**Figure 3-1. LandAirSea 54 GPS Tracker (Source: LandAirSea)**

The device measures 2.27 inches in diameter and 0.95 inches in height and weighs 2.65 ounces (75 grams). It is powered by an internal rechargeable lithium-ion battery with a capacity of 1,500 mAh. To extend battery life, the LandAirSea 54 incorporates a motion-sensing "sleep mode" that suspends data transmission when the device remains stationary for a predefined period and resumes reporting when motion is detected. This feature is particularly relevant for work zone applications in which workers may alternate between active movement and stationary tasks.

A high-strength magnet is integrated into the device housing, allowing for rapid and secure attachment to metal surfaces such as construction equipment, trailers, or temporary signage without the need for additional mounting hardware. The device also provides access to historical location data and time-stamped position logs, supporting post-processing and integration with external platforms.

### 3.3.2 Tracki Tracker

The Tracki device is a compact and lightweight tracking solution designed for personal and asset tracking (Figure 3-2). The device primarily relies on GNSS for outdoor positioning and uses 4G LTE cellular connection for data transmission. In addition to satellite-based positioning, Tracki employs a hybrid location algorithm that supplements GNSS with Wi-Fi–based positioning when satellite signals are obstructed, such as under heavy infrastructure or near buildings. In these cases, the device can passively detect surrounding Wi-Fi router identifiers to assist in position estimation, akin to mobile handset hybrid positioning techniques. This ability allows it to maintain approximate location information even where GNSS alone may be degraded.


**Figure 3-2. Tracki Tracker (Source: Tracki)**

The Tracki device measures approximately 1.75 × 1.5 × 0.55 inches and weighs 1.26 ounces (36 grams). It is powered by a rechargeable 600 mAh lithium-ion battery. Due to its smaller battery capacity, the device relies on power management strategies to balance reporting frequency and operational lifespan.

Multiple attachment options are available, including a belt clip, magnet, and lanyard, allowing the device to be mounted on PPE or equipment as needed. The compact size and flexible mounting options make the Tracki device adaptable for different deployment configurations; however, its reduced battery capacity relative to other GNSS devices introduces potential operational constraints for extended deployments without frequent recharging.

### 3.3.3 Roadlytics Tracker

The Roadlytics device is a GNSS enabled tracking unit that uses cellular communication to transmit location data to a cloud endpoint (Figure 3-3). The device is designed as a flexible, general-purpose tracking solution with streamlined firmware and open-access software, prioritizing data availability and system integration over consumer-oriented features. A key characteristic of the Roadlytics device supports configurable reporting intervals, allowing frequent and consistent location updates to be enabled as needed. It also provides direct access to raw, time-stamped location data through a dedicated application programming interface (API), which facilitates seamless integration with external platforms.


**Figure 3-3. Roadlytics (Source: Roadlytics)**

The Roadlytics device measures approximately 1.06 × 1.50 × 2.32 inches and weighs 1.94 ounces (55 grams). It is powered by a rechargeable lithium-ion battery with a capacity of 1,200 mAh, providing sufficient operational duration for extended field testing under typical reporting configurations.

The Roadlytics tracker does not include dedicated mounting hardware or attachment features such as clips or magnets. Due to its compact size and lightweight design, the device can be carried unobtrusively in a pocket, pouch, or small PPE accessory during field deployment.

### 3.3.4 Apple AirTag

The Apple AirTag represents a crowdsourced Bluetooth-based tracking architecture that operates within the Apple "Find My" network (Figure 3-4). Unlike cellular-based trackers, the AirTag does not contain a cellular modem or require a subscription or SIM card. Instead, it periodically broadcasts an encrypted Bluetooth signal that can be detected by nearby Apple devices, which then relay the location information to Apple's cloud services.


**Figure 3-4. Apple AirTag (Source: Apple)**

The AirTag is the smallest device evaluated in this study, measuring 1.26 inches in diameter and weighing 0.39 ounces (11 grams). It features an IP67 ingress protection rating and is powered by a user-replaceable CR2032 coin cell battery with an estimated service life of approximately one year. When in close proximity to compatible iPhones, the AirTag can also utilize UWB technology to support short-range "precision finding," enabling direction and distance estimation.

For this study, the AirTag was evaluated strictly as a standalone tracking device without assuming continuous access to worker-owned smartphones. The device's reliance on nearby Apple devices for location reporting and its limited access to raw coordinate data are important considerations when assessing its suitability for highway work zone deployment.

### 3.3.5 Tile Pro

The Tile Pro is a BLE tracking device designed for cross-platform compatibility with both iOS and Android operating systems (Figure 3-5). It is marketed for rugged outdoor use and offers an extended Bluetooth transmission range of up to 400 feet (approximately 120 meters) under open, unobstructed conditions, representing the longest nominal range among the BLE devices evaluated in this study.


**Figure 3-5. Tile Pro (Source: Tile)**

The device measures approximately 2.3 × 1.3 × 0.3 inches and weighs about 0.5 ounces (14 grams). It is powered by a replaceable CR2032 coin cell battery with an estimated one-year service life. When outside direct Bluetooth range of the user's device, the Tile Pro relies on the Life360/Tile crowdsourced network, in which nearby users running the Tile application anonymously relay the device's location to the cloud.

The Tile Pro includes a built-in keyhole, allowing it to be easily attached to equipment or assets using zip ties or carabiners without additional mounting accessories. As with other BLE-based trackers, their dependence on nearby mobile devices and limited access to raw location data are key factors considered in subsequent evaluation of its performance and integration potential.

## 3.4 Technology Field Evaluation Methodology

Field evaluations were conducted to assess the performance of candidate location technologies across a range of operational and connectivity conditions representative of Missouri highway work zones. The evaluation was designed to examine device accuracy, connection reliability, and data continuity under both controlled conditions and real-world operational use. To achieve this, the methodology combined structured research testing at selected sites with an operational pilot involving MoDOT personnel in active work zones.

### 3.4.1 Controlled Research Testing

Controlled testing was conducted at multiple sites selected to represent urban and rural highway environments with differing levels of cellular network availability, surrounding infrastructure, and traffic activity. These factors are known to influence the performance and reliability of location technologies, particularly those that rely on cellular communication.

- **Testing Sites**

Urban/suburban testing was conducted at two locations representative of high-volume highway corridors with robust cellular infrastructure. The Lenoir Street Commuter Lot, located at 3401–3733 Lenoir Street in Columbia, Missouri, adjacent to US 63, is situated near the high-traffic intersection of US 63 and Grindstone Parkway. The Midway Auto Truck Plaza, located at 6401 West US-40 in Columbia, Missouri, adjacent to Interstate 70 at Exit 121, was selected to represent an interstate freight corridor with continuous traffic flow and strong network coverage. These urban/suburban sites served to evaluate device and connectivity performance under high-density traffic conditions. Testing at these locations assessed tracking accuracy and connection reliability when cellular service is fully available, reflecting conditions commonly found in urban interstate environments.

To evaluate performance under connectivity-challenged conditions, rural testing was conducted at two locations identified as areas with limited or no cellular coverage based on coverage maps and prior field verification. These sites included the Dry Fork Recreation Area near New Bloomfield, Missouri, and Peters Lake on County Road 207 in Fayette, Missouri. These rural sites were used to simulate rural work zones where cellular connectivity is often weak or non-existent. Testing in these environments allowed the research team to assess the robustness of device communication and the persistence of data reporting during signal loss. The four controlled testing sites are shown in Figure 3-6.


**Figure 3-6. Map of Technology Evaluation Sites**

- **Testing Protocol**

At each controlled testing site, a two-phase evaluation protocol was implemented to assess device performance under different connectivity assumptions and to evaluate dependence on smartphones. Each phase lasted approximately 30 minutes and involved continuous movement of the test subject within the testing area.

In the smartphone-enabled phase, the test subject carried a smartphone with active cellular and Bluetooth connectivity, allowing evaluation of devices that rely on smartphone support or crowdsourced networks. In the smartphone-disabled phase, the smartphone was powered off, terminating all wireless connectivity associated with the test subject. This phase was designed to simulate MoDOT operational conditions in which workers are generally prohibited from using personal smartphones within active work zones.

This protocol enabled direct comparison of device performance with and without smartphone support, allowing the research team to assess standalone functionality, quantify the impact of smartphone availability on tracking accuracy and reporting continuity, and identify technologies suitable for deployment under different operational constraints.

### 3.4.2 MoDOT Volunteer Operational Pilot

To supplement the controlled research testing, an operational pilot was conducted with two MoDOT employees who voluntarily participated during active I-70 work zones associated with the Rocheport Bridge and Kingdom City projects. The purpose of this pilot was to observe device performance under authentic work conditions, including natural movement patterns, task transitions, and varying traffic and connectivity environments that cannot be fully replicated in controlled testing.

