Final Report

Work Zone Safety Alert System Pilot

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16. Abstract

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Utilizing a portable, solar-powered trailer equipped with dual Ouster OS1/OS2 LiDAR sensors, a 360-degree camera, and edge-computing hardware, Bear Alert continuously tracks the speed and trajectory of upstream traffic. Upon calculating a predictive Time to Entrance (TTE) that indicates a severe threat, it wirelessly triggers a three-tiered warning: a high-decibel siren, a flashing beacon, and personal wearable haptic buzzers.

A 22-day Phase 1 pilot on a segment of Hillen Road in Baltimore monitored 112,770 vehicles, logging an average Daily Traffic (ADT) of 5,126 vehicles. The edge computer flagged 737 severe speed violations where vehicles traveled 45 MPH or more despite the 35 MPH posted speed limit.

Qualitative feedback from seven field workers demonstrated exceptional user acceptance. Workers rated the personal haptic vibration as the most effective alert modality (3.9 out of 5), noted the devices did not cause dangerous distractions (4.6), and expressed a strong desire to use them in the future (4.7). Ultimately, the Bear Alert pilot proved the technical viability and human-factors efficacy of sensor-based predictive safety systems for roadside personnel. Future steps include securing a provisional patent, conducting longitudinal testing, expanding statewide, and integrating Cellular V2X (C-V2X) communications.

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LIST OF ACRONYMS

ADT	Average Daily Traffic
FHWA	The Federal Highway Administration
CAVs	Connected and Automated Vehicles
LED	Light Emitting Diode
V2X	Vehicle-to-Everything
AWARE	Advanced Warning and Risk Evasion
LiDAR	Light Detection and Ranging
DSRC	Dedicated Short-Range Communications
BLE	Bluetooth Low Energy
PPUs	Personal Protection Units
EPUs	Equipment Protection Units
TTE	Time to Entrance

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ABSTRACT

Highway crews' vulnerability to high-speed civilian vehicles is a critical infrastructure safety challenge, highlighted by a 50% increase in national work zone crashes over the past decade. To address this, this project deployed the "Bear Alert" Work Zone Safety Alert System. The system gives on-foot workers a 4- to 5-second advance warning of encroaching vehicles, providing vital time to evacuate.

Utilizing a portable, solar-powered trailer equipped with dual Ouster OS1/OS2 LiDAR sensors, a 360-degree camera, and edge-computing hardware, Bear Alert continuously tracks the speed and trajectory of upstream traffic. Upon calculating a predictive Time to Entrance (TTE) that indicates a severe threat, it wirelessly triggers a three-tiered warning: a high-decibel siren, a flashing beacon, and personal wearable haptic buzzers.

A 22-day Phase 1 pilot on segment of Hillen Road, Baltimore, monitored 112,770 vehicles, logging an average Daily Traffic (ADT) of 5,126 vehicles. The edge computer flagged 737 severe speed violations where vehicles traveled 45 MPH or more despite the 35 MPH posted speed limit.

Qualitative feedback from seven field workers demonstrated exceptional user acceptance. Workers rated the personal haptic vibration as the most effective alert modality (3.9 out of 5 average rating), noted the devices did not cause dangerous distractions (4.6), and expressed a strong desire to use them in the future (4.7). Ultimately, the Bear Alert pilot proved the technical viability and human-factor efficacy of sensor-based predictive safety systems for roadside personnel. Future steps include securing a provisional patent, conducting longitudinal testing, expanding statewide, and integrating Cellular V2X (C-V2X) communications.

Keywords: Work Zone, Safety Alert, LiDAR sensors, Wearable Device, Traffic Safety, CAV, ITS

1. INTRODUCTION

1.1. Background and Safety Challenge

Work zones play a crucial role in maintaining and improving roadways. The Federal Highway Administration (FHWA) reports that 20% of the national highway system undergoes repairs during the construction season, with nearly 12 billion vehicle miles traveled through work zones annually. However, work zones increase the likelihood of crashes, injuries, and fatalities due to reduced roadway capacity, altered traffic flow patterns, lane configuration changes, and narrower rights-of-way. Despite these challenges, work zones are essential for maintaining and rehabilitating our transportation infrastructure. In 2022, there were a total of 891 fatalities and 37,701 injuries resulting from work zone crashes in the United States. Most of these injuries or fatalities occurred within the boundaries of work zones, as well as during entry or exit from them. Of the 891 fatalities, 528 occurred in construction zones, 305 in work zones of unknown type, 49 in maintenance zones, and 9 in utility zones (*1*).

