DEPARTMENT OF TRANSPORTATION

User-Centered Smart Traffic Sign Development Implementation Study

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16. Abstract (Limit: 250 words)

Flaggers maintain traffic flow through a work zone area despite a shutdown of lanes by providing temporary traffic control. In terms of occupational safety, flaggers have one of the highest risk jobs in the country, with 41 out of every 100,000 workers killed on the job each year. This project developed and tested technology for automatically detecting and documenting the occurrence of near-intrusions into a flagger-controlled work zone. The project developed a low-cost portable device for automatically tracking vehicle trajectories, detecting potential intrusions, and providing audio-visual alerts to warn any errant drivers who might cause a danger to flaggers and workers in the construction zone. A radar sensor on the device is deployed by using a telescoping pole and collects simultaneous measurements from approaching vehicles in multiple lanes.

Tests were conducted in six real-world traffic scenarios, including work zones at one rural location (Cook County), three urban locations (Saint Paul, White Bear Lake, and Eden Prairie), a synthetic urban zone involving pedestrian crossings (Saint Paul) and one suburban/rural location (Mound). Detailed results and analysis are presented in this report. The results indicate that multiple design iterations have improved the device and enabled it to work reliably – Very few false alarms (if any) are triggered and the intrusion detection curves implemented in the system are verified to work well. The vehicles which were alerted using audio-visual warnings in the last work zone test responded appropriately with a majority of them slowing down in response to the alarms.

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The project deeply acknowledges Lee Alexander for playing a key role in the design and fabrication of the initial smart sign prototypes developed in this project. Very unfortunately, Lee passed away during the course of this project, and his passing was a significant source of sorrow and a major loss to the group. Lee's expertise in mechanical system design and fabrication, as well as his ability to work with and guide students and colleagues, will be greatly missed.

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Executive Summary

Flaggers maintain traffic flow through a work zone despite lane closures by providing temporary traffic control. In terms of occupational safety, flaggers have one of the highest-risk jobs in the country, with 41 out of every 100,000 workers killed on the job each year. This project developed and tested technology to automatically detect and document near-intrusions into flagger-controlled work zones. Specifically, we built a low-cost, portable device that tracks vehicle trajectories, detects potential intrusions, and provides audio–visual alerts to warn errant drivers who could endanger flaggers and other workers.

The device design was iteratively refined in response to feedback from transportation agency staff who regularly work in construction zones. An initial flagger-operated traffic-signal device with embedded radar sensors was modified into a wheeled unit with switchable STOP and SLOW signs, but this proved too heavy for frequent loading and unloading from a pickup truck. We then developed a lightweight portable device with the form factor of a handheld toolbox (approximately 15 lb) that can be easily moved to support rolling work zones. The device anchors to the road surface using quickly deployed brackets. A radar sensor on a telescoping pole collects simultaneous measurements from approaching vehicles in multiple lanes. Vehicle-tracking software on a Raspberry Pi estimates, in real time, each vehicle's distance, velocity, orientation, and lane position. Audio–visual alerts are triggered when necessary to warn drivers posing an intrusion risk, including those approaching the flagger's position.

We conducted six real-world traffic deployments: one rural work zone (Cook County); three urban work zones (Saint Paul, White Bear Lake, and Eden Prairie); one surrogate urban scenario with staged pedestrian crossings (Saint Paul); and one suburban/rural location (Mound). In four of the six tests, only monitoring and offline analyses were performed to (i) quantify how many vehicles would have triggered an alarm and (ii) verify the tracking and intrusion-detection performance. In the remaining two tests, audio–visual alerts were enabled to assess driver response. In the first of these two tests, no alerts were triggered because no vehicles posed an intrusion risk. In the second, 11 vehicles triggered upstream alerts; of these, six slowed, and five subsequently triggered additional alerts at a downstream device.

Detailed results and analysis are provided in this report. Overall, iterative design improvements produced a reliable device: false alarms were rare to nonexistent, and the implemented intrusion-detection thresholds performed as intended. In the final work-zone test with audio–visual warnings enabled, most alerted drivers responded appropriately by reducing speed.

Chapter 1: Field Study Site Selection and User Needs

1.1 Literature Review & Background

Road work zones can be dangerous spaces for those who work and drive through them. Nationwide in 2020, it is estimated 102,000 work zone crashes occurred, which resulted in 857 deaths [1]. Improving Minnesota work zone safety is an important step in the state's advancement toward zero deaths on our roadways. More specifically, examining and improving current road work flagging may significantly reduce injuries and deaths. Road work flaggers protect maintenance workers by providing temporary traffic control and maintaining traffic flow through a work zone, despite a shutdown of lanes. They are often the first line of defense to stop distracted, inattentive, or aggressive motorists from intruding into the work area. In terms of occupational safety, flaggers and other maintenance workers have one of the highest risk jobs in the country, with workers struck by vehicles accounting for 63% of deaths at road work sites [2]. While a 2019 law empowered flaggers to report dangerous drivers who intrude into their workspace to Minnesota State Patrol (MN Statute 169.06, Subd. 4a), they still need more support to detect, warn, and document when drivers breach the work zone.

1.1.1 Intelligent Work Zone Signage

Developing smart signage systems may be an effective method in reducing work zone intrusions or providing timely alerting to workers of intrusions. Smart signage systems have the potential to significantly reduce fatalities among road workers [3, 4, 5]. One of the most common functions of such safety systems is to warn workers of vehicles illegally entering the work zone, often done with a very loud noise or alarm [6, 7]. This noise has the additional benefit of potentially alerting the intruding driver that they are illegally entering a work zone or approaching dangerously [8].

Developing systems with the intent to provide clearer and more direct instructions to drivers with regards to stopping and work zone safety has been attempted through numerous methods and varying levels of complexity [3, 9, 10]. Some designs incorporate signage for drivers and worker warnings together. Smart safety systems have been shown to effectively improve safety in road work zones through communicating safety instructions to drivers and effectively warning workers of work zone intrusions [9]. Systems that attempt to control traffic do so through a variety of different signage. Some use a stop/slow sign [3, 5, 9, 11, 12]. A stop/slow sign is useful for its familiarity, but when not accompanied by a flagger, drivers may treat the stop sign as indicating that they must only come to a complete stop before continuing, as opposed to stopping and waiting for the sign to change [12]. Other systems use a light similar to a stop light [3, 11, 12]. This kind of signage conveys clearly that the driver should stop and stay stopped [3, 11]. However, most of these lights only have red and amber lights, to clarify that one should continue with caution, as opposed to at a regular speed. These amber lights can be confusing to drivers in some situations [11]. However, other signs often accompany such signage systems. These additional signs often convey instructions such as "stop here on red," or "go on slow" [3, 11, 12]. Such signs have been shown to be effective in getting drivers to stop and stay stopped [12]. Another function some signage systems employ is a raising and lowering stop arm [3, 12]. This arm, in conjunction with a red/amber light or a stop/slow sign, has been shown to be effective at conveying to drivers that they should not go [12].

Many of these systems, however, require considerable amounts of setup and are not easily handled by a lone worker. Getting road workers to always employ these measures is a slight hurdle in its own right, with some workers not completely understanding the benefits the safety systems provide or when best to deploy the systems, and some safety systems being cumbersome to transport, install, and remove [6, 7]. Larger, more complicated warning device systems that have been developed are appropriate for highway work zones where two or more lanes in the same direction are reduced. Some of these systems are large enough that they require a trailer to be transported which may be feasible for construction operations that need such large and visible devices. Furthermore, the price of some systems can be prohibitive, which means limited deployment across operations [9]. Such systems are not practical in more rural areas or roads with two lanes traveling in opposite directions. Therefore, the development of a portable, low-cost, and easy-to-use device is needed in order to provide both adequate signaling to drivers and warnings to employees in the work zone when an intrusion is imminent or dangerous activity is occurring. A safety device that could be quickly and painlessly set up by a single flagger and transported in a truck bed or trunk could be significantly beneficial for safety in such road work conditions, allowing flaggers to improve safety without encumbering them so much as to discourage use of the system.

1.1.2 Radar based Vehicle Tracking

Millimeter wave technology on industrial/automotive radar systems has advanced significantly since its introduction [13, 14]. Radar can be a relatively low-cost solution to detecting on-road objects such as vehicles and pedestrians. It is also robust to low-light and severe weather conditions. With sensors such as modern radar, lidar and camera, vehicle tracking is often considered as an extended object tracking (EOT) problem, where each object generates multiple detections in each sensor scan. This poses challenges in both inter- and intra-object data association [15, 16, 17, 18]. In this project, the data association problem is handled efficiently by assigning measurement points directly to established tracks, considering the rigid body motion of vehicles and the individual position and range-rate measurements from the radar. Meanwhile, multiple detections from a single object also bring the possibility for better estimation performance when the information from multiple points is strategically used [19, 20]. For example, Kellner et al. [19] computed vehicle orientation from a single frame by analyzing the velocity profile from multiple detection points. Unlike Kellner et al. [19], which uses RANSAC to eliminate outliers and formulates the orientation estimation problem as an optimization problem, here outliers are rejected by both the data association step and the filtering step. Based on the condition number of the position measurement matrix, two measurement models are proposed to maximize the use of measurement information while rejecting unreliable measurements. With continuously improved sensor resolution, different spatial representation models are developed [21, 22, 23].

1.1.3 Advanced Warning Systems

The use of such radar-based tracking, as well as other forms of tracking such as microwave and infrared based, has long been implemented as part of advanced warning systems used to share information with drivers prior to an event [24]. These advanced warning systems are often aimed at either informing a driver of an area they are approaching (i.e., work zone or train track) or are used as general reminders to drivers that are exhibiting dangerous behavior (i.e., speeding) via audio and/or visual messages. By providing an advanced warning to drivers, such systems are capable of providing the driver opportunity to anticipate and respond to the warning prior to reaching the work zone; however, the duration between when the warning is provided and the work zone can be key in maximizing warning effect [25, 26, 27, 28].