The operational pilot spanned from 9:00 a.m. on April 22 to 12:00 a.m. on April 30, 2025, covering multiple work shifts and overnight periods. Participants carried two commercial tracking devices, the Tile Pro and the LandAirSea GPS tracker, during normal work activities. Devices were not actively managed by the research team during this period, allowing evaluation of performance under realistic usage conditions, including variable charging behavior, movement frequency, and network availability.

Data collected during this pilot were analyzed using the same evaluation metrics applied in the controlled testing. While precise ground-truth labeling was not available for every movement, the pilot provided valuable insight into device reliability, data continuity, and operational practicality during real highway construction activities.

Together, the controlled research testing and the MoDOT volunteer operational pilot provided a comprehensive assessment of tracking technology performance. The controlled testing phase enabled systematic evaluation under known conditions, while the operational pilot captured realistic usage behavior and long-duration performance characteristics. Findings from both evaluation phases informed the device selection decisions and platform design refinements described in subsequent sections.

## 3.5 Assessment Results and Key Findings

This section summarizes the results of the technology and device field evaluations described in Section 3.4. The analysis focuses on the performance of candidate tracking devices with respect to accuracy and connection reliability, data availability and integration readiness, battery performance, and overall operational practicality in highway work zone environments. Results from both controlled research testing and the MoDOT volunteer operational pilot informed the findings presented below.

### 3.5.1 Accuracy and Connection Reliability

Accuracy and connection reliability were evaluated using horizontal position error, continuity of location reporting, frequency and duration of data gaps, and the ability of devices to recover from connectivity interruptions.

In the urban testing environment, all three GNSS-based devices, LandAirSea 54, Tracki, and Roadlytics, reported location coordinates that were consistent with known reference positions during both the smartphone-enabled and smartphone-disabled phases. Reported horizontal position errors remained within an acceptable range for work zone–level awareness, with the maximum observed error not exceeding 52 feet, and location updates were continuous throughout the test periods. LandAirSea and Tracki demonstrated effective motion-based power management, suspending transmissions when stationary and resuming reporting upon movement, which reduced unnecessary updates without compromising data continuity.

During the smartphone-enabled phase, the Tile Pro tracker also produced location reports consistent with the test subject's movement. However, when the smartphone was disabled, Tile Pro exhibited substantial degradation in accuracy and reporting continuity. Observed location deviations reached up to approximately 3,150 feet, and reporting became intermittent. These errors were attributed to passive detection by unrelated third-party devices participating in the Tile crowdsourced network rather than a persistent connection to the tracked device. Apple AirTag exhibited similar behavior under smartphone-disabled conditions, with observed location deviations of up to approximately 800 feet.

In the rural testing environment, LandAirSea and Tracki maintained continuous location updates despite weak or intermittent cellular coverage, demonstrating a high percentage of successful location reports and rapid recovery following brief signal degradation. In contrast, the Roadlytics device experienced a communication interruption of approximately 10 minutes while entering the rural test area, indicating sensitivity to extended cellular dead zones. Although the device resumed reporting once connectivity was restored, this interruption represents a measurable data gap under low-connectivity conditions.

Both the Tile Pro and Apple AirTag ceased producing location updates entirely in the rural environment once smartphone connectivity was removed and did not recover during the testing period. This result confirms that BLE-based trackers dependent on crowdsourced or smartphone-mediated networks lack the connection reliability required for deployment in rural or connectivity-challenged highway work zones.

These findings were reinforced during the MoDOT volunteer operational pilot conducted within active I-70 work zones at the Rocheport Bridge and Kingdom City projects. Although these work zones were located in rural areas, cellular coverage remained functional throughout the evaluation period. The LandAirSea device produced stable one minute location updates when in motion and showed no abrupt or unrealistic GNSS position jumps, so its dataset was used as the reference for comparison.

In contrast, Tile Pro devices reported locations only when opportunistically detected by nearby smartphones running the Tile application. Because participants did not pair Tile Pro with their smartphones, Tile Pro reporting was intermittent and often appeared as either prolonged gaps or bursts of multiple records within the same minute.

As shown in Figure 3-7, the separation distances between the two Tile Pro devices and the LandAirSea reference device were highly variable after temporal alignment of records. In some instances, Tile Pro and LandAirSea reported identical coordinates, resulting in a separation distance of zero, as reflected in the figure. However, these cases were intermittent and did not represent sustained tracking accuracy. Overall, the mean separation exceeded 1,500 feet, with occasional extreme errors reaching several miles, indicating substantial inconsistency in BLE-based location reporting. These results indicate that BLE trackers relying on crowdsourced smartphone networks do not provide temporally consistent or sufficiently accurate location reporting for worker presence detection in highway work zones.

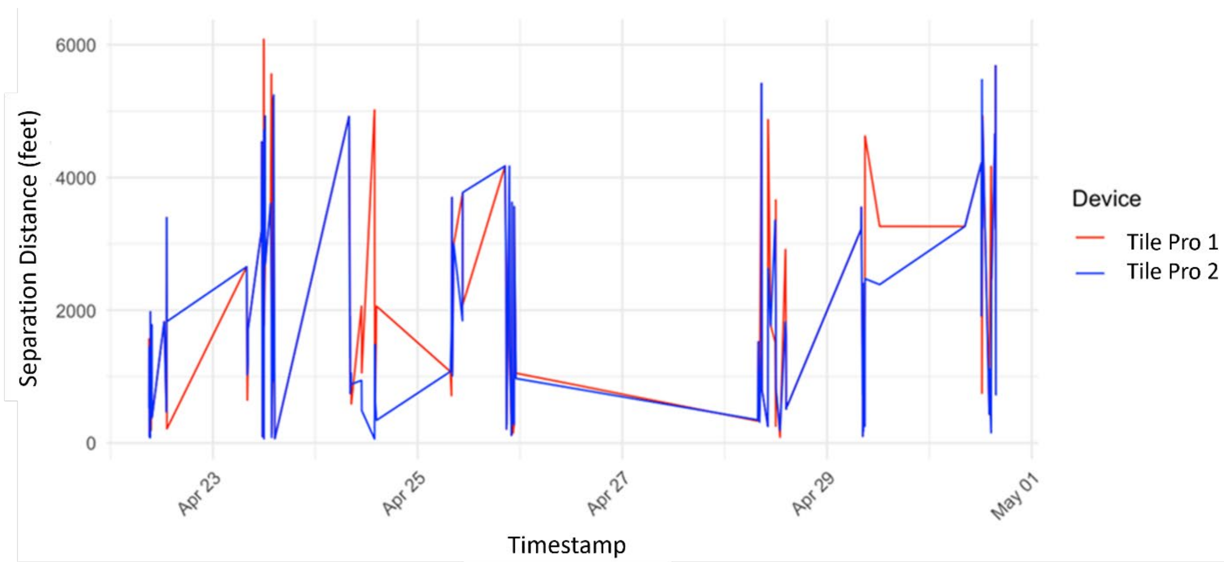


**Figure 3-7. Separation Distance between Tile Pro and LandAirSea 54**

### 3.5.2 Data Integration Capability

Data content and integration capability were assessed based on reporting frequency, availability of operational attributes, access to raw data, and compatibility with automated data processing and WZDx requirements.

LandAirSea and Tracki provide proprietary, web-based dashboards that support real-time tracking, historical playback, and battery status monitoring. Both platforms support data export, allowing latitude-longitude coordinates with timestamps to be extracted and ingested into the project data processing pipeline. These exported data streams enable automated processing and filtering for worker presence determination and downstream data sharing.

The Roadlytics device demonstrated the highest degree of integration flexibility. It provides direct, programmatic access to raw, time-stamped location data through a token-authenticated API. In addition to coordinates, the API exposes device status information such as battery level and network metrics, enabling automated data ingestion and system-level monitoring without reliance on proprietary user interfaces.

In contrast, the Apple AirTag and Tile Pro demonstrated significant limitations in data accessibility. AirTag location data are confined to the Apple "Find My" ecosystem and accessible only through registered Apple devices, with no public API or mechanism for exporting raw geodetic coordinates. Tile Pro similarly restricts data access to its consumer-facing application and does not provide third-party access to raw location data. As a result, both BLE-based devices were deemed incompatible with the data integration and WZDx sharing requirements of the worker presence system.

### 3.5.3 Operational Practicality and Battery Performance

Operational practicality was evaluated using observed setup requirements, user interaction needs, and measured battery performance under defined reporting configurations.

Battery performance varied substantially across devices and was influenced by both battery capacity and power management strategies. Measured operational durations under test conditions were as follows:

- LandAirSea 54 (1,500 mAh): Approximately 21 days and 8 hours of operation, supported by an effective motion-based sleep mode.
- Tracki (600 mAh): Approximately 8 days and 23 hours of operation, reflecting higher reporting frequency combined with limited battery capacity.
- Roadlytics (1,200 mAh): Approximately 9.5 hours of operation, corresponding to a high-frequency reporting configuration without an active sleep mode.
- Apple AirTag and Tile Pro: Manufacturer-estimated battery lifespans of approximately one year using non-rechargeable CR2032 coin cell batteries; however, these extended lifespans are achieved at the expense of continuous, independent location reporting.