The vulnerability of highway construction and maintenance crews to high-speed civilian vehicles represents a critical safety challenge for developers and transportation authorities. The urgency of this issue was tragically underscored in March 2023, when an erratic vehicle entered a work zone on Baltimore's I-695, resulting in the fatalities of six construction workers. This mirrors a severe national trend; over the past decade, work zone crashes have increased by 50% in the U.S., culminating in over 100,000 crashes and 899 fatalities in 2023 alone, with an annual economic cost of approximately $39 billion (*2*). Within Maryland, between 2020 and 2024, work zone collisions resulted in 6,701 crashes, 2,365 injuries, and 50 fatalities (*3*). New technologies such as Connected and Automated Vehicles (CAVs) can improve safety by alerting drivers and work zone workers.

Many researchers and practitioners have proposed solutions to increase work zone safety for construction workers and motor vehicle occupants. New technologies, such as CAVs, can improve safety by alerting drivers and work zone workers. This section provides a comprehensive review of developments in worker alert technologies, focusing on empirical findings from field deployments and evaluations.

1.1.1. Wearable and Haptic Alert Systems

Wearable alert devices (such as smart safety vests, helmets, or armbands with integrated sensors) have been developed to inform workers of upcoming dangers. These wearables typically deliver alerts via haptic feedback (vibration), audible tones, and/or visual alerts (LED lights) (*4*).

For example, prior research explored a connected Smart Vest prototype designed to warn workers and predict potential collisions in real time. This previous system functioned as follows:

- The vest used GPS to identify the position and movement of workers and transmited data to a base station or nearby vehicles, warning the worker (via vibrations or alarms) of approaching potential hazards.
- The system could also broadcast alerts to passing connected vehicles using Vehicle-to-Everything (V2X) communication to share messages about potential collisions with workers.

Personal wearable alert devices have also proven to be more effective than conventional centralized alarms like sirens. A recent virtual reality experiment evaluated the efficacy of different alert modalities: no alert, a centralized work zone alarm, and personalized wearable alerts. The study found that personalized alerts consistently led to faster reaction times and more effective responses. Haptic feedback has been shown to be capture workers' attention immediately, reducing response times even in ambient construction noise (*5*).

1.1.2. Radar and LiDAR-Based Intrusion Detection

Another class of safety device focuses on detecting vehicles that encroach into work zones to trigger alerts. Older alarm systems relied on "tripwire" designs made from pneumatic tubes or infrared beams placed at the work zone entrance, sounding an alarm when a vehicle physically crossed the hazard line. The limitation of these systems is that the alert comes only after a vehicle has already entered the work zone, leaving minimal time for workers to react (*6*).

A notable radar-based system is Advanced Warning and Risk Evasion (AWARE), which continuously tracks oncoming vehicle speed and trajectory using Doppler radar and triggers alarms if a vehicle is projected to intrude (*7*).

Field testing demonstrated that AWARE can correctly identify genuine threats and avoid false alarms. The system also includes wearable receiver units ("WorkTrax") that activate when a threat is detected and directly alert workers (*7*).

Light Detection and Ranging (LiDAR) has also been introduced for intrusion detection. Alpha SafeNet's Overwatch device, for example, uses 360° LiDAR to create an invisible buffer around the work zone. If a vehicle enters that buffer, it sets off lights and sirens (*5*).

Research by Abdallah et al. assessed the AWARE and LiDAR units in utility work zones and concluded that an effective alert system should employ multi-modal alerts (audio, visual, and haptic) (*6*).

Furthermore, Darwesh et al. (*8*) demonstrated that roadside LiDAR can effectively distinguish and track vehicles in a work zone environment using 2D bird's-eye projections and clustering algorithms.

1.1.3. Video and Connected Vision Systems

Researchers have explored computer vision to detect dangerous situations in work zones using AI-powered cameras. For instance, a 2022–2023 project by Akhavian et al. (*9*) developed a holistic safety alert system by using video analytics and smartphone alerts. In this system, surveillance cameras monitor traffic and detect speeding or careless vehicles, while smartphone sensors track workers' exposure to vibration and other potential hazards. If a threat is detected, the smartphone generates an audible and haptic alert, showing that smartphones are a feasible platform for delivering alerts. Additionally, some systems now integrate with Dedicated Short-Range Communications (DSRC) or cellular V2X messages to broadcast alerts directly to connected vehicles (*4*).

1.1.4. Proximity Alert Systems (RFID and Bluetooth)

Not all work zone dangers come from public vehicles; heavy equipment also poses risks. Proximity warning systems using Bluetooth Low Energy (BLE) or Radio-Frequency Identification (RFID) allow workers and equipment operators to be alerted when within unsafe distances (*10*). One example developed by Cho et al. includes wearable Personal Protection Units (PPUs) and vehicle-mounted Equipment Protection Units (EPUs), forming a wireless mesh network. Field trials showed that the BLE system provided about 2.2 seconds of reaction time, and obstructions could be warned about by using multiple flashing beacons (*10*).