Depending on their placement, these advanced warning systems can also warn workers within the work zone of potentially dangerously approaching drivers. When the advanced warning system is positioned within several hundred feet of the work zone [25, 29], the audio alarm intended for the approaching driver is audible to those in the work zone as well. Even with this added benefit to work zone staff, it is important to note that many of these systems in the past have failed or have gone unused due to a lack of worker acceptance [25, 30, 31]. Workers have noted that such systems, while effective at improving driver behavior, can be too cumbersome to implement due to a lack of mobility and proneness to failure [30]. This lack of acceptance by work zone staff to use advanced warning systems in some cases highlights the need to assess the needs of the workers in future advanced warning system designs.

1.1.4 Previous Work from Phase 1

Phase 1 of the study focused on the development of a user-centered smart traffic sign both in regard to testing the overall proposed sign design in a simulator from a driver behavior perspective and the sensing capabilities to detect and track oncoming traffic using low-cost sensors. Through this work a modified traffic signal was constructed capable of being operated via handheld remote. The modified traffic signal included a sensing system that would monitor vehicles that were either approaching the work zone at dangerous speeds or entering the work zone when the traffic signal was indicating for the driver to wait. Usability testing of the modified traffic signal in a driving simulation found lower expectancies and stopping rates of the traffic signal-based alarm system compared to a traditional flagger but did demonstrate evidence that drivers may be less likely to stop and remain stopped with the flagger STOP sign than the red ball indicator of the traffic signal. A follow up test found that the addition of the sensor audiovisual alarm system to a more traditional stop/slow flagger paddle saw improved performance. Based on these findings from phase 1 of the study, the proposed work to be accomplished within phase 2 is aimed toward field validation testing of the flagger style smart traffic signal prototype in regard to sensing capabilities, usability from the perspective of the workers, and resulting driver behavior.

Figure 1.1: Photograph of the implemented smart work zone traffic signal from Phase 1.

1.2 User Requirements & Feedback Gathering

1.2.1 Methods

Participants

User interviews were held remotely with two senior level (supervisor or assistant supervisor) roadway maintenance employees and two in person interviews conducted with day-to-day field employees to collect direct feedback from anticipated end users. Supervisors interviewed work for Washington County and Scott County while the day-to-day field operators work for Washington County.

Procedure

User interviews lasted 30 minutes to an hour. Prior to or at the beginning of each interview, participants were presented with the prototype system as well as preliminary findings from phase 1 of the study. Additionally, they were informed that the discussion would focus on how they envisioned using the proposed system and whether there were any needs or concerns not addressed via the prototype. Semi-structured interview questions, included in Appendix A, guided the conversation during interviews, allowing additional discussion or elaboration as needed.

1.2.2 Key Findings

Supervisor Considerations

Supervisors interviewed were surprised at previous Phase 1 findings which showed that a remotely operated traffic signal resulted in poorer driver behavior (i.e. intrusions). Both supervisors interviewed expressed interest in pilot testing of the smart traffic signal prototype within their regular operations. Additionally, both supervisors interviewed expressed concern regarding the audio component of the alarm, highlighting a potential issue in volume where the alarm would be too quiet to get the attention of drivers but too loud for nearby workers.

One supervisor suggested a revised approach of moving the system away from the flagger (i.e., minimum of 50 ft) and incorporating it into other advanced signage warning drivers of a flagger ahead. Such a system may provide additional warning for workers when a fast approaching vehicle is detected.

Flagger Considerations

Both flagging staff interviewed expressed concerns regarding the mobility and structural stability of the sign. They dynamically move the sign to attract the driver's attention or hold traffic in the lane, which they may be restricted from doing with the current design. Flaggers recommended either decreasing the overall size of the system to allow for easy mobility or separation of the warning system from the stop/slow paddle. Similarly, the flaggers noted that the current system may be too bulky which may become a burden, particularly in regard to work zones that are continuously moving, requiring the flagger to frequently move along the roadway with the work zone. Their movements may require some slight shifting (i.e., walking), but frequently require more significant shifting in which they load their equipment and signage into a truck and drive the distance to the new start of the work zone. Additionally, the flagging staff expressed concern regarding wind blowing the proposed design over and recommended looking into measures such as kick stands that could increase stability without increasing the overall weight.

In addition to physical concerns regarding the proposed system, staff interviewed expressed concerns regarding the alarm system and its ability to adequately warn dangerously approaching drivers before they reach the flagger. The primary concern noted regarding the alarm was the volume required to garner a driver's attention and whether this would be too loud to be positioned directly next to the flagger. Similar to supervisor feedback, flaggers recommended moving the system upstream toward oncoming traffic to separate the flagger from the speaker. Moving the system upstream may also alleviate another concern noted during the interviews which is the concern whether the system would notify drivers early enough to safely stop prior to the flagger. Flagging staff interviewed highlighted that it would be best to warn drivers as early as possible allowing for additional space/time for drivers to reduce their speed prior to reaching the flagger who would then serve as a second line of defense for the work zone.

Summary & Design Modifications/Considerations

Based on recommendations received from both supervisors and flagging staff, the human factors team has made the following design modifications/recommendations:

1. Regarding the stability of the proposed system, the human factors team has recommended the addition of a tilt prevention mechanism to the system
2. Due to concerns raised regarding the audio portion of the alarm system, the human factors team has recommended exploring solutions to move the alarm system upstream toward traffic similar to an advance warning system
3. Due to currently used behavior noted by flaggers, the human factors team has recommended exploring solutions to separate the alarm system from the stop/slow paddle to allow flaggers greater flexibility and mobility of the paddle.
4. The human factors team has recommended that the initial weight of the system be no greater than 50 lbs to support safe lifting.

1.3 Field Study Plans

Field testing of the smart traffic signal at work zones will take place over two separate field study periods. Washington County south station has been identified as the primary location and group to coordinate pilot testing as a result of informal buy-in and coordination conducted as part of the interview process.

While the Washington County maintenance group expressed strong support to provide access and participation in the flagging operation field studies, the identification of candidate flagging operations during the scheduled dates of Field Study 1, i.e, May through August 2024, was not successful. This was because the majority of flagging operations occur during the county's brushing season, which begins in the fall and ends in the spring. The slightly shifted timeline following administrative changes to this project shifted the dates of the first pilot study to the summer months. Only very limited and unpredictable flagging operations occur in the summer months as crews complete crack filling maintenance tasks. The request for at least one week of data collection during the summer was not able to be met by Washington County. The maintenance team instead recommended a delay of the first pilot until the fall, when the brushing season resumes, and the second pilot in the following spring as the brushing season is reaching its end. This delay required a 6-month, no-cost extension to accommodate the downstream impacts on the remaining tasks.

1.3.1 Field Study 1 - Pilot Test of Sensor Capabilities & Usability

The first field study, conducted in Fall 2024, was carried out with the smart traffic signal deployed without the audiovisual alarm component at work zones, focusing on data collection of the sensing system and the overall usability of the system.

The primary research questions for the first field study were as follows:

1. Did the sensor system accurately and reliably measure oncoming vehicles?
2. Were there any usability issues with the current design?
3. Was the threshold for triggering the alarm appropriate?
4. Were there any unforeseen or unintended issues with the system's deployment?

Sensor Capability Testing

The first aim for the initial round of field testing was to assess the capability of the sensing system. As part of this aim, the sensing system was included in the field deployment and tracked and recorded vehicle position throughout the field study. The resulting vehicle tracking data were then analyzed in comparison to video recordings to ensure that oncoming vehicles were tracked accurately and reliably throughout the deployment period. Results of key interest for the sensor capability testing included hints of dangerous driving behavior that were observed, false alarms, misses, and correct cases in which a vehicle was observed but the warning threshold was not triggered.

1.3.2 Field Study 2 - Full System Deployment Testing

The plan for the second field study, to be conducted in spring and summer 2025, followed a deployment plan similar to the first field study but included the introduction of the audiovisual alarm component to the smart traffic signal.

The primary research questions for the second field study were as follows:

1. Was the alarm system effective in reducing dangerous driving behavior (i.e., reduced approach speed and reduced intrusion rates)?
2. Were the style and frequency of the alarm appropriate for both drivers and workers?
3. Were there any remaining usability issues or areas for improvement?
4. What modifications should be made to improve system performance and acceptance?

Chapter 2: Design and Fabrication of Second Generation Prototype Smart Signs

This intermediate task developed a second generation prototype instrumented STOP/SLOW sign for use by flag workers near a construction zone. The prototype sign was developed so as to be portable, lightweight, and rugged. Most importantly, it incorporated a radar sensor and embedded electronics with which trajectories of nearby vehicles can be tracked and the danger of potential intrusion by any vehicle into the construction work zone predicted. The developed radar and software system enables multiple vehicles in adjacent lanes to be simultaneously tracked using compact embedded electronics and algorithms implemented on a microprocessor. The rest of this chapter provides details on the features of the developed second generation prototype system and plans for field testing of the prototype in real-world construction zones.

2.1 Desirable Features of New Prototype Instrumented Sign

In a previous phase 1 research project titled "User-centered Smart Traffic Sign Development Study", a remote-controlled traffic signal was developed for use by a flag operator to control traffic near a construction zone. The instrumented traffic signal included an embedded radar sensor and electronics for detecting the danger of a potential vehicle intrusion and sounding an alarm to alert the errant vehicle driver. A vehicle simulator study conducted by the Human Factors team in the previous project concluded that a flag operator stationed next to an instrumented STOP/SLOW sign had a slightly higher rate of success in alerting errant drivers and making them respond to intrusion warnings. An instrumented STOP/SLOW sign could also be more lightweight and portable compared to the instrumented traffic signal. Based on these findings, it was decided to pursue the design, fabrication and in-field testing of an instrumented STOP/SLOW sign in actual construction zones in this implementation project. The desirable features for the instrumented STOP/SLOW sign were determined to be as follows:

- It should be a portable and wheeled device with easily switchable STOP and SLOW signs and an embedded intrusion danger detection system.
- Its weight should be less than 50 pounds.
- It is desirable that the sign can be easily disassembled by the flag worker into two parts for carrying on a pickup truck.
- The device should be rugged for operation on rough terrain and for rough handling.
- It should incorporate a speaker for providing audio alarms to errant drivers and a battery that enables 8 hours of continuous operation.
- The vehicle trajectory tracking and intrusion detection system should be embedded on the device with all sensors, microprocessor and electronics onboard the portable device.