GNSS-based devices required minimal user interaction beyond charging and initial deployment, whereas BLE-based devices required the presence of nearby mobile devices to maintain meaningful functionality. These findings underscore the importance of configurable reporting intervals and power management logic for achieving operationally viable battery performance in highway work zone deployments.

### 3.5.4 Cost-Effectiveness

Cost-effectiveness was evaluated using total cost of ownership metrics, including unit hardware cost, recurring subscription fees, and estimated annual operating cost per device. Costs varied significantly across devices and depended on selected service plans and contract durations.

GNSS-based devices generally incurred higher upfront and recurring costs but offered reliable standalone operation, access to raw data, and compatibility with automated data integration and WZDx requirements. BLE-based devices offered lower initial hardware costs and minimal recurring fees; however, their limited functionality, dependence on external mobile networks, and lack of data accessibility significantly constrained their applicability for MoDOT work zone deployments.

A detailed cost comparison for all five candidate devices is presented in Table 3-1, summarizing hardware costs, subscription fees, and estimated long-term operational expenses relevant to potential MoDOT deployment scenarios.

**Table 3-1. Annual Unit Cost Summary**

| Cost Category | LandAirSea | Tracki | Roadlytics | AirTag | Tile Pro |
|---|---|---|---|---|---|
| Device Price (1 unit) | $29.95 | $9.88 | $149.99 | $29.00 | $34.99 |
| Monthly Sub. (per unit) | $19.95/mo or $179.95/yr (3-min sync) | $19.95/mo or $167.40/yr (1-min sync) | $14.99/mo | $0.00 | $2.99/mo or $29.99/yr |
| 1-Year Total Cost | $209.90 | $177.28 | $329.87 | $29.00 | $64.98 |

### 3.5.5 Key Findings

The device evaluation produced three findings that directly shaped the next phase of this study. First, GNSS-based tracking devices with dedicated communication provided the most consistent reporting continuity across smartphone enabled and smartphone disabled conditions, and they remained operationally usable in rural environments where crowdsourced detection is limited. Second, BLE based devices that depend on third-party smartphones showed fundamental limitations in reporting continuity and location validity. Their performance degraded substantially when smartphones were not available, which is inconsistent with MoDOT operational constraints and rural work zone conditions. Third, practical deployment feasibility depends not only on accuracy but also on scalable data access and recurring cost structure. Devices that restrict raw data access or require a separate cellular subscription per unit create barriers to large scale deployment and automated processing.

Together, these findings motivated development of the WZ Gateway Node prototype. The prototype was intended to preserve the reporting reliability and data content advantages observed in GNSS based solutions while reducing recurring per device communication costs and ensuring direct access to raw, time-stamped data needed for downstream activity classification and false positive avoidance.

## 3.6 Prototype Device: WZ-Gateway Node

To address the limitations identified in commercial tracking solutions, specifically high recurring subscription costs, reliance on proprietary cellular ecosystems, and restricted access to raw data, this study developed a customized tracking prototype referred to as the WZ-Gateway Node. The prototype was designed to support worker presence determination using streamlined hardware architecture and open-source software, providing a scalable and transparent alternative for research and potential future deployment.

Rather than optimizing consumer-facing features, the WZ-Gateway Node prioritizes data accessibility, flexible communication, and cost efficiency. The design reflects the project's emphasis on deriving reliable worker presence information at the work zone level while maintaining control over data ownership and workflow integration.

### 3.6.1 Hardware Architecture and Components

The WZ-Gateway Node was constructed using modular, commercially available components selected to provide accurate location data with minimal hardware complexity. The primary components include the following:

1. Microcontroller and Connectivity: A Teyleten Robot ESP32-C3 development board serves as the central processing unit. The board provides integrated Bluetooth and Wi-Fi capabilities, enabling wireless data transmission without the need for an embedded cellular modem.

2. Satellite Positioning: The device utilizes a GPS mode of ATGM336H positioning module. Multi-constellation support improves location reliability in open highway environments and supports lane-level positioning accuracy suitable for worker presence determination.

3. Power System: Power is supplied by a 3.7 V, 2,000 mAh lithium polymer battery manufactured by EEMB. A TP4057 charging and discharging board manages battery charging and power regulation during field operation.

4. Manual Control: A micro slide switch is integrated into the hardware to allow manual activation and deactivation of the device during field testing, supporting controlled deployment and data collection.

### 3.6.2 Software Design and Integration

The system architecture of the WZ-Gateway Node was developed to address two primary needs identified during the evaluation of commercial tracking solutions: reducing recurring operational costs and ensuring full access to tracking data for platform-level processing. These objectives guided both the communication strategy and the software design of the prototype.

Rather than relying on embedded cellular modems that require individual service subscriptions for each tracking unit, the WZ-Gateway Node uses Wi-Fi–based communication. Each device connects to a shared MiFi unit or mobile hotspot, allowing multiple nodes to transmit data through a single communication gateway. This shared-connectivity model significantly reduces ongoing communication costs and improves scalability when deploying multiple devices within a single work zone or across multiple sites.

Custom firmware was developed to enable direct transmission of location and status data to a secure server or cloud endpoint. This approach eliminates dependence on proprietary vendor dashboards and enables seamless integration with the Work Zone Data Exchange framework and ensures consistency between device-level reporting and platform-level processing.

The open-source software architecture further ensures full access to raw, time-stamped location and speed data generated by the device. This level of data accessibility is essential for implementing platform-based activity classification logic, evaluating reporting latency, and minimizing false-positive worker presence indications. It also provides flexibility for future algorithm refinement and system enhancement without constraints imposed by closed-source systems.

Through a limited pilot test, the WZ-Gateway Node validated the feasibility of a shared-connectivity, open-data architecture for deriving reliable worker presence information. During platform evaluation, multiple WZ-Gateway Nodes successfully transmitted time-stamped location data through a single MiFi gateway with consistent reporting and acceptable latency, supporting accurate worker presence determination at the work zone level. The prototype provides a flexible foundation for continued system refinement and future deployment.

### 3.6.3 Deployment Architecture and Cost Considerations

The WZ-Gateway Node was designed to support practical deployment in highway work zones using a shared communication architecture rather than individual cellular subscriptions for each worker-worn device. In the proposed configuration, multiple WZ-Gateway Nodes operate concurrently within a work zone and transmit device-level location data to a single mobile gateway using Wi-Fi connectivity. A commercially available MiFi device (e.g., Inseego MiFi Jetpack 8800L) functions as the communication gateway, aggregating data from all nodes and forwarding it to the backend server through one cellular connection. This architecture reflects common field communication practices and avoids the operational complexity of managing multiple SIM cards or service plans.

For cost comparison, a representative crew size of eight workers is assumed. Under the WZ-Gateway Node deployment model, a single MiFi unit is assigned per crew, with an initial hardware cost of approximately $99 and a recurring monthly service fee of $20. Each worker is equipped with a WZ-Gateway Node with an estimated material cost of $36 per unit. Because all devices share one cellular connection, recurring communication costs remain constant regardless of the number of workers, resulting in a low per-worker operating cost as deployment scales.

In contrast, commercial GNSS-based solutions such as LandAirSea 54, Tracki, and Roadlytics rely on a one-device–one-subscription model. When applied to an eight-person crew, each device requires its own cellular service plan, leading to substantially higher recurring costs. While these devices offer mature vendor-supported platforms, their subscription-based cost structure presents challenges for long-term or multi-site deployment where worker presence detection may be needed across many concurrent work zones.

Table 3-2 summarizes the estimated first-year cost comparison across evaluated devices for an eight-person crew. Hardware and subscription costs reflect typical service plans used during this study and are intended to illustrate relative cost differences rather than exact procurement pricing.

**Table 3-2. Estimated First-Year Cost Comparison for an Eight-Person Crew**

| Device | Hardware Cost (Initial) | Communication Cost (Annual) | Total First-Year Cost |
|---|---|---|---|
| WZ-Gateway Node + MiFi (8 devices, 1 gateway) | $387 (8 × $36 + $99) | $240 (1 × $20/mo) | $627 |
| LandAirSea 54 (8 devices) | $240 (8 × $29.95) | $1,440 (8 × $179.95/yr) | $1,680 |
| Tracki (8 devices) | $79 (8 × $9.88) | $1,339 (8 × $167.40/yr) | $1,418 |
| Roadlytics (8 devices) | $1,200 (8 × $149.99) | $1,439 (8 × $14.99/mo) | $1,418 |

By decoupling device hardware from cellular service and centralizing communication through a shared gateway, the WZ-Gateway Node approach substantially reduces recurring costs while preserving access to time-stamped location and speed data. When deployed across multiple crews or over multi-year maintenance programs, the shared-gateway architecture provides substantial long-term cost savings compared to per-device subscription models.