In summary, researchers have deployed a variety of technologies to alert highway work zone workers to safety hazards. Wearable smart vests and haptic devices improve reaction times. Radar- and LiDAR-based detection systems offer predictive capabilities and multi-modal alerts. Video/computer vision systems and connected V2X alerts extend coverage and communication range. Bluetooth proximity systems protect workers from construction equipment through direct alerts.

1.2. Project Goal and Objectives

This project aims to alert work zone workers of any unsafe situations. To achieve this goal, we selected a work zone in Baltimore City to install the Work Zone Safety Alert System (Bear Alert), giving field workers a 4- to 5-second advance warning of approaching danger and crucial reaction time to avoid the hazard. We propose using a portable LiDAR-based detection system to alert work zone workers. To achieve this, the system processes real-time trajectories and broadcasts alerts through visual, auditory, and haptic channels. The proposed solution was tested and evaluated for validation and refinement.

2. SYSTEM ARCHITECTURE AND METHODOLOGY

This section introduces the technical approach for designing, applying, and evaluating the proposed smart work zone safety system.

2.1. Hardware Configuration

The project utilizes a custom, solar-powered trailer equipped with edge-computing hardware, a radio transmitter, two LiDAR sensors, a 360-degree camera, and a 5G router to maximize spatial coverage without requiring hardwired grid power. It is a stand-alone, solar-powered mobile system with LiDAR detection and edge computing. **Figure 1** shows the portable trailer deployment in a roadside work zone, and **Figure 2** shows the sensor deployments.



Figure 1. Solar-powered trailer deployment – Hillen Rd

2.2. Sensor Deployment and Spatial Coverage

To ensure comprehensive monitoring of the work zone, the system relies on high-fidelity spatial sensors shown in **Figure 2**:

- **LiDAR Monitoring:** The system utilizes a dual Ouster LiDAR sensor configuration, fusing OS1 and OS2 sensors. This configuration maximizes spatial coverage, supporting both near-zone perimeter monitoring and extended-range tracking of oncoming vehicles upstream. The LiDAR monitors all objects passing through the area and provides cloud point data for the environment.
- **Video Monitoring:** A 360-degree camera was installed on the trailer mast to monitor the work zone in real-time, providing ground-truth visual verification of the site conditions.



Figure 2. Sensor deployment

2.3. System Integration and Communications

A 4G cellular connection, a network switch, an RF transmitter, and a communication device receive data from the LiDAR Edge computer, along with an On/Off relay, to connect different parts of the system.

2.4. Detection Logic and Processing

The edge computing box processes real-time LiDAR trajectories against predefined safety and trigger zones.

- **Speed Tracking:** The edge computer performs perception using AI, finds the speed and location of approaching road users, and draws trajectories of moving objects. Based on the existing trajectory, the system calculates the projected position of moving objects and identifies potential risks. A Time to Entrance (TTE)-based model predicts collision risk between approaching vehicles and a worker or a work vehicle within the monitored perimeter. When TTE is below a defined threshold, alerts are generated.
- **Late Merging Logic:** Specific proximity zones were drawn near the barriers of the physical work zone. If a vehicle approaches the work zone too closely without safely merging, a late-merging alert is designed to trigger. Notably, during this specific 22-day study, no vehicles breached these defined proximity zones, resulting in zero late-merging alerts.

2.5. The Bear Alert Warning Mechanism

When a potential hazard is detected, the system calculates a 4- to 5-second reaction window and broadcasts a radio signal to trigger a three-tiered warning:

- **Audible Siren:** A loud, high-decibel beeping siren warns workers of incoming danger.

- **Wearable Haptic Device:** A compact buzzer equipped with vibrators, batteries, and a radio receiver provides a vibration buzz strong enough to be felt during heavy, active work. **Figure 3** shows the haptic device prototype which used for the first pilot setup.



Figure 3. Wearable Haptic Device Prototype

- **Flashing Warning Light:** A solar-powered flashing beacon activates, visible to both workers and oncoming drivers from a distance. **Figure 4** shows the solar-powered flashing beacon.



Figure 4. Solar-powered flashing beacon

Figure 5 demonstrates the work zone safety schematic view, and **Figure 6** shows the operational plan.