2.2 Device Design and Prototype Fabrication

Fig. 2.1 shows a photograph of a fully developed prototype instrumented STOP/SLOW sign. The device is built on a wheeled box with rugged wheels. Electronics and a heavy battery are located inside the box. A photograph of the box itself with the electronics and battery inside it are shown in Fig. 2.3. The weight of the battery and of the bottom box itself ensure that the device will not topple over even in the presence of a strong wind.

A dual telescoping pole system is mounted on the wheeled box. The upper pole can be easily rotated to either the STOP or the SLOW side of the signs and locked into place by the flag operator. The upper pole can also be removed and stored separately while transporting on a pickup truck.

A radar chip and antenna, a Raspberry Pi microprocessor, a loudspeaker and other accessory electronics are mounted on the lower pole. The lower pole does not rotate so that the radar on it is always facing in the same direction to monitor oncoming traffic.

Figure 2.1 Photograph of instrumented sign for use by flag workers

The developed sign is portable and can be easily wheeled, as shown by one of the co-authors of this report in Fig.2.4.

The developed radar-based vehicle detection and tracking system works well and is able to track vehicles in multiple lanes, as shown in videos during the TAP presentation. The used slide contains synchronized videos of images from a camera and animations from the radar tracking system. Fig.2.5 is a still image of the same video.

The complete set of major electronic components used for a microprocessor-implemented distance tracking and audio-visual alert system that has been developed is shown in Fig.2.6. The integrated electronics with microprocessor have also been tested and preliminary tests show good performance.

Fig. 2.7 shows the integrated electronics enclosed inside a waterproof box and an adjacent waterproof audio-alert speaker.

Figure 2.2 Photograph of instrumented sign being used with a taller height, showing adjustability of desired height

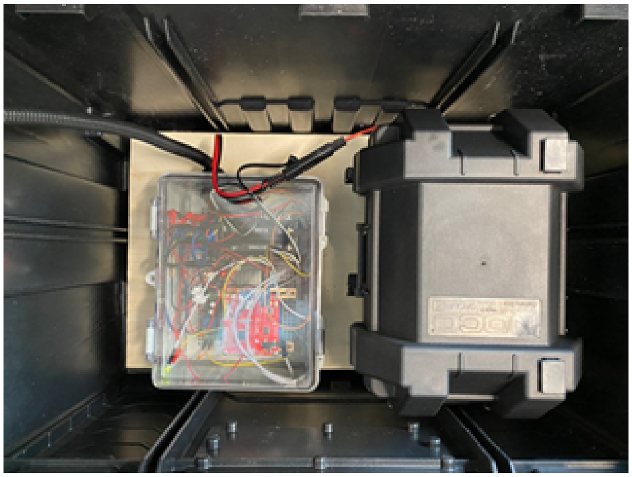


Figure 2.3 Photograph of the wheeled box on which the prototype sign is built, showing the electronics and battery located inside the box

Figure 2.4 Photograph showing that the portable device can be easily wheeled over a concrete floor

Figure 2.5 Complete electronics for a microprocessor-implemented distance tracking and audio-visual alert system

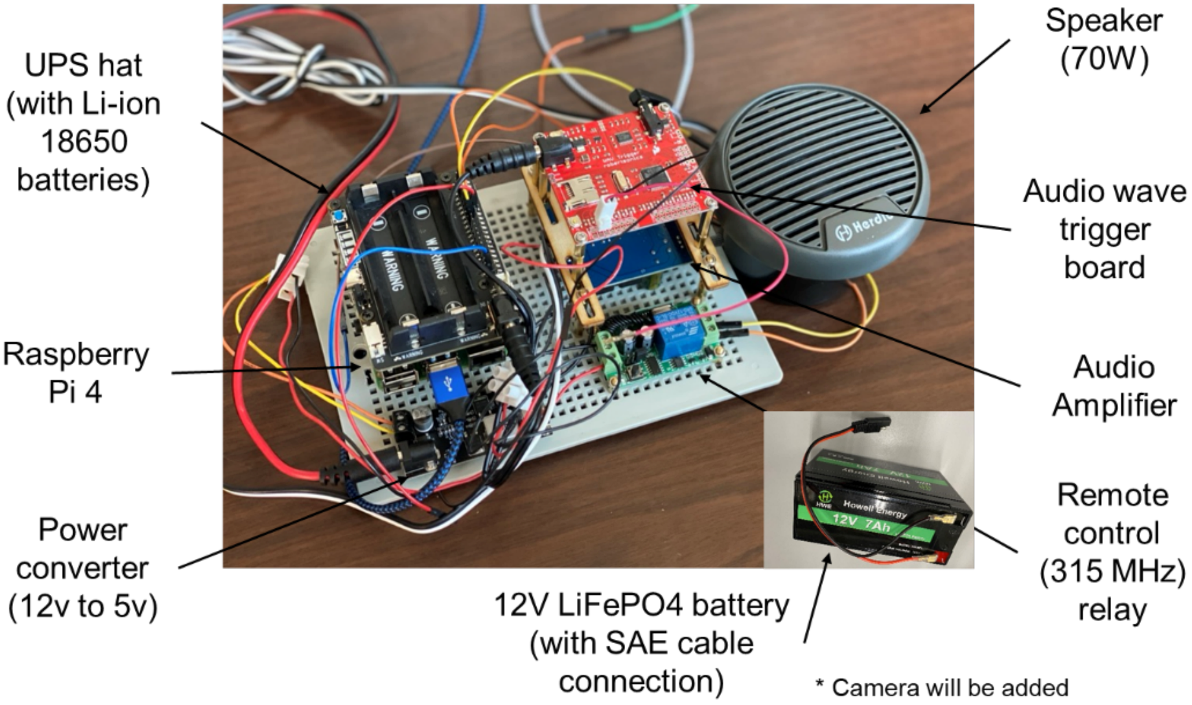


Figure 2.6 Complete electronics for a microprocessor-implemented distance tracking and audio-visual alert system

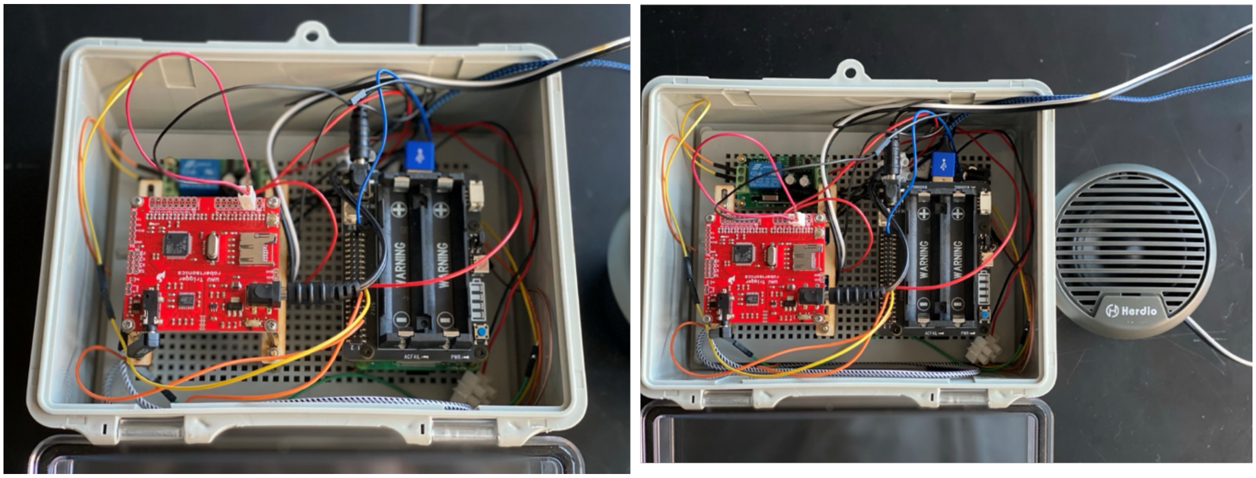


Figure 2.7 Electronics enclosed inside a waterproof enclosure

2.3 Test Plans

Based on the recommendations of the Human Factors team from Task 1, the following field studies were planned to be conducted:

2.3.1 Field Study 1 - Pilot Test of Sensor Capabilities & Usability

The first field study, to be conducted in Fall 2024 (~October), will be carried out with the smart traffic signal deployed without the audiovisual alarm component at work zones, focusing on data collection from the sensing system and the overall usability of the system. The primary research questions for the first field study will be as follows:

1) Did the sensor system accurately and reliably measure oncoming vehicles?
2) Were there any usability issues with the current design?
3) Was the threshold for triggering the alarm appropriate?
4) Were there any unforeseen or unintended issues with the system's deployment?

2.3.2 Field Study 2 - Full System Deployment Testing

The second field study, planned to be conducted in Spring 2025 (~ March 2025), followed a deployment plan similar to the first field study and included the introduction of the audiovisual alarm component to the smart traffic signal. The primary research questions for the second field study will be as follows:

1. Was the alarm system effective in reducing dangerous driving behavior (i.e., reduced approach speed and reduced intrusion rates)?
2. Were the style and frequency of the alarm appropriate for both drivers and workers?
3. Were there any remaining usability issues or areas for improvement?
4. What modifications should be made to improve system performance and acceptance?

Chapter 3: Third Generation Prototype Design and Field Study 1

3.1 Redesign of the Smart Traffic Sign

The two previous Phase 1 designs for the smart-sign device are shown in Fig. 3.1. (left) shows the concept envisioned at proposal time, a wheeled STOP/SLOW sign. Fig. 3.1. (right) shows the Phase 1 prototype: a remote-controlled traffic light operating in solid-red or flashing-yellow modes with embedded radar and trajectory-tracking software. User interviews suggested a remote light could let flag workers step out of the direct traffic line. However, the Phase 1 simulator study indicated a wheeled STOP/SLOW sign used by a flag worker was more effective at influencing driver behavior. Consequently, the Gen 2 prototype in Fig. 3.2 was developed in Task 2 of Phase 2.