This deployment model also simplifies provisioning, reduces administrative overhead, and supports flexible scaling as crew sizes or work zone configurations change. The combined implementation and cost analysis demonstrates that the WZ-Gateway Node provides a viable, cost-efficient alternative for MoDOT-led deployment where affordability, scalability, and data ownership are critical considerations.

## 3.7 Device Selection Summary

Based on the evaluation results presented in Section 3.5, the candidate location tracking devices were assessed for suitability in supporting worker presence detection in Missouri highway work zones. The comparative evaluation matrix shown in Table 3-3 summarizes device performance across accuracy and connection reliability, data content and integration capability, operational practicality, and cost-effectiveness.

**Table 3-3. Comparative Evaluation Matrix for Candidate Location Tracking Devices**

| Criteria | LandAirSea | Tracki | Roadlytics | WZ-Gateway Node | AirTag | Tile Pro |
|---|---|---|---|---|---|---|
| Accuracy & Connection Reliability | ★★★★★ | ★★★★★ | ★★★★☆ | ★★★★☆ | ★★☆☆☆ | ★★☆☆☆ |
| Data Content & Integration Capability | ★★★★☆ | ★★★★☆ | ★★★★★ | ★★★★★ | ★☆☆☆☆ | ★☆☆☆☆ |
| Operational Practicality | ★★☆☆☆ | ★★★★☆ | ★★★☆☆ | ★★★☆☆ | ★★★★☆ | ★★★★☆ |
| Cost-Effectiveness | ★★★☆☆ | ★★★☆☆ | ★★☆☆☆ | ★★★★★ | ★★★★★ | ★★★★★ |
| Overall Suitability | ★★★★☆ | ★★★★☆ | ★★★☆☆ | ★★★★☆ | ★★☆☆☆ | ★★☆☆☆ |

Based on the evaluation results summarized in Section 3.5, BLE-based tracking devices were not selected for continued evaluation in this study. Apple AirTag and Tile Pro did not meet the reliability and data accessibility requirements for worker presence determination under MoDOT operational conditions, particularly in smartphone-restricted and rural environments.

Among the GNSS-based devices evaluated, Tracki and the WZ-Gateway Node were identified as suitable candidates for continued evaluation based on their overall performance and operational fit. Tracki provided stable location reporting across both urban and rural test environments and supported data export needed for downstream processing. Although its battery life is more limited than that of fleet-oriented devices, its compact form factor, light weight, and flexible mounting options make it practical for worker-worn use during routine field activities. The WZ-Gateway Node complements this capability by offering a configurable, low-cost architecture with full access to device-level location data and reduced reliance on per-device communication subscriptions. Together, these devices supported continued platform-level evaluation.

The LandAirSea 54 GNSS tracker demonstrated strong performance in terms of durability, accuracy, connection reliability, and battery life. However, due to its relatively larger size and heavier weight, the device was not considered suitable for routine worker-worn deployment during daily field activities. Instead, LandAirSea is more appropriately positioned for vehicle-, equipment-, or fleet-based tracking applications within work zones. While it is not advanced for worker-worn evaluation in this study, it is highly recommended for asset and vehicle management use cases where durability and long battery life are prioritized.

The Roadlytics device was identified as a highly flexible tracking solution with strong data accessibility and integration capabilities, enabled by its streamlined firmware and open-access API. These characteristics make it well suited for research and system development purposes. However, the relatively high unit cost of the device limits its practicality for large-scale deployment across multiple projects or districts. As a result, Roadlytics was not selected for continued large-scale evaluation, but its architectural flexibility informed subsequent system design decisions.

Collectively, the device evaluation demonstrated that while commercial GNSS-based trackers can provide reliable location data, no single off-the-shelf solution fully satisfies the combined requirements of wearability, cost scalability, data transparency, and operational flexibility needed for worker presence applications. These findings motivated the development of a customized tracking prototype and informed the design of a platform-level approach for deriving worker presence at the work zone level. The system architecture and processing framework developed to support this approach are described in Section 4.

# 4. System Architecture and WZDx Integration Framework

Worker presence determination in this project was implemented within the MU Worker Presence Platform as an enrichment of the WZDx WorkZoneFeed, rather than as a publicly published device-based feed. Although real-time location data originated from tracking devices and were conceptually aligned with a WZDx DeviceFeed, these device-level data were used internally only. They were processed to derive worker presence indicators that enriched MoDOT's authoritative WorkZoneFeed, preserving data ownership, privacy, and WZDx compatibility.

As shown in Figure 4-1, the MU Worker Presence Platform was developed as a centralized system to ingest authoritative work zone data and supplemental device-based location data, apply spatial and temporal logic to determine worker presence, and publish an enriched WZDx-compatible work zone feed. The platform followed a retrieve–analyze–publish architecture designed to support real-time operations, scalability, and secure data governance while aligning with MoDOT traveler information and data-sharing practices.

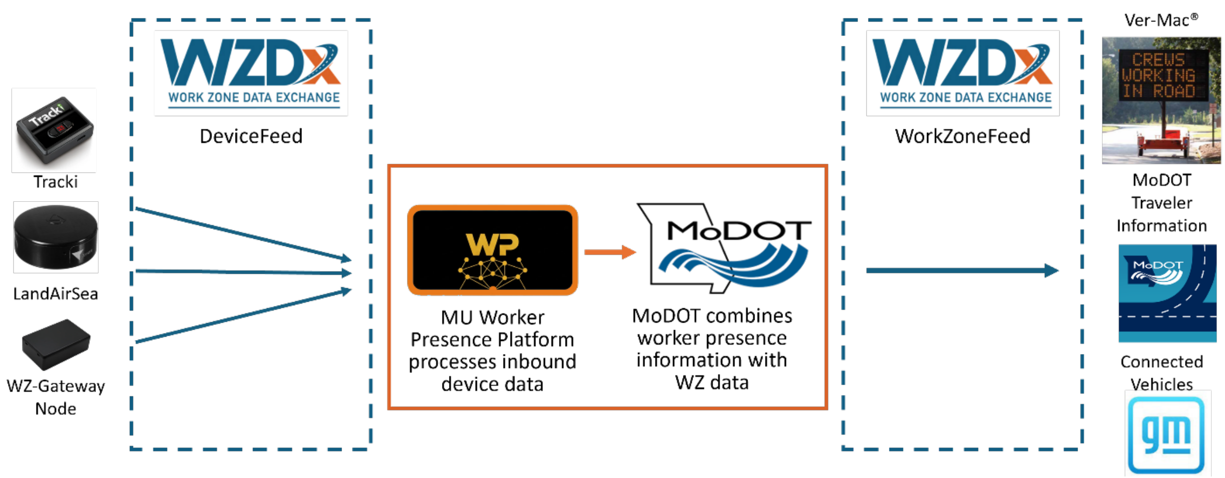


**Figure 4-1. System Architecture and WZDx Integration Plan**

## 4.1 Authoritative Work Zone Data Source

Authoritative work zone information was retrieved from the MoDOT Traveler Information Map through an ArcGIS REST service. This dataset served as the primary source of truth for active highway work zones across Missouri and provided the spatial geometry and descriptive metadata required to contextualize worker presence determination.

Work zone features were represented as line or polygon geometries and were categorized into three operational classes: Closed, Expect Delays, and Possible Delays. For each work zone, the following attributes were ingested and stored locally by the platform:

- TRAVELWAY_NAME: Highway identifier (e.g., I-70, US 63)
- DIRECTION: Affected traffic direction

- COUNTY_NAME: Jurisdictional county
- START_DATE / END_DATE: Temporal validity period
- WORK_TYPE: Type of construction or maintenance activity
- STATUS: Operational status (e.g., CLOSED)
- DESCRIPTION: Textual explanation of the activity or restriction
- EVENT_ID: Unique identifier linking the work zone to MoDOT internal systems

To maintain data currency while minimizing system overhead, synchronization with the Traveler Information Map was performed at scheduled intervals (e.g., every 12 hours). This approach ensured that the platform reflected current statewide work zone conditions without duplicating authoritative data management responsibilities.

## 4.2 Supplemental Worker Location Data Sources

Supplemental worker location data were collected from the tracking devices selected in Section 3, Tracki and the prototype WZ-Gateway Node. These devices transmitted time-stamped geographic coordinates representing the movement and position of workers in the field.

Raw location updates were polled at one-minute intervals and normalized into a standardized GeoJSON structure containing the device identifier, timestamp (Coordinated Universal Time [UTC]), latitude, longitude, and speed. This normalization ensured consistent handling of data from devices with differing data schemas and prepared the data for automated spatial analysis. Device-level location data were used exclusively for internal processing within the MU Worker Presence Platform and were not published as a standalone device feed.

## 4.3 Worker Presence Determination Logic (Derived WZDx Attributes)

The core analytical function of the MU Worker Presence Platform was the derivation of worker presence indicators associated with active work zones. This function was implemented through a spatial processing engine hosted on a secure university server and was aligned with WZDx practices for generating derived attributes.