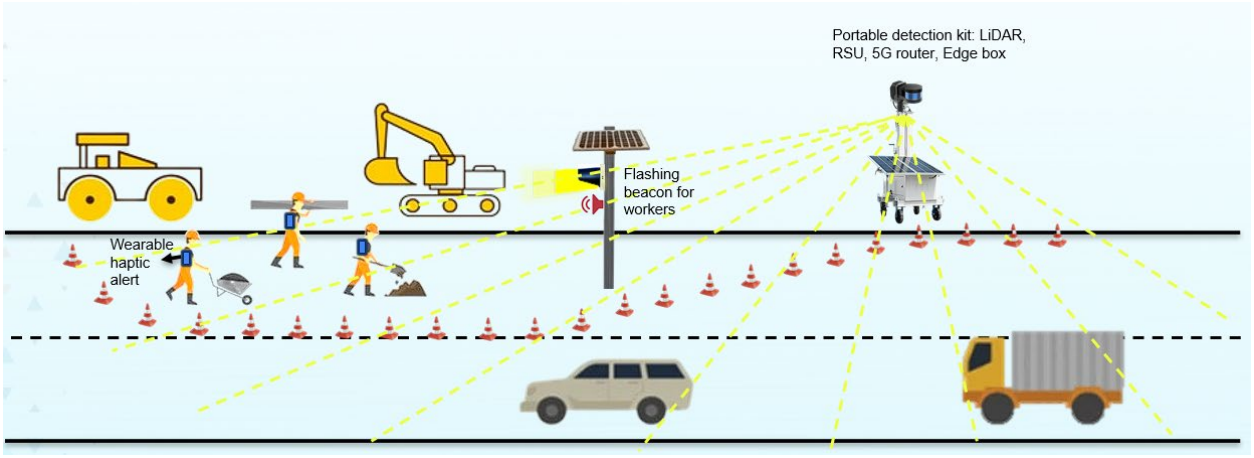


Figure 5. Work Zone Safety Project Schematic View

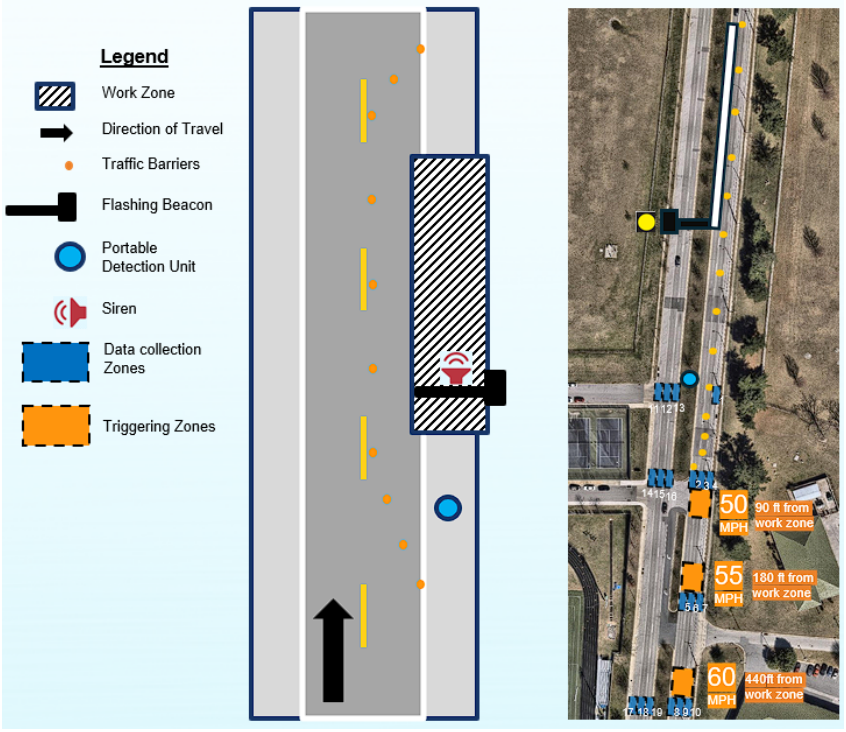


Figure 6. Work Zone Safety Project Operational Plan

3. PILOT DEPLOYMENT DETAILS

3.1. Site Location

The pilot was deployed on Hillen Road, monitoring the corridor between 33rd & Argonne. The posted speed limit through this regulated work zone was 35 MPH. **Figure 7** shows a satellite view of the site location.