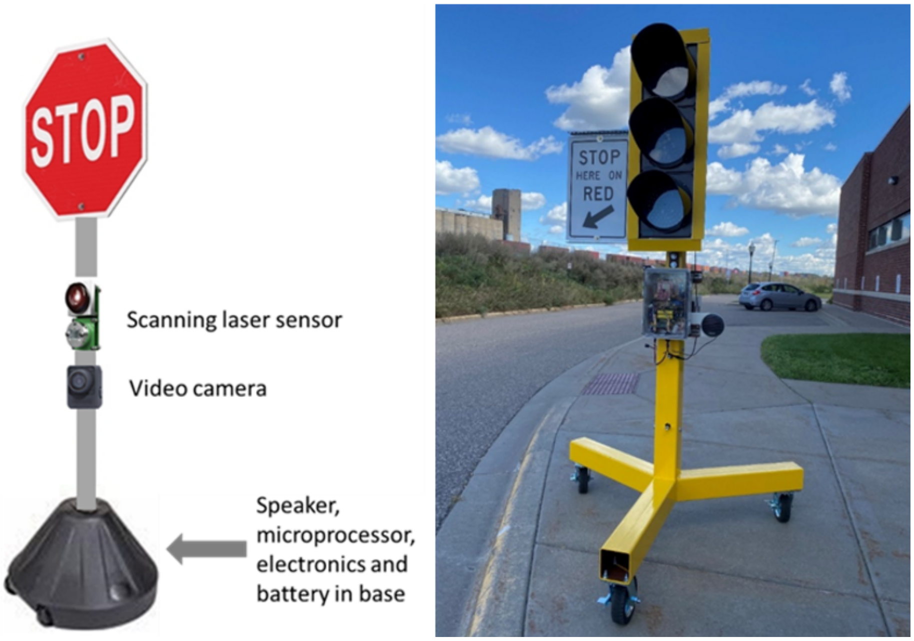


Figure 3.1 (left) Smart sign envisioned at proposal submission; (right) Phase 1 prototype developed from initial user inputs.

The Gen 2 prototype consists of a STOP/SLOW sign on a wheeled box with rugged wheels (Fig. 3.2). Electronics and a heavy battery are housed inside the box; their weight helps prevent toppling in strong winds. A dual telescoping pole mounts to the box. The upper pole rotates to present STOP or SLOW and locks in place; it can be removed and stored separately for transport. A radar chip and antenna, Raspberry Pi, loudspeaker, and ancillary electronics are mounted on the lower (non-rotating) pole, keeping the radar oriented toward oncoming traffic.

Figure 3.2 (a) Gen 2 prototype developed in Task 2; (b) radar and electronics decoupled from the STOP/SLOW sign.

3.1.1 Human Factors Heuristic Evaluation of Gen 2 Prototype

To evaluate risk to flagging staff while lifting the system, we assessed a standard lift (ground to truck bed) using the revised NIOSH lifting equation [32]. We assumed a 48 in truck-bed height based on discussions with flagging staff and included horizontal/vertical positions, lift frequency, and handle coupling. Lifting-index values at the origin ranged 1.63–2.39; at the destination 2.06–2.21. By risk thresholds, both origin and destination indicate increased risk of low-back pain/injury for some workers ($1 \leq \text{LI} \leq 3$).

3.1.2 Task Analysis of Gen 2 Prototype

Because the system may be frequently moved and redeployed multiple times per shift, we conducted an abbreviated hierarchical task analysis for setup/breakdown in a work zone. We identified 6 major tasks comprising 15 steps. The tasks for disassembly and storage are summarized in Fig. 3.3. Measured setup/breakdown time was 45 s (excluding radar boot time, since the system need not power down during moves).

Proposed Design Modifications

From the NIOSH and task-analysis findings and informal usability evaluations, we recommended:

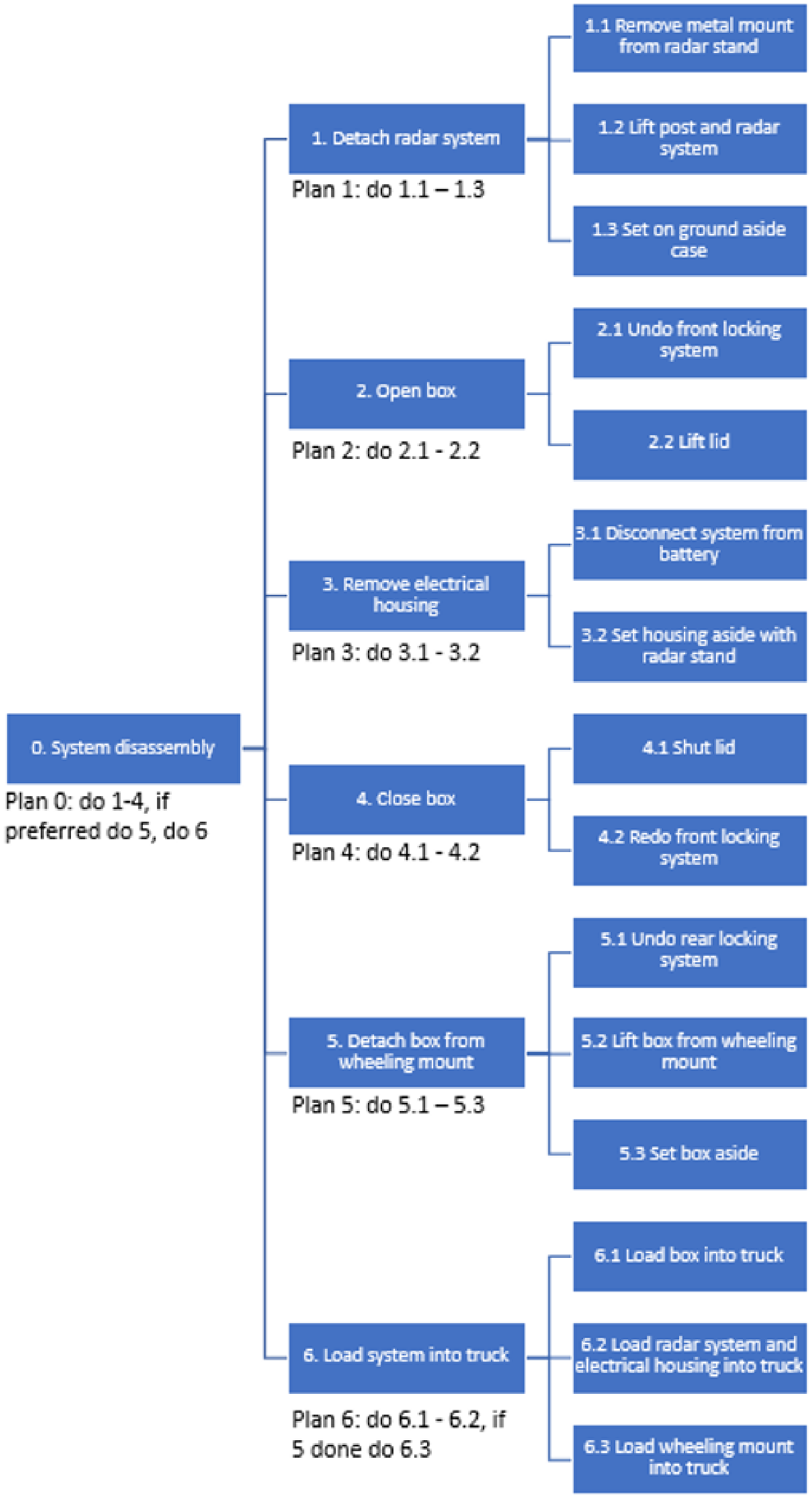


Figure 3.3 Hierarchical task analysis for disassembly of the Gen 2 prototype and loading into a truck.

1. Reduce overall system weight, improve handle comfort, and/or reduce reach distance required for lifting.
2. Reduce the time required to dis/assemble the system.
3. Move the electrical disconnect from the battery to the radar mount to reduce dis/assembly steps.
4. Enable all components to be stored together during transport or provide a dedicated transport enclosure.
5. Add a power indicator to reduce user confusion.

3.2 Device Redesign Description (Generation 3)

A full redesign was necessary because the Gen 2 wheeled box weighed 20 lbs by itself, limiting achievable weight reduction while retaining rugged wheels. We therefore adopted a lightweight toolbox-style case housing the main electronics and battery. An initial CAD model is shown in Fig. 3.4.

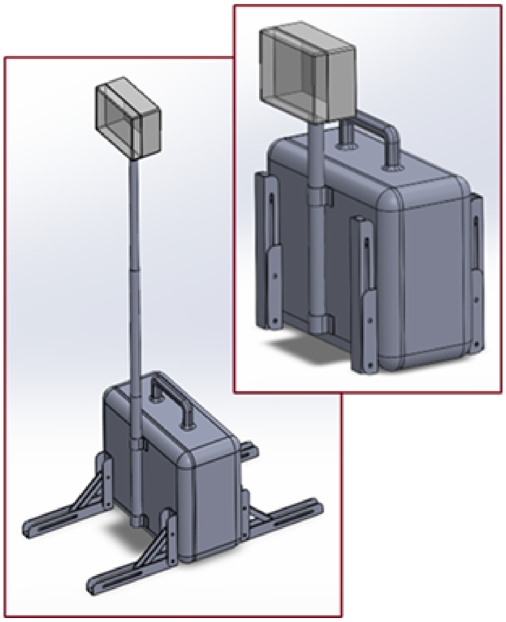


Figure 3.4 CAD drawing of proposed Gen 3 prototype.

The Gen 3 prototype is a waterproof box containing the radar sensor and dash-cam. It collapses into a compact case for transport and expands for operation. A telescoping pole raises the radar to the needed height; folding shelf brackets stabilize the case against wind.

The built Gen 3 device is shown in Fig. 3.5. Two identical units were fabricated. Wiring holes were sealed for weatherproofing. A green laser level assists alignment (special glasses are required in daylight).

Electronics from Gen 2 were integrated into the new design (Fig. 3.7). The Raspberry Pi, power splitter, WAV Trigger board, and amplifier mount on a removable panel; the battery is secured with Velcro straps.

Figure 3.5 Front view of Gen 3 prototype (left) and rear view (right).

Figure 3.6 Expanded Gen 3 prototype ready for deployment.