### 4.3.1 Spatial Buffer-Based Detection

As illustrated in Figure 4-2, the platform generated a 200-foot total spatial buffer for each active work zone by applying a 100-foot lateral offset to either side of the centerline. This threshold was established to encompass the full right-of-way, accounting for roadway geometry variability and adjacent staging areas. Additionally, the buffer mitigated the risk of false negatives resulting from positional drift or signal degradation—challenges particularly prevalent in urban environments due to urban canyon effects and multi-path interference.

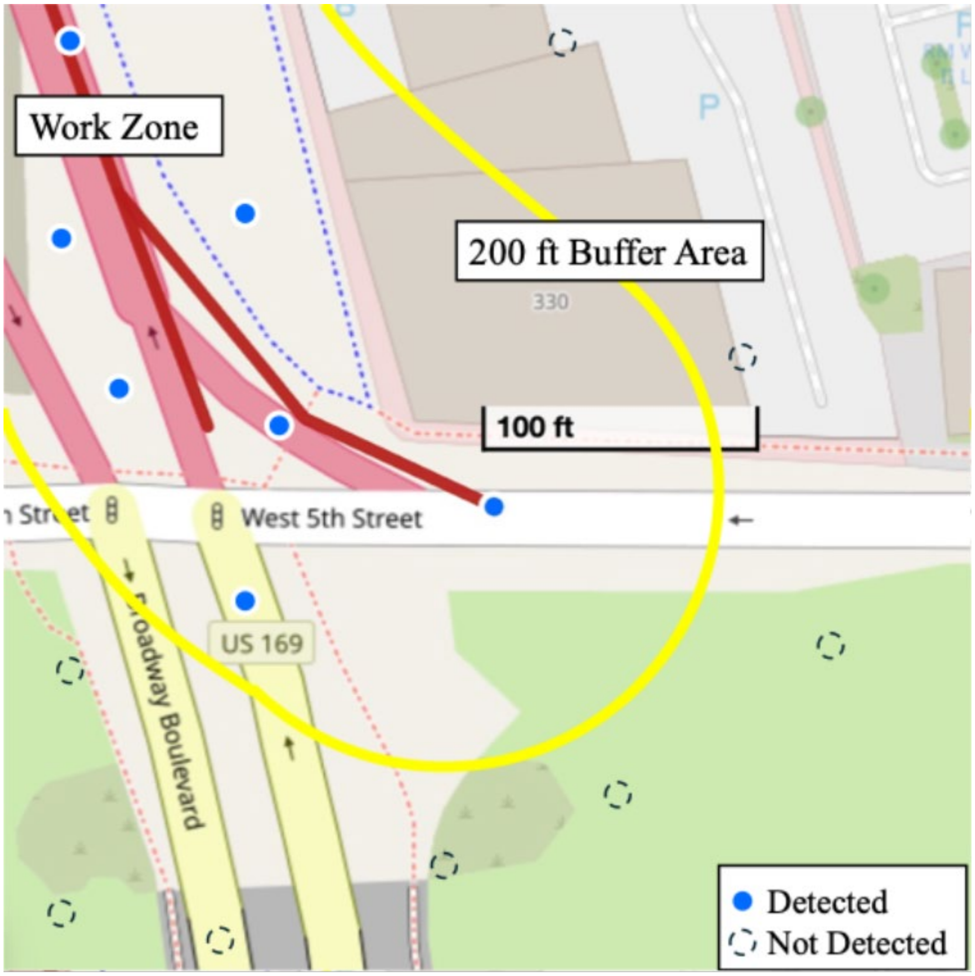


**Figure 4-2. Example of 200-foot Spatial Buffer Zone**

While 200 feet served as the standard baseline, the platform allowed this parameter to be modified on a case-by-case basis or adjusted for specialized work zone configurations in the future. Consequently, any tracking device reporting coordinates within the designated buffer radius was classified as spatially associated with that work zone.

### 4.3.2 Speed-Based Activity Classification

While spatial proximity to a work zone was a necessary condition for worker presence, it was not sufficient on its own to reliably identify active work activities. In practice, highway workers may travel through active work zones for commuting, staging, or repositioning purposes without performing maintenance or construction tasks. If all device detections within the work zone buffer were treated as worker presence, these scenarios could result in false-positive indications.

To implement speed-based activity classification, the MU Worker Presence Platform utilized device-reported velocity when available, as most GNSS-based tracking devices provided instantaneous speed estimates derived from satellite positioning. For devices that did not natively report speed, velocity was computed internally using successive time-stamped location updates. In both cases, a speed threshold of 30 mph was applied to classify device activity state.

This threshold reflected typical operational characteristics of highway work activities, including mobile pavement and maintenance operations, which are generally performed at low speeds or under stop-and-go conditions. Sustained speeds above 30 mph were more consistent with normal traffic flow or commuting behavior rather than active work. Devices reporting speeds greater than 30 mph were classified as Transit or Passing, indicating that the device was likely associated with a worker commuting through the work zone or with a vehicle traversing the corridor without active work involvement. Devices classified as transit were excluded from worker presence determination.

While 30 mph served as the standard baseline, the platform supports configurable speed thresholds that may be applied systemwide or tailored to individual work zones to accommodate specialized operations and future requirements.

## 4.4 WZDx Feed Augmentation and Publication

Following worker presence determination, the MU Worker Presence Platform generated an enriched WZDx-compatible WorkZoneFeed that augmented MoDOT's authoritative work zone data with dynamic worker presence information. Consistent with WZDx design principles, the platform preserved the original work zone geometries and core attributes and appended worker presence as derived attributes rather than publishing device-level location data.

Worker presence was expressed at the work zone level to ensure that the resulting feed remained actionable for traveler information systems, traffic management centers, and connected vehicle applications. This approach eliminated the need for downstream users to perform additional spatial joins or interpret raw device data and ensured that worker presence information could be readily consumed alongside existing WZDx attributes.

For each active work zone feature, the following derived attributes were generated:

- workers_present (Boolean):

Indicates whether at least one device classified as an Active Worker (speed $\leq$ 30 mph) is detected within the work zone buffer.

- first_worker_detected (Timestamp):

Records the timestamp when worker presence was first identified for the current work zone event.

- worker_not_detected_from (Timestamp):

Records the timestamp corresponding to the most recent worker detection; this value is updated when worker presence is no longer observed.

- description (String):

Provides a human-readable summary that combines roadway context and detected activity (e.g., “Worker Present: WZ-Gateway Node (3.5 mph)”), supporting downstream interpretation by traveler information systems and data consumers.

The enriched WorkZoneFeed was refreshed at a fixed interval (e.g., every 60 seconds) to balance near real-time responsiveness with system stability.

## 4.5 Visualization and Quality Assurance Interface

A web-based visualization interface was developed as part of the MU Worker Presence Platform to support real-time monitoring, verification, and quality assurance of worker presence detection logic. The interface was intended for internal use by researchers and agency partners and was not designed as a public-facing application.

As shown in Figure 4-3, the interface—developed using the Leaflet.js mapping library—provided a spatially explicit view of platform operations. This allowed users to validate both spatial detection accuracy and speed-based activity classification. Key components included:

- Map Visualization:

Active work zones are rendered as color-coded geometries reflecting traffic impact severity: red (Closed), orange (Expect Delays), and yellow (Possible Delays). Tracking devices are displayed only when they enter a work zone buffer. Within the buffer, devices classified as Active Workers are shown as blue markers, while devices classified as Transit or Passing are shown as gray markers. This visual distinction supports rapid verification of classification logic.

- Work Zone Status Dashboard:

A dynamic side panel lists all active work zones retrieved from the MoDOT Traveler Information Map and displays a binary worker presence indicator—O (Worker Present) or X (Worker Not Present)—based on the most recent analysis.

- Device Registry:

A registry panel lists all tracking devices currently reporting to the platform, including the most recent update timestamp and detected work zone association. Devices that are reporting but not currently associated with any work zone are explicitly identified, enabling operators to distinguish between connectivity issues and legitimate off-zone activity.

- Latency and Time Window Controls:

Adjustable historical look-back windows (1, 10, 30, or 60 minutes) allow users to visualize recent or last-known device locations. This capability supports diagnostic review in rural or connectivity-challenged environments where intermittent latency may occur.