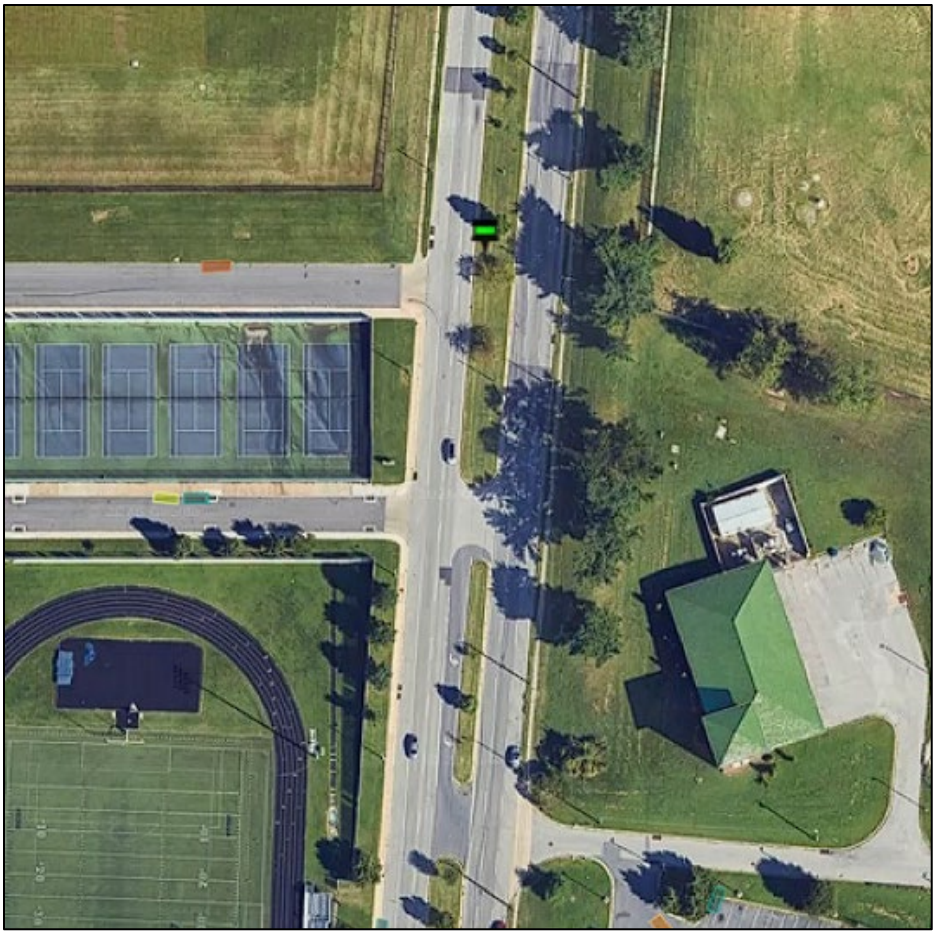


Figure 7. Work Zone Location – Hillen Rd

3.2. Study Duration and Phasing

Phase 1 field testing spanned 22 working days from April 8 to May 10, with data collection during active working hours from 7:00 AM to 5:00 PM. The deployment was structured into two distinct intervals:

- **Baseline Period (April 8 – April 19):** The dual-LiDAR trailer operated passively for approximately one week. No alerts were triggered, establishing a baseline for driver behavior and natural traffic speed profiles.
- **Active Intervention Period (April 20 – May 10):** The Bear Alert system was fully activated. Seven field workers wore haptic buzzers while the flashing beacon and siren were live. During this phase, workers received an average of 10-12 alerts per day.

3.3. Deployment Site Layout

To detect speeding vehicles, three zones with speed thresholds are created; for vehicle behavior when approaching the work zone, 19 lane-specific zones are defined. **Figure 8** shows the layout map.