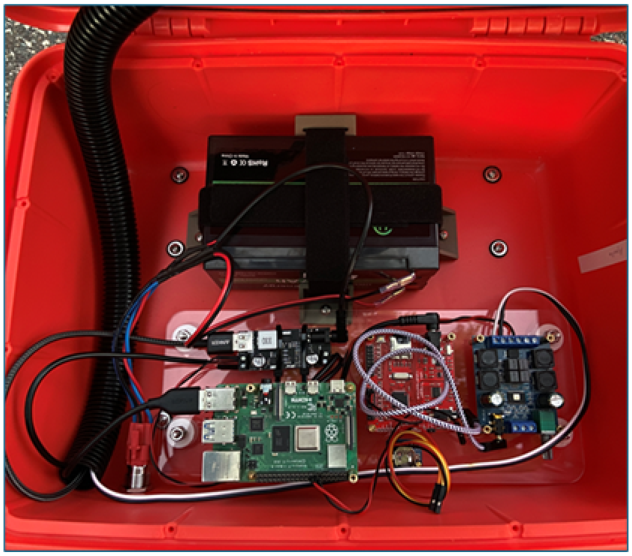


Figure 3.7 Battery, microprocessor, and other electronics inside the Gen 3 toolbox connected to the external radar and camera.

We upgraded to the AWR1843 radar ($299). It offers better resolution, accuracy, and range (configured for 120 m) and, crucially, tracks stationary vehicles reliably (the previous radar sometimes dropped stationary targets). Overall, the AWR1843 is more suitable for reliable long-range vehicle tracking.

The alarm algorithm now includes lane identification. The code models three lanes; warnings are issued only for vehicles in lanes 1 or 2, reducing false alarms from non-threat objects (e.g., pedestrians/bikes) outside those lanes.

3.2.1 Human Factors Heuristic Evaluation of Gen 3 Prototype

Using the revised NIOSH equation for the same ground-to-truck-bed lift, the lifting index at the origin was 0.24–0.71 and at the destination 0.50–0.86. By risk thresholds, neither lift stage imposes increased risk of low-back pain or injury (LI ≤ 1). Although designed for two-handed lifts, prior work indicates similar risk between one- and two-handed lifts [33, 34].

3.2.2 Task Analysis of Gen 3 Prototype

The Gen 3 hierarchical task analysis identified 4 major tasks and 7 total steps (Fig. 3.8). Several tasks/steps were eliminated relative to Gen 2—for example, the shut-off procedure shrank from 3 tasks/7 steps (tasks 2–4 in Fig. 3.3) to a single step (task 1 in Fig. 3.8). Setup time decreased from 45 s to 15 s.

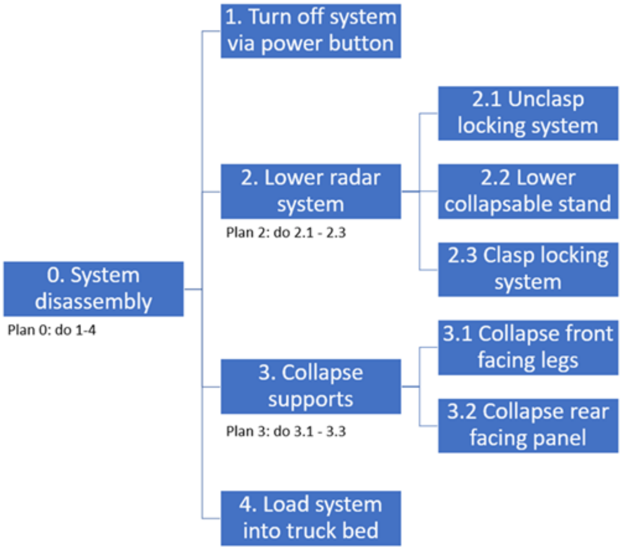


Figure 3.8 Hierarchical task analysis for disassembly of the Gen 3 prototype and loading into a truck.

3.2.3 Summary

Redesign produced measurable gains: lifting-index reductions (from “increased risk” to “no/minimal risk”) and faster dis/assembly (15 steps/45 s to 7 steps/15 s). Detailed results appear in Table 3.1.

Table 3.1 Usability metrics for both the Gen 2 and Gen 3 prototypes

NIOSH LIFTING RESULTS			
	Origin LI	**Dest. LI**	**Risk**
Gen 2	1.63–2.39	2.06–2.21	Increased risk
Gen 3	0.24–0.71	0.50–0.86	No increased risk
TASK ANALYSIS RESULTS			
	Tasks	**Steps**	**Time (s)**
Gen 2	6	15	45
Gen 3	4	7	15

3.3 Sensing Capabilities

Multiple conversations with the South Workshop preceded testing; an active work zone was difficult to schedule. On Nov. 6, 2024, Washington South Highway Shop employees set up a mock work zone with a flagger; we collected data and user feedback.

The pilot configuration and location appear in Figs. 3.9 and 3.10. The alarm was disabled (enabled in code, speaker unplugged); the code logged events when the alarm would have triggered. Radar data are saved continuously and can be replayed for any trigger.

Data from Device 2 (Fig. 3.10) were used for analysis; its placement farther from the four-way stop let

Figure 3.9 Pilot testing with the Washington County South Workshop in Woodbury.

Figure 3.10 Locations of the pilot test.

vehicles accelerate before entering the monitored region, yielding a better test of the alarm algorithm.

3.3.1 Results

The system tracks vehicle trajectories well. Radar-predicted motion matched video observations. Synchronized camera/radar animations (see TAP slides) show four consecutive approaching vehicles (screenshot in Fig. 3.11), demonstrating consistent, reliable tracking.


Time: 17.35
Frame: 2389
Warning State: 0 0

Figure 3.11 Screenshot of radar-tracking animations synchronized with video.

Speeds at 50 m from the radar (Fig. 3.12) cluster near 30 mph, below the posted 55 mph—likely due to proximity to the four-way stop and construction signs. Only a few vehicles approached substantially faster, suggesting few would require warnings.

At 20 m (Fig. 3.13), speeds center near 28 mph, indicating additional slowing near the zone—likely due to visible personnel and signage.

Only one vehicle triggered the alarm during the 30-minute session. The warning curve was configured for a 35 mph limit at 0 m, allowing higher speeds farther out and lower speeds closer in. One fast vehicle accelerated through the zone and passed the flagger and Device 2 at 60 mph, clearly exceeding the limit; the alarm trigger was therefore correct. No false alarms occurred.

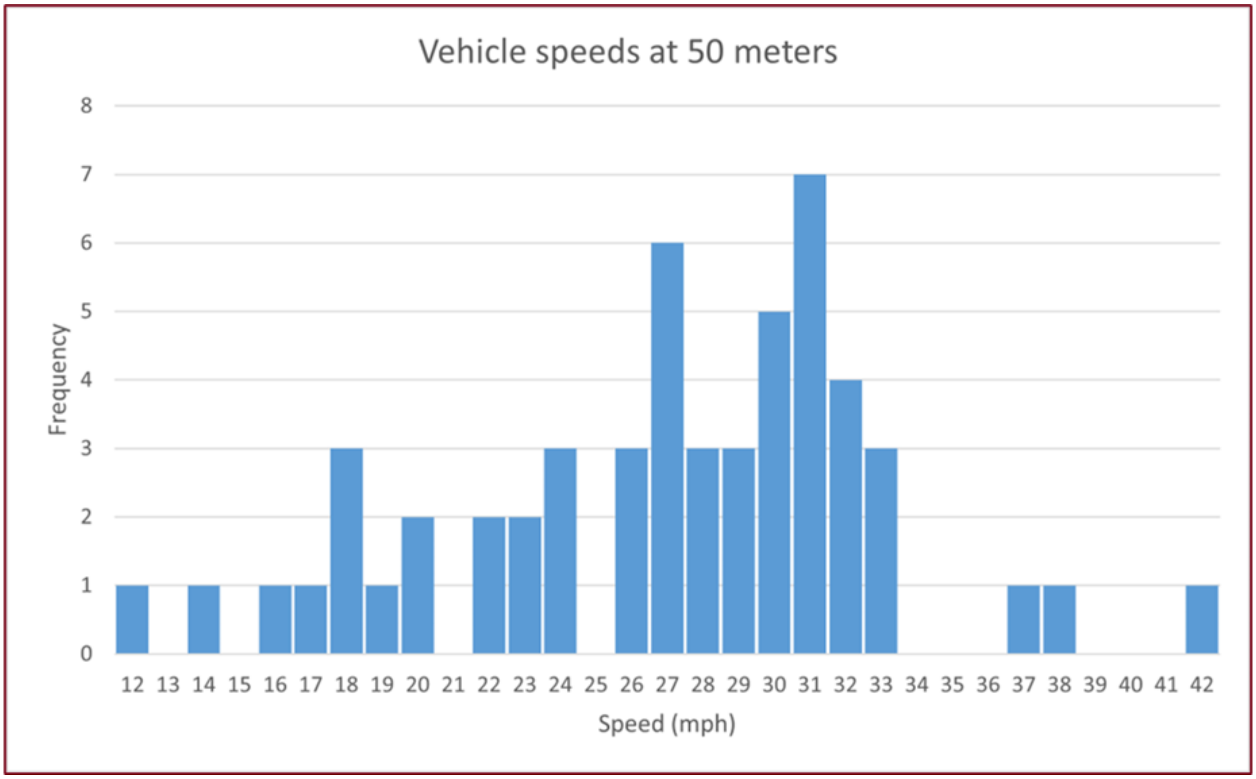


Figure 3.12 Distribution of speeds at 50 m by the radar system in Device 2 (Part 1 pilot).