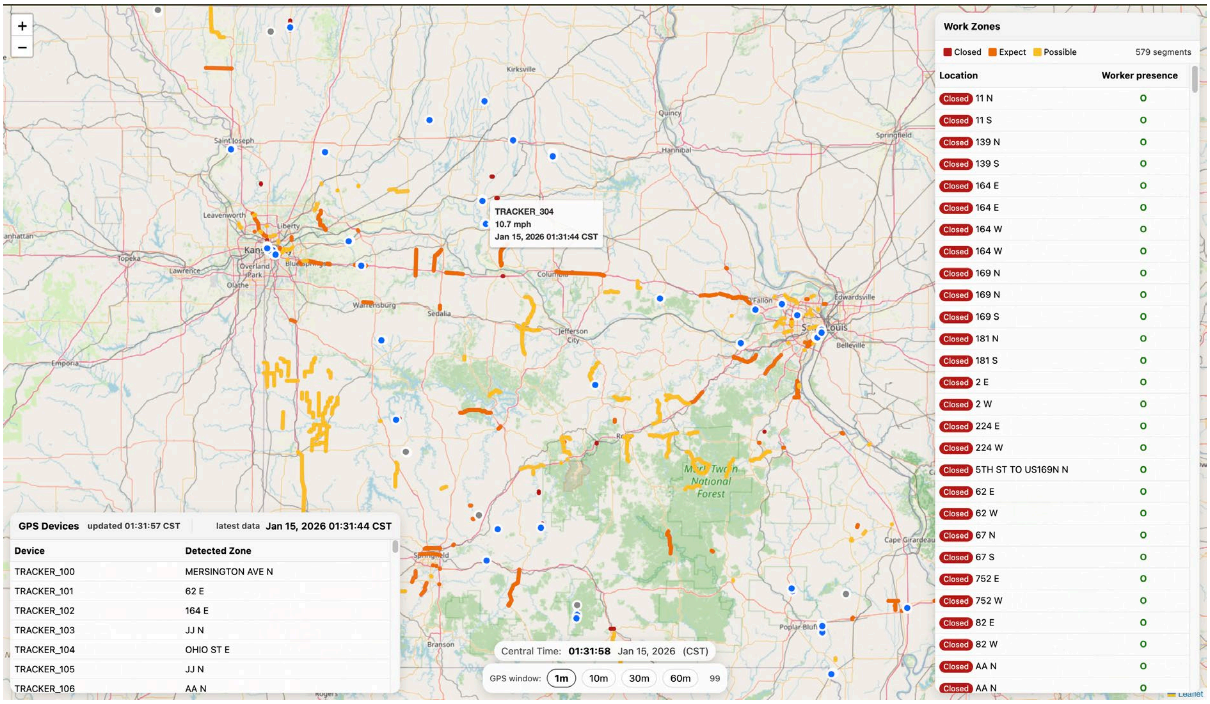


**Figure 4-3. MU Worker Presence Platform Interface**

In addition to supporting worker presence verification and quality assurance, the internal visualization interface provided a flexible foundation for future operational applications. With additional system design and validation, the interface could be extended to support incident management activities, project-level monitoring, and integration with work zone intrusion detection systems. For example, incident management staff could use the interface to quickly confirm field conditions during reported events, while project managers could leverage aggregated activity patterns to support coordination and oversight. Similarly, real-time device detections could be integrated with intrusion detection logic to support automated alerts for unauthorized vehicle entry into active work zones. At present, these functions have not been implemented and would require further system development, operational testing, and stakeholder input to ensure reliability and alignment with MoDOT workflows.

## 4.6 Data Governance, Security, and Privacy Architecture

Data governance, security, and privacy considerations were integral to the design of the MU Worker Presence Platform, particularly given the use of worker-associated location data. The platform was explicitly designed to align with MoDOT policy, WZDx guidance, and best practices for workforce data protection.

The system enforced a one-way data ingestion architecture, in which device-based tracking data flowed into the platform but could not be queried, modified, or accessed externally. Both the visualization interface and the enriched WZDx output feed operated in a read-only capacity, preventing external manipulation of source data.

To further protect worker privacy, device locations were processed and visualized only when they fall within defined work zone buffers. Location data outside these buffers were suppressed and were neither displayed nor published. This spatial masking ensured that commuting behavior, off-duty movements, and non-operational travel were not exposed through the platform.

By publishing worker presence exclusively as a derived work zone–level attribute, rather than as individual device locations, the MU Worker Presence Platform preserved worker anonymity while still providing meaningful, actionable information to downstream WZDx consumers. This approach ensured that the system supports improved work zone awareness without introducing new privacy or data ownership concerns.

# 5. Platform Evaluation

This section presents the field evaluation activities conducted to assess the performance of the **MU Worker Presence Platform** under real-world operating conditions. The evaluation focused on validating worker presence detection logic, examining system behavior across common work zone activity patterns, and assessing platform robustness when ingesting and processing tracking data over an extended period. The results provide practical evidence of the platform's ability to enrich WZDx WorkZoneFeeds with reliable worker presence information while minimizing false-positive reports.

## 5.1 Platform Evaluation Overview

Field evaluation was conducted over an extended period from October 27 through January 3, allowing the MU Worker Presence Platform to be tested across varying traffic conditions, work zone configurations, and operational contexts. Data collection occurred within active highway work zones along I-70 and US-63.

A total of four tracking devices were deployed during the evaluation period, including WZ-Gateway Nodes and Tracki. During the field evaluation period, the research team conducted a total of 24 field trips in November and December to examine worker presence detection under controlled yet realistic conditions.

## 5.2 Evaluation Scenarios

Field evaluation activities were structured around two representative operational scenarios commonly observed in highway work zones. These scenarios were used to examine the effectiveness of the platform's spatial buffering and speed-based activity classification logic under realistic conditions.

- Stationary Construction and Maintenance Activities

This scenario represents workers performing fixed-location tasks within a work zone, such as construction, equipment operation, or localized maintenance. Devices remained within limited spatial areas for extended periods, allowing evaluation of the platform's ability to maintain continuous worker presence detection with limited movement.

- Pass-Through and Commuting Movements:

This scenario represents workers traveling through active work zones without engaging in work activities, such as commuting between sites or repositioning vehicles. Devices exhibited higher travel speeds through work zones, allowing evaluation of the speed-based activity classification logic designed to suppress false-positive worker presence indications.

During the field evaluation period, the research team conducted a total of 24 field trips in November and December to examine worker presence detection under controlled yet realistic conditions. Of these trips, 12 were designed to simulate stationary construction activities. In these scenarios, a team member wearing a tracking device remained stationary near an active work zone in a safe and controlled manner for approximately 20–30 minutes per trip. Locations included commuter parking areas adjacent to work zones or outer roadways positioned approximately 30 feet from the edge of the construction area, ensuring proximity representative of active work while maintaining safe separation from live traffic.

The remaining 12 trips were conducted as pass-through scenarios, in which a team member traveled through the same work zones at normal prevailing traffic speeds (typically 55–70 mph, depending on the corridor). Each pass-through trip lasted approximately 2–5 minutes, depending on work zone length and traffic conditions. These trips were designed to represent commuting or non-working movements through active work zones.

Across the evaluation window, more than 40,000 GPS records were collected, transmitted, and processed by the platform. Across all trips, tracking devices reported location and speed data at regular intervals, generating multiple observations per minute for each scenario. These data were ingested by the MU Worker Presence Platform in near real time, spatially associated with authoritative MoDOT work zone geometries, and processed to determine worker presence status at the work zone level.

## 5.3 Platform Evaluation Results

The field evaluation results are summarized in Table 5-1. The Ground Truth Condition reflects whether workers were actively present in the work zone, while the Platform Classification indicates the worker presence status generated by the system for the same interval. The Result column classifies each comparison as a true positive, true negative, false positive, or false negative. A true positive occurs when active workers are correctly identified, and a true negative occurs when the absence of workers is correctly indicated. False positives represent instances where worker presence is incorrectly reported, while false negatives indicate missed detections when workers are present. The Results column therefore reflects the correctness of each worker presence determination.

**Table 5-1. Field Evaluation Results**

| Device Used | Ground Truth Condition | Platform Classification | Result Types | Results | Average time to report |
|---|---|---|---|---|---|
| Tracki | Worker actively present near work zone | Worker Present | True Positive | 6 of 6 | 2.1 min. |
| WZ-Gateway Node | Worker actively present near work zone | Worker Present | True Positive | 6 of 6 | 4.3 min. |
| Tracki | Worker actively present near work zone | Worker Not Present | False Negative | 0 of 6 | n/a |
| WZ-Gateway Node | Worker actively present near work zone | Worker Not Present | False Negative | 0 of 6 | n/a |
| Tracki | Worker transitioning / no active work | Worker Present | False Positive | 1 of 6 | 2 min. |
| WZ-Gateway Node | Worker transitioning / no active work | Worker Present | False Positive | 1 of 6 | 3 min. |
| Tracki | Worker transitioning / no active work | Worker Not Present | True Negative | 5 of 6 | n/a |
| WZ-Gateway Node | Worker transitioning / no active work | Worker Not Present | True Negative | 5 of 6 | n/a |

Across both device types, all stationary worker activities were correctly identified, resulting in 12 true positives and no false negatives. However, worker presence status was typically updated 2–6 minutes after workers entered or exited work zones. This delay is attributable to a combination of device reporting intervals, platform processing cycles (configured at 60 seconds), and network latency. The delay was more pronounced for the WZ-Gateway Node, which relies on MiFi or cellular hotspot connectivity, compared to the Tracki device, which includes a dedicated cellular communication module.