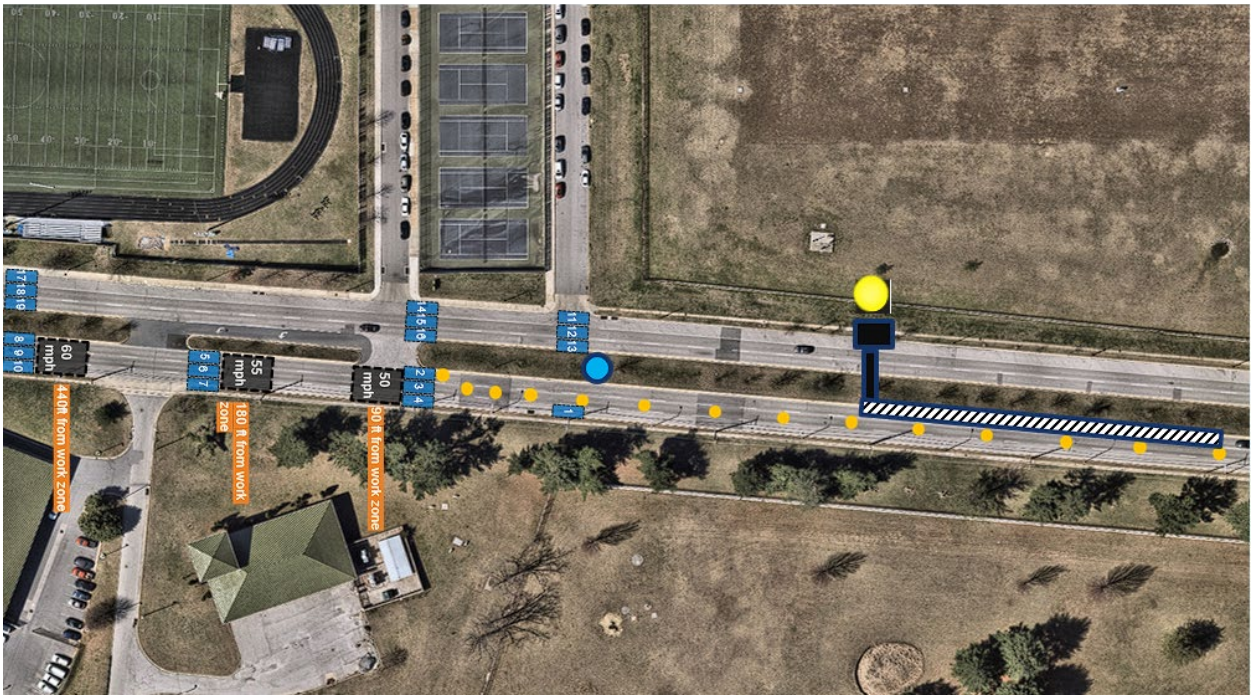


Figure 8. Deployment Site layout – Hillen Rd

4. TRAFFIC VOLUME AND SPEED ANALYSIS

4.1. Traffic Volume Overview

Throughout the 22-day study period, the dual-LiDAR system captured continuous traffic flow data.

- **Total Monitored Traffic Volume:** 112,770 vehicles passed through the work zone from 7:00 AM to 5:00 PM during the working window.
- **Average Daily Traffic (ADT):** 5,126 vehicles per day during working hours.

4.2. Speed Violations

The system was calibrated to flag vehicles exceeding 45 MPH. This threshold represented a severe 10+ MPH violation of the 35 MPH posted limit and triggered a high speed alert in the system. In total, 737 vehicles triggered passed this threshold. Most of the excessive speeding occurred between 10 and 30 MPH over the posted limit, with a significant drop-off past 65 MPH. **Table 1** and **Figure 9** show the speeding violations by threshold.

Table 1. Speeding Violations by Threshold (Over 35 MPH Limit)

Speed Range	Total Vehicle Count	Cumulative Total (Over Threshold)
45–55 MPH	395	737 (Total > 45 MPH)
55–65 MPH	302	342 (Total > 55 MPH)
65–75 MPH	37	40 (Total > 65 MPH)
> 75 MPH	3	3 (Total > 75 MPH)

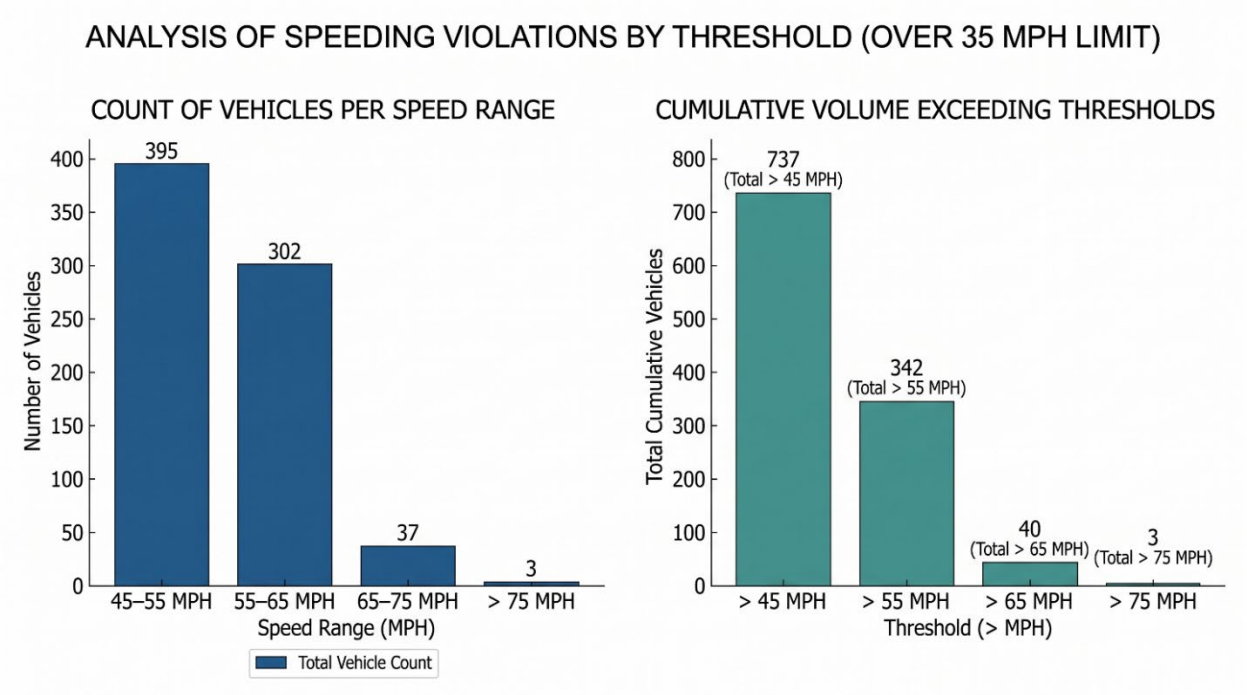


Figure 9 - Analysis of Speeding Violations by Threshold (Over 35 MPH Limit)