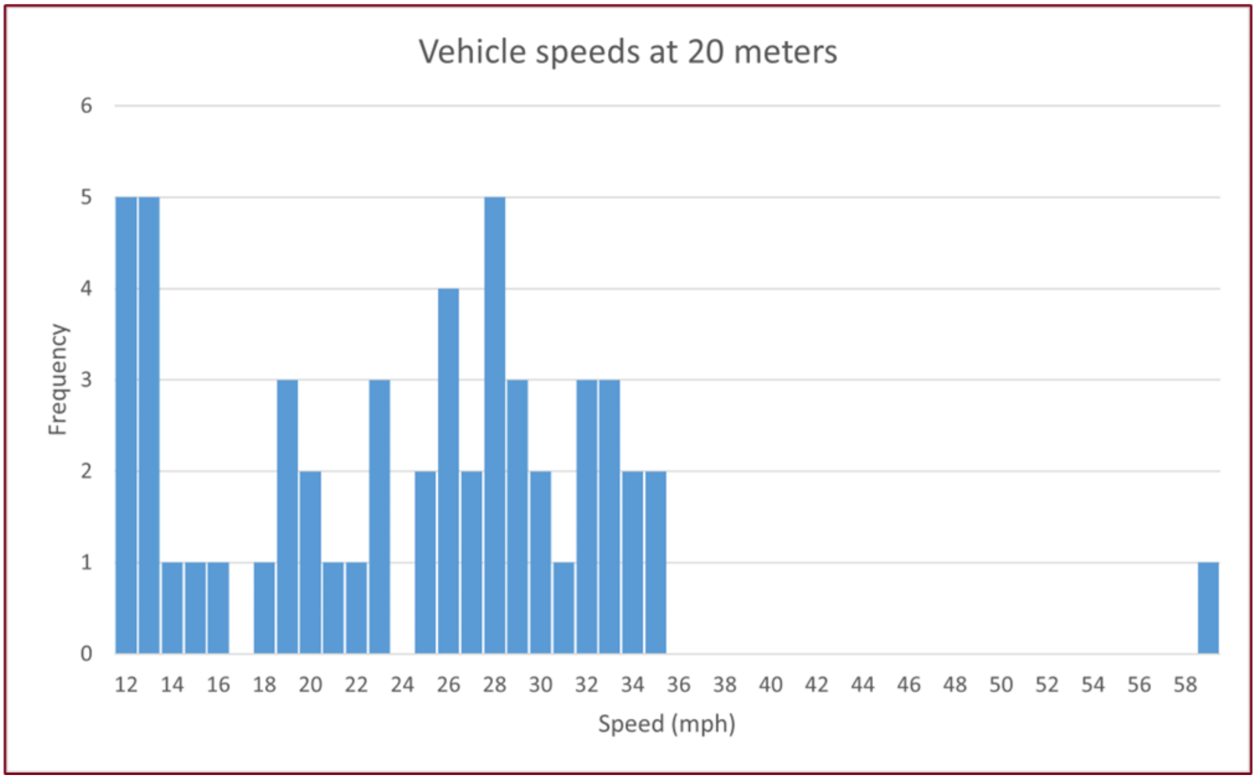


Figure 3.13 Distribution of speeds at 20 m from Device 2 (Part 1 pilot).

3.4 Usability Analysis

To address Task 1 questions about usability and unforeseen deployment issues, we interviewed South Workshop employees. Key suggestions from them were as follows:

- Add a strobe on top to improve driver visibility.
- Trigger a flashing light with the alarm to complement audio; some drivers may not hear audio (e.g., loud music).
- Consider alarm volume impacts in residential areas.
- Minimize burden during brushing operations; even 1–2 devices may be heavy to carry frequently.
- Provide tunable options (e.g., set roadway speed limit).
- Account for varying distance between an upstream device and a flagger-adjacent device; consider GPS-based distance calculation.
- Consider a wearable to alert the flagger of intrusions (feasible with more development time).
- Provide an in-truck/on-rack mounting system to secure the device during transport.
- Consult the North Workshop regarding use in fixed construction zones.

Chapter 4: Device Modifications for Field Study 2

4.1 Field Study 1 Findings & Recommendations

4.1.1 Summary of Field Study 1 Findings

As part of Field Study 1, the research team conducted both field testing of the modified system at a mock work zone, as well as informal interviews and usability testing with work zone flagging staff. The system was tested in a mock construction zone set up by the South Washington County Workshop. Data analyzed from the pilot tests showed that the developed system tracks vehicles reliably and accurately estimates their distances, velocities, and lane positions. One vehicle triggered the intrusion alarm, even with just 30 minutes of testing. The test verified that most vehicles tend to slow down and pass the mock construction zone with sufficient distance. Through the interviews conducted following the field testing, the flagging staff provided insight and feedback regarding the system to support design iteration for the second field study.

4.1.2 Recommended Modifications

In addition to continued field testing in Field Study 1 and ongoing discussions with flagging staff regarding system usability, a follow-up study—Field Study 2: Full System Deployment Testing—was planned to be conducted in Spring 2025. This study followed a similar deployment plan to Field Study 1 but incorporated system changes based on prior findings. Drawing on usability testing and Field Study 1 results, the following device modifications were implemented prior to Field Study 2:

1. Ability to measure distance from the work zone / flagger to the system via GPS
2. Addition of visual component to the alarm system, preferably in the form of a strobe light
3. Introduce ability for flagging staff to set and adjust the threshold for the alarm system, likely based on entering the speed limit of the roadway

4.2 GPS

GPS tracking capability was added to the revised system to accommodate feedback from workers to measure the distance between the two devices. This tracking system would allow for the primary device to measure its distance from the secondary device, a proxy measure of the distance to the flagger. A GPS module that provides updates with a frequency of 10 Hz has been integrated into each device to enable real-time reporting of their geographic coordinates. As illustrated in Fig. 4.1, the module is mounted on the back of the case. Wireless communication between devices is facilitated by a radio frequency (RF) module (detailed in the following section), allowing multiple devices to exchange GPS coordinates. This functionality is potentially beneficial for tuning the intrusion detection algorithm parameters, especially in dynamic construction zone scenarios where the relative distance of the upstream and downstream warning devices can change. Adjusting the algorithm of the target speed of approaching vehicles based on their distance to the flagger was suggested as an important feature to reduce false alarms of vehicles traveling at higher speeds further from the work zone and elevate warnings for vehicles quickly approaching the work zone at shorter distances.

Figure 4.1 Component configuration.

4.3 Warning Lights

A pair of LEDs has been mounted on top of the device, as shown in Fig. 4.1. These LEDs serve as additional visual warning signals to alert violating drivers and are capable of operating in multiple modes, combining both white and amber lights. In addition to the audio alerts, the visual warnings offer a range of flashing frequencies for enhanced visibility. Since the LEDs require a 12 V power supply while the Raspberry Pi GPIO pins provide only 3.3 V, a relay is used as a switch between the battery and the LEDs. The relays are shown in Fig. 4.2.

4.4 Radio Frequency (RF) Module

This module facilitates communication between multiple intrusion detection devices, enabling the exchange of data between them, specifically GPS coordinates in this application. It is housed within the

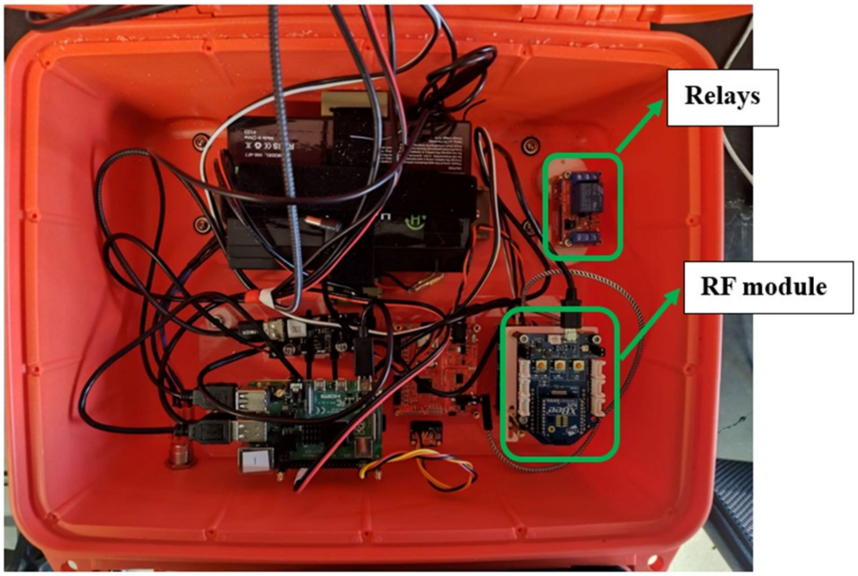


Figure 4.2 Electronics box with the newly implemented relays and the RF module.

electronics box, as illustrated in Fig. 4.2. The specifications of the RF device are detailed in Table 4.1, which indicates that the RF module operates at a data rate of 250 Kbps. Given that the maximum GPS update frequency is only 10 Hz, this data rate is more than sufficient to transmit and receive GPS data reliably without loss.

4.5 Conclusions

The system enhancements—GPS tracking, radio-frequency (RF) communication between devices, and a revised alignment mechanism—were implemented in response to flagging-staff feedback and to expand system capabilities. GPS synchronization between devices enabled measurement of the device–work-zone separation, supporting dynamic, distance-aware speed-threshold algorithms. This can prove especially useful for moving work zones where the device–flagger distance can change during operations.

Table 4.1 Radio frequency (RF) module specifications

Specification	**XBee Zigbee S2C**
Indoor/urban range	Up to 60 m (200 ft)
Outdoor RF line-of-sight	Up to 1200 m (4000 ft)
Transmit power output (maximum)	6.3 mW (+8 dBm), boost mode 3.1 mW (=5 dBm), normal mode; channel 26 max power is +3 dBm
RF data rate	250,000 b/s
Receiver sensitivity	-102 dBm, boost mode -100 dBm, normal mode

Chapter 5: Data Collection and Analysis from Field Study 2

Following lessons learned from Field Study 1, we updated the smart sign by adding a louder audio alarm, GPS sensors, wireless communication between upstream and downstream devices, and a remote-operated STOP/SLOW mode to enable different warning thresholds. Six tests were conducted in Field Study 2: one rural work zone, three urban work zones (Saint Paul, White Bear Lake, and Eden Prairie), one surrogate test (staged pedestrian crossing) and one greater Minnesota (Mound) zone. At the rural site in Cook County, only 7 vehicles were tracked in 105 minutes. At the urban sites, hundreds of vehicles were tracked and their speed–distance trajectories were obtained reliably. The audio alarm was permitted in only three tests; in one of them (White Bear Lake), false alarms occurred during the SLOW mode, prompting a redesign to support separate STOP/SLOW thresholds. After this change, the final two tests were run with all audio–visual alarms enabled: vehicles were tracked reliably, trajectories were accurate for intrusion detection. No intrusions or false alarms were observed in the test at Eden Prairie. In the tests at Mound, 11 vehicles were issued audio-visual alerts by the upstream device, 6 of those vehicles slowed down and the other 5 were issued audio-visual alerts by the downstream device. Overall, the device consistently tracked vehicle trajectories correctly and worked with no false alarms.

5.1 Device & Software Modifications

Because of delays in securing work zones for testing, we used the time to reassess and refine the alarm subsystem (audio and visual).