Two false-positive classifications were observed during pass-through scenarios. These cases occurred when traffic speeds dropped below the defined 30 mph threshold within the 200-foot work zone buffer, causing pass-through vehicles to temporarily meet the platform's criteria for active worker presence. This outcome reflects a deliberate design choice favoring conservative detection to minimize missed worker presence, with false positives occurring primarily under congested traffic conditions.

Overall, field observations demonstrated that the platform reliably detected worker presence during both stationary and mobile work activities while correctly excluding pass-through movements that exceeded the defined speed threshold. These results confirm that the combined use of spatial buffering and speed-based activity classification is effective for distinguishing active work from transit behavior in operational highway environments. However, due to the presence of false-positive results, additional mitigation strategies, such as temporal persistence logic and work zone-level aggregation, were incorporated. The details are discussed in Section 6.1.

## 5.4 Scalability Assessment

While the field evaluation generated more than 40,000 GPS records over the evaluation period, this volume reflects realistic deployment conditions rather than a stress test of system capacity. For context, a hypothetical large-scale deployment involving 300 tracking devices reporting once per minute over an eight-hour work shift would generate approximately 144,000 records in a single day (300 devices × 60 minutes × 8 hours). Higher reporting frequencies would increase data volumes proportionally.

To assess the scalability of the MU Worker Presence Platform under such conditions, the system was tested against high-volume synthetic data streams designed to exceed expected field deployment loads. During this assessment, the platform successfully ingested and processed data from more than 300 simultaneous synthetic trackers reporting at a frequency of one update per second, representing a substantially higher data rate than anticipated under normal operations.

Under these conditions, the backend spatial processing loop maintained stable execution times and consistently refreshed the enriched WZDx WorkZoneFeed at the configured 60-second update interval without observable latency degradation or processing backlogs. These results demonstrate that the platform architecture can scale to support dense device deployments, higher reporting frequencies, and concurrent work zones without compromising data timeliness or system stability.

## 5.5 Summary of Evaluation Findings

The field evaluation and system performance assessment demonstrated that the MU Worker Presence Platform is capable of reliably detecting and reporting worker presence in highway work zones under realistic operating conditions. Across an extended evaluation period spanning multiple corridors, device types, and operational scenarios, the platform consistently integrated device-based location data with authoritative MoDOT work zone geometries to generate accurate worker presence indicators.

Field-based testing confirmed that the combined use of spatial buffering and speed-based activity classification effectively distinguishes active work activities from pass-through or commuting movements. The platform successfully detected worker presence during both stationary operations. These results validate the core logic used to derive worker presence at the work zone level.

Scalability testing further demonstrated that the platform architecture can support substantially higher data volumes than those observed during field deployment. The system maintained stable processing behavior and timely WZDx feed updates when ingesting data from hundreds of simultaneous devices reporting at high frequencies. This confirms that the platform is suitable for expanded deployment across multiple concurrent work zones and larger device fleets without compromising performance or data timeliness.

# 6. Discussion and Implementation Consideration

This section discusses key design decisions, tradeoffs, and implementation considerations associated with worker presence determination in highway work zones. The discussion focuses on how technical findings, operational constraints, and policy considerations informed system architecture and deployment strategies, rather than reiterating evaluation results.

## 6.1 Negative-Positive Avoidance

In this research, greater emphasis was placed on preventing false-positive worker presence reports than on eliminating all potential false negatives. This prioritization reflects how motorists perceive and respond to work zone information. If drivers repeatedly encounter messages indicating worker presence but do not visually observe workers in the work zone, they may begin to question the reliability of the information and disregard future warnings. Over time, this loss of trust can reduce the effectiveness of worker presence messaging and undermine broader Smart Work Zone safety objectives. By contrast, the impacts of short delays or occasional false-negative reports are comparatively limited. A brief delay in detecting worker presence typically affects only a narrow time window and does not fundamentally alter driver expectations. Similarly, a missed detection during a transitional period, such as when workers are entering or exiting the work zone, poses less risk to system credibility than persistent false-positive messaging.

To further reduce false-positive reporting, the MU Worker Presence Platform incorporated two additional platform-level strategies beyond spatial buffer–based detection and speed-based activity classification:

- **Temporal Confirmation and Persistence Logic**

Worker presence was not triggered by a single location report. Instead, presence was confirmed through consecutive detections within the work zone over a defined three-minute time window, during which the device remained inside the buffered area and operated at low speed. Similarly, worker presence was cleared only after a sustained three-minute absence was observed. This temporal smoothing approach reduced transient false positives caused by brief stops or positioning noise.

- **Work Zone-Level Aggregation**

Presence was published as a work zone-level attribute rather than at the device level. This aggregation allowed the platform to consider multiple devices and movement patterns collectively, reducing the likelihood that a single anomalous device report will trigger a false-positive condition.

## 6.2 Device Selection Tradeoffs

The evaluation of candidate tracking technologies revealed that device selection for worker presence applications involves multiple tradeoffs among accuracy, operational practicality, cost, and data accessibility. These tradeoffs directly influenced both the system architecture of the

MU Worker Presence Platform and the recommended deployment strategy.

From a technical standpoint, GNSS-based tracking devices demonstrated clear advantages over proximity-based technologies in highway work zone environments. Their ability to operate independently of fixed roadside infrastructure and crowdsourced networks makes them better suited for large linear work zones, rural corridors, and mobile maintenance operations. In addition, GNSS devices provide direct access to speed and time-stamped location data, which is critical for activity classification and for reducing false-positive worker presence indications.

However, not all GNSS devices are equally suitable for worker presence applications. Devices designed primarily for fleet or asset tracking tend to be larger and heavier and are optimized for vehicle mounting rather than continuous worker-worn use. While such devices offer durability and extended battery life, their form factor may limit practicality for daily deployment on field personnel. Conversely, smaller personal tracking devices offer improved wearability but typically rely on reduced battery capacity or aggressive power management strategies. As a result, these devices may require more frequent charging, introducing additional effort for workers to maintain device operation on a regular basis and potentially affecting reporting frequency and temporal resolution.

Cost considerations further complicate device selection. Commercial off-the-shelf solutions that provide robust data access and long-term support services may be costly when scaled across multiple work zones or extended deployment periods. In addition to initial hardware costs, recurring subscription fees and cellular data charges can significantly influence total cost of ownership. These factors motivated exploration of alternative architectures that separate sensing, communication, and data processing functions. For example, the WZ-Gateway Node architecture reduces per-device communication costs by allowing multiple sensing devices to share a common data exchange service, improving scalability and cost efficiency without sacrificing data availability.

Equally important is data accessibility and system control. Devices that expose raw, time-stamped location and speed data through programmable interfaces enable tighter integration with custom platforms, more transparent validation, and iterative refinement of detection logic. In contrast, devices that restrict access to processed or proprietary data streams limit the ability to assess performance, adapt algorithms, or integrate seamlessly with downstream systems such as WZDx and Smart Work Zone platforms.

The optimal balance among devices cannot be fully resolved through technical evaluation alone. These tradeoffs will be further explored and refined through future implementation studies that incorporate direct feedback from workers regarding usability, comfort, charging requirements, and day-to-day integration into field activities. Incorporating worker perspectives will be essential to identifying configurations that achieve both reliable worker presence detection and sustainable long-term adoption.

## 6.3 Future Implementation Plan

### 6.3.1 Integration with Smart Work Zone Messaging Systems

The worker presence attribute associated with a work zone can be operationally integrated with contractor-managed SWZ platforms, such as Ver-Mac JamLogic (Figure 6-1), to automate Changeable Message Sign (CMS) operations.

- Integration

The MU Worker Presence Platform publishes an enriched WZDx WorkZoneFeed as a GeoJSON endpoint that includes authoritative work zone geometries and derived attributes, such as worker presence indicators. JamLogic can ingest this output as a third-party external data source by activating the Data Feed Ingestion module for the associated project. Integration involves registering the WZDx feed URL and mapping relevant WZDx fields—such as work zone identifiers, status flags, and worker presence attributes—to JamLogic variables. Once configured, WZDx events are represented within JamLogic as External Events or Virtual Sensors and can be viewed on the dashboard map to verify spatial alignment, data freshness, and attribute availability.