5. WORKER SURVEY AND FEEDBACK ANALYSIS

To evaluate qualitative system reception and perceived safety benefits, we conducted structured before-and-after surveys with the 7 field workers who used the wearable Bear Alert haptic buzzers. The survey was administered in two distinct phases:

- **Pre-Deployment Questionnaire:** Prior to using the system, workers completed a baseline assessment that captured their demographics, professional roles, years of experience, current perceptions of safety (rated on a 1 to 5 scale), and historical occurrences of near-misses.

- **Post-Deployment Assessment:** Following the active pilot, participants evaluated the system using a 16-metric questionnaire. Responses were recorded on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). These metrics were grouped into four core categories to evaluate the technology's overall viability: System Trust, Physical Integration, Alert Modality Effectiveness, and False Alarms.

5.1. Participant Demographics and Hazard Perception

The pilot cohort consisted entirely of male workers, none of whom had previously used any wearable safety device or automated safety alert. Six of the seven participants fell into the 25-34 age group, and one was in the 18-24 range. Professionally, six were Equipment Operators, and one was a Site Supervisor. **Table 2** shows the details.

When surveyed about baseline safety, six of the seven participants had previously experienced near misses (ranging from 1 to over 10 incidents in their careers). Moreover, these partcipants also explicitly identified driver speeding or aggressive driving as the primary cause.

Table 2. Pre-Questionnaire Participant Overview

Participant ID	Age Group	Role	Experience	Current Safety Feeling (1-5)	Near-Misses Experienced
RM	25-34	Equipment operator	15 years	3	> 10
BML	25-34	Equipment operator	8 years	3	3
CS	25-34	Site supervisor	4 years	4	0 (None)
DC	18-24	Equipment operator	4 years	3	1

EM	25-34	Equipment operator	11 years	4	10
HC	25-34	Equipment operator	8 years	3	>5
NS	25-34	Equipment operator	6 years	2	>3

5.2. System Efficacy and Comfort Metrics

Participants rated various metrics on a 5-point scale (1=Strongly Disagree, 5= Strongly Agree). The results highlighted exceptional physical comfort and strong potential for future adaptation.

- **System Trust:** Workers strongly agreed that the equipment was safely positioned (4.9 average) and expressed a high desire to use the system in the future (4.7 average).
- **Physical Integration:** The wearable buzzers were well-received. Participants agreed the system did not distract them from working safely (4.6), was lightweight and comfortable (4.1), and did not physically interfere with their duties (4.4).
- **Alert Modality Effectiveness:** The haptic vibration was easily felt by the users (3.9), significantly outperforming both auditory alerts (2.7) and visual alerts (1.9) in perceived effectiveness on a noisy work site.
- **False Alarms:** Workers reported low frustration with false alarms (2.3), noting that they did not significantly reduce attention (2.1).

Figure 10 shows the survey results.