5.1.1 Audio Alarm Enhancements

To ensure the alarm is audible inside vehicles, we informally tested candidate audio sources in the Mechanical Engineering parking lot (University of Minnesota): a car horn, a 70 W speaker, and a 120 W speaker, measured from 50 ft to 200 ft in 50 ft increments. The setup is shown in Fig. 5.1; results appear in Table 5.1. The car horn was consistently louder than either speaker at all distances; the two speakers were within ± 2 dB of each other. To ensure detectability at up to 80 m (262 ft), we selected the car horn for both prototypes. During field deployments, the *audio–visual alerts were issued by the downstream device*.

Table 5.1 Sound intensities (dB) by source and distance

Distance (ft)	**Car horn (dB)**	**70 W speaker (dB)**	**120 W speaker (dB)**
50	100	80	80
100	96	75	76
150	90	70	72
200	83	68	70

5.1.2 Different Warning Thresholds for STOP and SLOW Modes

Phase 1 envisioned a concentric rotating pole with operator-set STOP/SLOW modes. Based on Washington County feedback in Field Study 1, the smart sign is now used upstream of the flagger and decoupled from the

Figure 5.1 Aerial view (Google Maps) of sound testing site with distance overlay.

flagger's STOP/SLOW paddle. Early Field Study 2 tests showed the need for different STOP/SLOW thresholds: audio warnings were triggered during SLOW but worked correctly during STOP. We added a remote wireless mode switch. In Eden Prairie where it was field tested, this switch worked reliably with no false alarms; STOP/SLOW warning curves are discussed in that section.

5.2 Field Testing

six locations and scenarios were identified for deployment of the system as part of the second round of field testing, which included both active work zones and a surrogate road scenario aimed at simulating vehicles approaching a flagger. Due to time constraints of the research schedule, as well as the difficulty finding appropriate work zones, the surrogate scenario was used for field testing which was a pedestrian crossing in which drivers were expected to come to a stop for the crossing pedestrian, similar to how they should come to a stop when approaching a flagger. In total the system was implemented for data collection across six separate data collection periods which were as follows:

i) Rural Work Zone Testing (Cook County):

- The systems were deployed at a rural work zone where 7 vehicles were observed over a period of 1 hour and 45 minutes.

ii) Urban Work Zone Testing (Ramsey County):

- The systems were deployed at an urban work zone, where approximately 567 vehicles were tracked over the course of one hour.
- We were not allowed to turn the audio alarm on for these tests.

iii) Urban Crosswalk Testing (Larpenteur Ave):

- The systems were deployed across two data collection sessions at an urban crosswalk where approximately 433 vehicles were tracked across a series of 52 pedestrian crossing events.
- The audio alarm was not used during these tests.

iv) Urban Work Zone Testing (White Bear):

- The systems were deployed at an urban work zone where approximately 481 vehicles were tracked over a period of approximately 2 hours.
- The audio alarms were initially deployed for the first time during these tests but triggered false alarms during the “Slow” mode of the flagging operation in which the vehicles were allowed to proceed by the flagger. Hence, the audio alarms had to be turned off. The device was redesigned to allow for remote wireless communication of Stop and Slow settings to the smart device.

v) Urban Work Zone Testing (Eden Prairie):

- At this urban work zone site, 37 vehicles were observed over an operating period of about 1.5 hours.
- The audio alarms were kept on with different warning thresholds for the Stop and Slow modes. The warning system worked reliably and did not trigger any false alarms. No intruding vehicles were detected in these tests and the data was analyzed in detail, as presented in the section of the report on the Eden Prairie tests.

vi) Suburban greater Minnesota work zone (North Shore Dr, Mound, MN)

- 66 vehicles were accurately tracked in 1.5 h.
- Different Warning curves were used for the upstream and downstream units. With the stop/slow modes applied to the downstream device.
- 11 alarms were triggered on the upstream device and 9 on the downstream unit in total.

5.2.1 Rural Work Zone (St.Louis County)

The first field implementation as part of field study 2 took place just outside of Cook, MN near the intersection of Goodwill Road and Deerwood Drive, which was a one-lane two-way roadway with low traffic density. This deployment was conducted in coordination with St. Louis County public works Cook Shop who were conducting brushing along Goodwill Road. This construction involved a stationary work zone which spanned the brushing range for the given shift that required lane closure and flagging operations while brushing. A diagram of this scenario is presented in Fig. 5.2, which includes the locations of where the systems were deployed for data collection shown via orange stars. This test involved very few vehicles – Only 7 vehicles were encountered in 1 hour and 45 minutes of data collection. Although the audio alarm was switched on, none of the public vehicles encountered triggered the alarm. A test carried out with our own vehicle traveling at a high speed beyond the speed limit did trigger the audio alarm correctly.

5.2.2 Urban Work Zone (Ramsey County)

The second field implementation as part of the second round of data collection took place near the intersection of Dale St N and Orange Ave W in Saint Paul, MN. This deployment was conducted in coordination with Ramsey County Public Works who were conducting a repavement of Dale St N. This construction site offered both a rolling work zone to conduct feasibility testing of the system as well as stationary work zones

Figure 5.2 Aerial view (Google Maps) of Goodwill Rd with work-zone layout and device locations (stars).

requiring flagging when the repaving process reached a pedestrian refuge at the intersection of Dale and Or-ange with moderate traffic density. A diagram of this scenario is presented below in Fig 5.3, which includes the locations of where the systems were deployed for data collection shown via orange stars.

Figure 5.3 Aerial view (Google Maps) of Dale St & Orange Ave with device locations (stars).

In this test, a total of 576 vehicles were successfully tracked over approximately two hours of data collection. Among them, 28 were identified as potential violators, representing 4.86% of the total. However, only two of these cases occurred when a flagger was present using the Stop mode; in all other instances, drivers were not expected to come to a complete stop (the Slow mode was in operation and no flagger was present). The audio alarm was kept switched off during these tests per request.

Figure 5.4 illustrates the velocity versus distance profiles of the 28 potential violators relative to the device, using a maximum deceleration of $0.2\,g$ to generate the warning curve. To further evaluate detection sensitivity, the analysis was repeated with different maximum deceleration thresholds. As shown in Fig. 5.5, the number of identified violators varies with the chosen deceleration limit. This parameter must be selected carefully so that it is neither overly lenient nor excessively strict, and its appropriate value is influenced by the roadway speed limit.

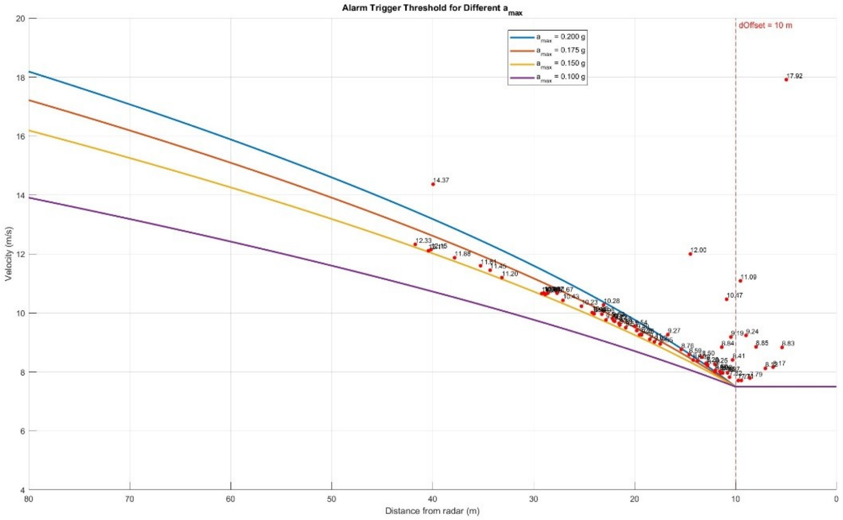


Figure 5.4 Violator speed vs. distance relative to the downstream device (0.2 g curve).

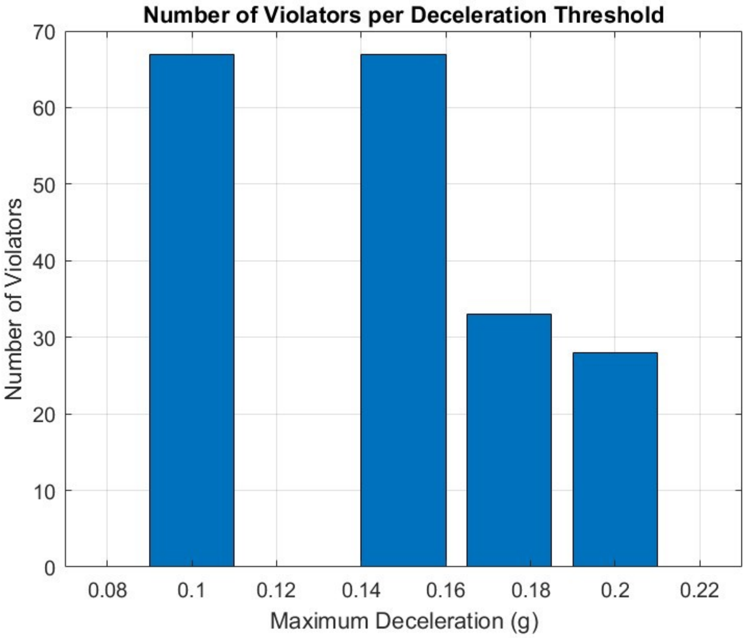


Figure 5.5 Violator count vs. different maximum deceleration thresholds.

5.2.3 Urban Crosswalk Testing (Larpenteur Ave)

The third field implementation as part of the data collection took place at the intersection of Larpenteur Ave W and Galtier St in Saint Paul, MN. This deployment was conducted by the research team at a crosswalk and monitored vehicles traveling eastbound on Larpenteur approaching the crosswalk when a researcher was present acting as a pedestrian attempting to cross the crosswalk. These pedestrian crossings served as a surrogate for a flagger, in which the approaching vehicle is expected to come to a stop prior to the crosswalk, similar to coming to a stop before the flagger at a work zone. This surrogate form of data collection was selected as a potential method for collecting driving stopping behavior without the need to test at a work zone, providing more flexibility and opportunity to the research team. A diagram of this scenario is presented in Fig 5.6, which includes the locations of where the systems were deployed for data collection shown via orange stars.