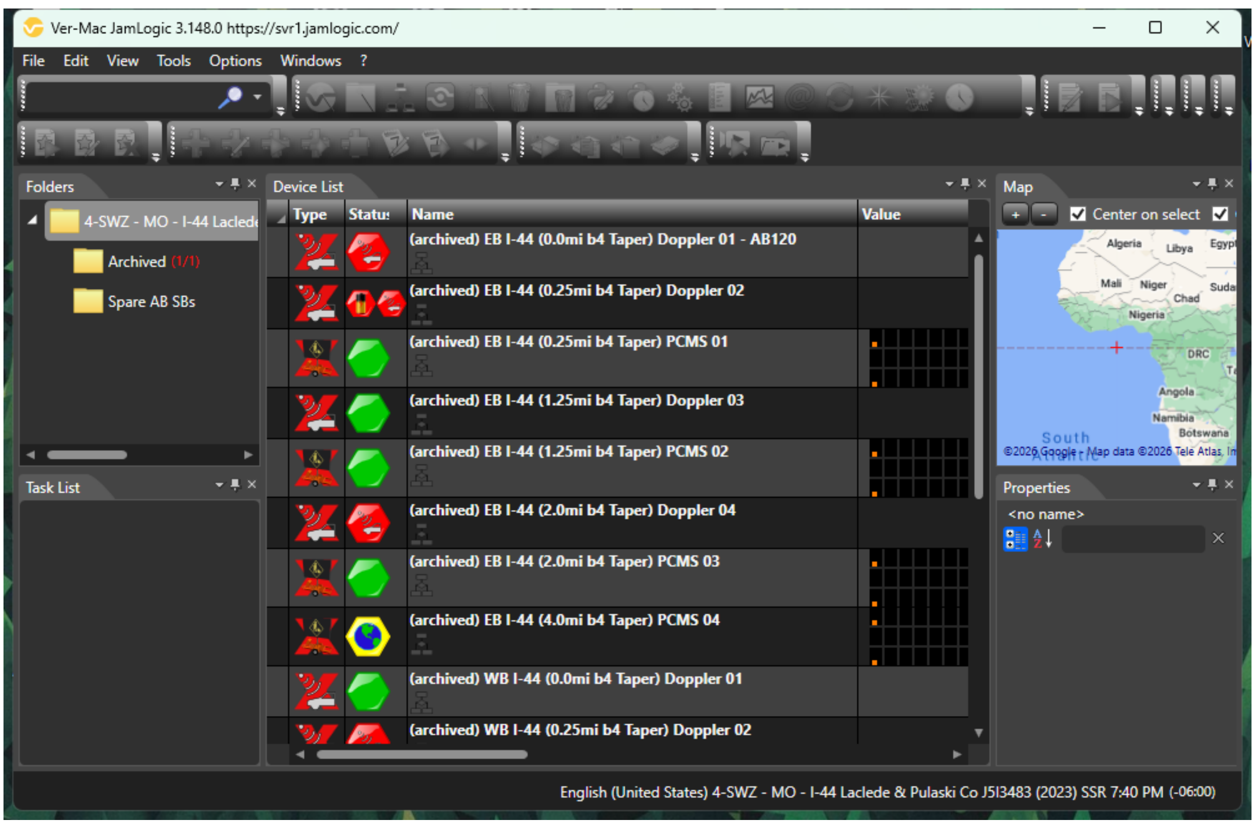


**Figure 6-1. Ver-Mar JamLogic Interface for CMS Operations**

- Automation Logic for CMS Control

After the WZDx feed is successfully ingested, JamLogic's Smart Work Zone automation engine is used to associate worker presence conditions with CMS messaging behavior. Within the SWZ configuration interface, operators define conditional If/Then logic based on WZDx attributes.

For example: IF WorkZone_Status = Active AND Workers_Present = True, THEN display "WORKERS PRESENT – REDUCE SPEED."

CMS messages are created in advance using JamLogic's message editor. As a best practice, worker presence–related messages should be reviewed and approved by the project engineer or traffic operations staff. When the WZDx feed updates—such as when workers enter or leave the work zone—JamLogic automatically evaluates the logic rules and pushes the appropriate message to the associated CMS units.

This integration approach aligns with MoDOT SWZ policy by emphasizing condition-based messaging, minimizing manual intervention, and leveraging existing contractor-managed infrastructure.

### 6.3.2 Integration with Traveler Information and V2X Data Flows

While Section 6.3.1 focuses on on-site messaging through changeable message signs, worker presence data also provides value when distributed through MoDOT's digital traveler information ecosystem. This section describes how verified worker presence information can be operationalized by MoDOT to enhance traveler awareness and connected vehicle messaging using existing data-sharing frameworks.

- **Integration with MoDOT Traveler Information Map**

The MoDOT Traveler Information Map provides motorists and traffic management personnel with a comprehensive view of roadway conditions, including planned work zone locations, lane closures, traffic speeds, and camera feeds. At present, however, the map primarily reflects scheduled or reported work zone activity and does not include a real-time indicator confirming whether workers are actively present in the field.

Worker presence information derived from device-based observations can be incorporated as an additional operational attribute within MoDOT's existing work zone data services. By publishing a verified "active worker presence" status alongside established work zone geometries, MoDOT can distinguish between planned work zones and those with confirmed on-site activity. This distinction allows traffic management centers and the traveling public to better understand when heightened caution is warranted, based on actual field conditions rather than schedules alone.

From an operational perspective, this integration would be implemented and managed by MoDOT through its traveler information services. The role of the research effort is limited to demonstrating feasibility and defining data structures. MoDOT would control how worker presence attributes are ingested, filtered, and displayed, consistent with agency policies and operational priorities. Potential query and visualization capabilities include filtering to display only work zones with active worker presence or isolating activity by corridor, district, or time window to support operational decision-making.

- **V2X and Digital Alerting Data Flow**

Once incorporated into MoDOT's traveler information systems, worker presence data can also be distributed through existing digital and connected vehicle channels. By publishing worker presence as part of a Work Zone Data Exchange feed, MoDOT can enable downstream consumers to access a unified, authoritative data source.

Third-party navigation providers, such as consumer mapping and routing applications, can ingest the enriched work zone feed and use the worker presence attribute to trigger context-specific alerts, such as "workers present ahead." These alerts provide advance notice to drivers before visual contact with the work zone, supporting safer driving behavior in advance of lane shifts or reduced shoulder clearance.

Similarly, worker presence data can be incorporated into vehicle-to-infrastructure messaging workflows. When connected vehicles approach a work zone, roadside units managed by MoDOT can broadcast traveler information messages triggered by the active worker presence status.

This approach enables direct, low-latency warnings to connected vehicles and complements traditional signage and visual cues.

Importantly, all dissemination of worker presence information through traveler information systems and V2X channels would be governed and operated by MoDOT. The research effort does not assume responsibility for operational data publishing or system control. Instead, the work demonstrates how worker presence can be treated as a verified work zone attribute that integrates naturally into MoDOT's existing digital infrastructure, supporting both public-facing traveler information and future connected vehicle applications.

# 7. Conclusion

This study developed and evaluated a practical approach for detecting and reporting worker presence in highway work zones using portable location technologies and standardized WZDx mechanisms. Through a structured review of existing research, evaluation of commercial tracking devices, and targeted field testing under both controlled and operational conditions, the project identified key technical and operational considerations that influence the feasibility of worker presence applications for state departments of transportation.

The technology evaluation demonstrated that Bluetooth Low Energy–based tracking devices, while low-cost and compact, do not provide the reliability, temporal consistency, or data accessibility required for worker presence detection in highway work zones. Their dependence on crowdsourced smartphone networks and limited access to raw location data resulted in intermittent reporting and substantial spatial errors, particularly under smartphone-disabled and rural conditions. In contrast, GNSS-based tracking devices with dedicated communication capabilities consistently provided stable location updates across a range of environments and operational scenarios, supporting their use as foundational sensing technologies.

Field evaluations highlighted important tradeoffs among commercial GNSS devices related to wearability, battery life, data integration, and total cost of ownership. While several off-the-shelf devices demonstrated acceptable accuracy and reliability, none fully satisfied the combined requirements for large-scale, worker-worn deployment, including affordability, data transparency, and flexibility for system-level processing. These tradeoffs motivated the development of a customized location prototype, the WZ-Gateway Node, that relies on shared-connectivity and open-data architecture to reduce recurring communication costs while maintaining direct access to location data.

Beyond device-level performance, this research emphasized the importance of deriving worker presence as a work zone–level attribute rather than exposing individual worker trajectories. By aggregating device observations and publishing worker presence through standardized Work Zone Data Exchange feeds, the proposed approach supports real-time situational awareness while preserving worker privacy and aligning with existing DOT data-sharing practices. Field results showed that modest reporting delays and conservative detection logic can effectively minimize false-positive worker presence indications, reinforcing the value of prioritizing reliability and trustworthiness in operational messaging.

From an implementation perspective, the results support a phased deployment strategy led by MoDOT. Initial implementation could focus on pilot deployments within selected maintenance or construction activities using a small number of WZ-Gateway Nodes per crew supported by a shared mobile hotspot. Such pilots would allow refining configuration parameters, validation of field usability, and integration with existing traveler information and Smart Work Zone systems. Based on pilot outcomes and feedback from field personnel, the capability could be expanded at the district level and ultimately scaled statewide, enabling worker presence alerts to be based on verified field activity rather than planned schedules alone. This approach provides a practical pathway for enhancing work zone safety while remaining operationally realistic, scalable, and aligned with MoDOT policy.

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