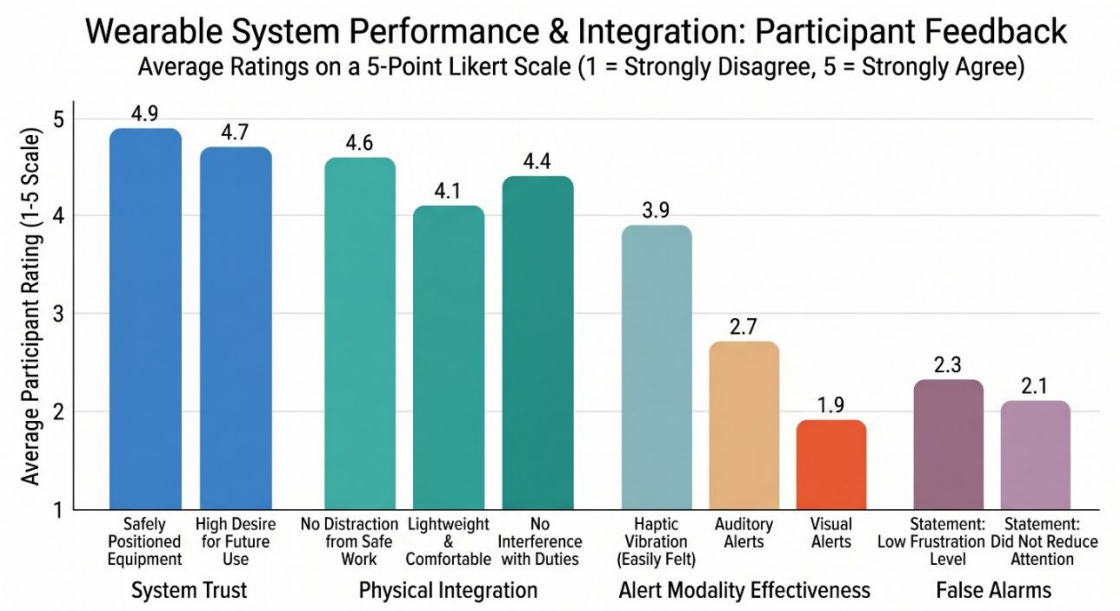


Figure 10. Survey results

6. CONCLUSIONS AND NEXT STEPS

The Phase 1 pilot deployment of the Bear Alert system on Hillen Road successfully demonstrated the technical viability of LiDAR-based trajectory tracking for worker safety. The system reliably captured volume and speed metrics, identifying a significant hazard profile of 737 extreme speed violations within a 22-day window.

Crucially, the human-factors evaluation revealed that standard auditory and visual warnings are insufficient in active work zones; field personnel definitively rated the wearable haptic alert as the most effective warning mechanism.

6.1. Strategic Next Steps

To transition this pilot into broader, standardized practice, the following initiatives are currently underway:

- **Intellectual Property:** A provisional patent is actively being pursued for the Bear Alert multi-sensory technology architecture.
- **Extended Testing:** Continued pilot testing and longitudinal data collection will proceed on the Hillen Road corridor.
- **Statewide Expansion:** Plans are in development to expand the system's deployment to additional, diverse work zone sites across Maryland to validate effectiveness under varying highway configurations and speed limits.

6.2. Project Partners and Acknowledgments

The success of the Bear Alert System pilot was made possible through the collaboration of several key organizations and agencies:

- **Baltimore City Department of Transportation**
- **Maryland Highway Safety Office / MDOT (SHA)**
- **Mead & Hunt** (Transportation Consulting)
- **TS&T** (Technology Support)
- **Stella May Contracting** (Civil Construction)

7. APPENDIX A. QUESTIONNAIRE

Work Zone Field Pilot Pre-Questionnaire

***Please note that all questions will be asked verbally, so this will be conducted as an interview rather than a questionnaire.**

1. Participant ID:
   (Assigned by the research team)
2. Age Group:
   ☐ 18–24
   ☐ 25–34
   ☐ 35–44
   ☐ 45–54
   ☐ 55–64
   ☐ 65 or older
3. Gender:
   ☐ Female
   ☐ Male
   ☐ Prefer not to say
   ☐ Other
4. How many years of experience do you have working in roadway work zones?
   _____ years
5. What is your current role?

   ☐ Flagger
   ☐ Equipment operator
   ☐ Site supervisor
   ☐ Other: _____

6. How safe do you feel while working in this current work zone? (1 = Very unsafe, 5 = Very safe) ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
7. Have you ever experienced a near-miss involving a vehicle intrusion in a work zone?

   ☐ Yes ☐ No

   If yes:

   - Approximately how many times? _____
   - What do you think was the main cause? (You can select all that apply)

     ☐ Worker error

     ☐ Driver speeding or aggressive driving

     ☐ Lack of warning signs or traffic control devices

     ☐ Other: _____

8. Have you ever used any wearable safety device or had any automated safety alert?

   ☐ Yes ☐ No

   If yes:

   - What type of device or alert was it?

Work Zone Field Pilot Post-Questionnaire

***For the following questions, use a 5-point scale (1 = Strongly Disagree, 5 = Strongly Agree).**

1. The wearable alert device was lightweight and comfortable to wear during my shift.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
2. The wearable alert device did not interfere with my physical movement or vision while I performed my tasks.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
3. The vibration of the wearable device was strong enough to be easily felt through my work clothing.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
4. The auditory (sound) alerts were effective in capturing my attention.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
5. The visual (flashing beacon) alerts were effective in capturing my attention.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
6. The alerts provided me with sufficient time to recognize and react safely to potential vehicle intrusions.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
7. When I received an alert, I changed my behavior (e.g., moved, looked, reacted).
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
8. The alert system did not distract me from my primary safety-critical responsibilities.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
9. The system generated too many false or unnecessary alarms.
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
10. Frequent false alarms reduced my attention to the alerts.
    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
11. The detection equipment (trailer & beacon) was positioned safely and did not obstruct my workspace.
    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

12. The initial training on how the alert system works was clear and easy to understand.

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

13. I felt safer working in the road zone with this alert system in place.

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

14. I trusted the alerts provided by the system.

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

15. Overall, I find this alert system useful for improving work zone safety.

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

16. I would like to use this system in future work zones.

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

    -Please provide any additional feedback or comments.

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