Figure 5.6 Aerial view (Google Maps) of Larpenteur Ave staged crossings with device locations (stars).

In this testing, two devices were deployed 150 ft apart—one positioned directly at the crosswalk where the pedestrian was crossing and the other located 150 ft upstream. The upstream unit was used only for vehicle tracking and post-processing to verify the accuracy of the tracking algorithm, while the downstream unit was responsible for detecting potential violators. Across 52 pedestrian crossings, the first approaching vehicle yielded in 34 cases, the alarm was triggered in only one case, and the remaining 17 cases did not stop so the pedestrian could cross. For this evaluation, and consistent with findings from previous similar tests, a $0.2\,g$ warning curve (speed versus distance) was selected as the warning threshold for the downstream device. The violator was traveling at 19.43 m s^{-1} when 70 m away, which was beyond the warning curve and therefore triggered a warning. The audio alarm was not turned on, since this test was conducted solely by the research team without any transportation-agency staff present.

5.2.4 Urban Work Zone (White Bear)

The fourth field implementation was conducted along County Road H2 E near the intersection with Fisher Street in White Bear Lake, MN. Unlike the earlier deployments, this test was designed specifically to evaluate and calibrate the threshold for the audio warning curves. Most importantly, it marked the first instance where the warning system was actively used with the audio turned on in a real-time application. To better understand the system's sensitivity, different warning curves were implemented for the upstream and downstream devices by applying distinct maximum deceleration thresholds. This allowed for a comparative evaluation of how varying thresholds influence violator detection and alarm triggering under real traffic conditions. The deployment was carried out adjacent to a stationary flagging operation, and the overall layout of the test is shown in Fig 5.7, where the device locations are indicated by orange stars.

Figure 5.7 Aerial view (Google Maps) of County Rd H2 E & Fisher St with layout and device locations (stars).

In this test, a total of 481 vehicles were successfully tracked over approximately two hours. Of these, only 6 were identified as violators, representing 1.25% of the total. For this deployment, a maximum deceleration of $0.175\,g$ was applied to define the warning curve on the downstream device, while a more lenient threshold of $0.1\,g$ was used for the upstream device, as illustrated in Fig. 5.8. Fig. 5.9 shows the velocity–distance profiles of the 6 violators relative to the device under this threshold. Similar to previous tests, additional analyses were performed using different maximum deceleration values to assess how the choice of threshold influences violator detection. As observed in Fig. 5.10, the number of detected violators varies with this parameter, emphasizing the importance of selecting a value that is neither overly lenient nor excessively strict, and that aligns with the prevailing speed-limit conditions of the roadway.

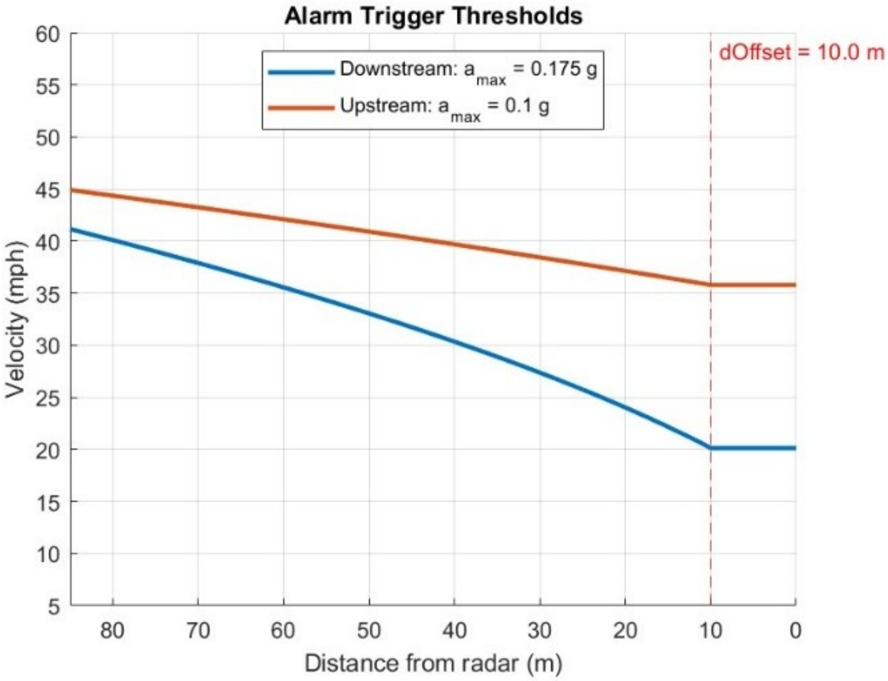


Figure 5.8 Downstream and upstream alarm thresholds.

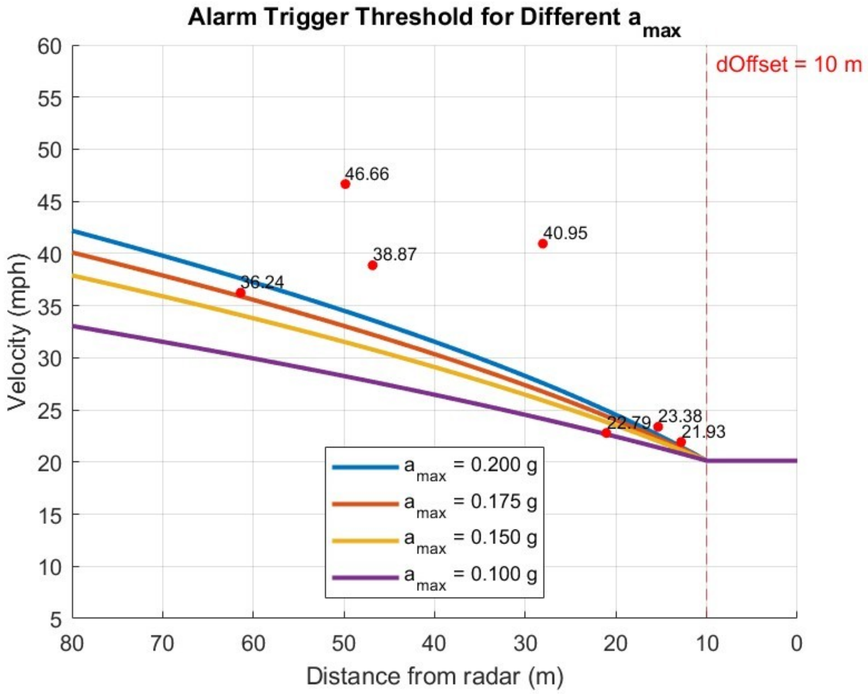


Figure 5.9 Violator speed vs. distance (downstream device).

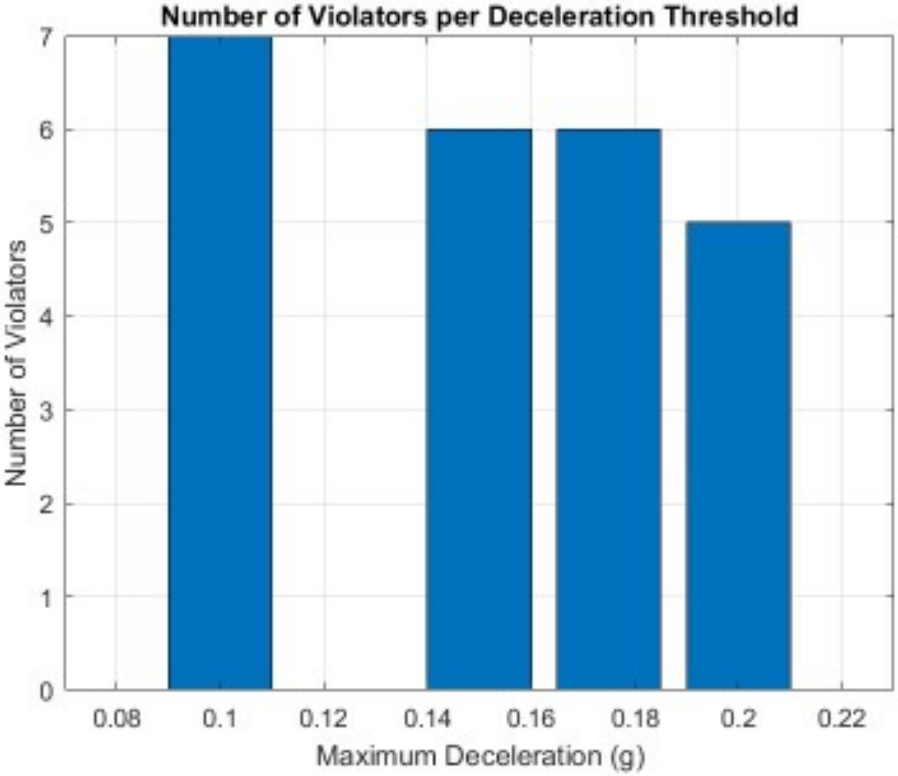


Figure 5.10 Violations vs. different maximum deceleration thresholds.

Due to the fact that we had to use the same warning thresholds for the Stop and Slow modes, the audio alarms were falsely triggered – All the 6 vehicles triggering the alarm did so during the Slow mode of operation. This test made us realize the importance of having different warning thresholds for the Stop and Slow modes. We then modified the device to take inputs from a wireless remote so that it could use the correct warning curve, depending on whether the Stop or Slow modes was in use. The modified device was then used for the next tests in Eden Prairie.

5.2.5 Urban Work Zone (Eden Prairie)

The next field implementation was carried out in Eden Prairie, MN, where the system was tested with dynamic STOP and SLOW modes for the first time, switching the mode in real time based on the flagger's indications. The downstream device was positioned approximately 5 m ahead of the flagger, while the upstream device was installed about 55 m upstream. Both devices were equipped with audiovisual alarms to warn approaching drivers. On the downstream device, the alarm was activated only when the flagger signaled "STOP" and was deactivated when switching to "SLOW." In contrast, the upstream device maintained the warning in both modes, ensuring continuous visibility to approaching traffic. The layout of this deployment is illustrated in Fig. 5.11, where the device positions are marked with orange stars.

Figure 5.11 Aerial view (Google Maps) of Spring Rd (Eden Prairie) with layout and device locations (stars).

For this deployment, a maximum deceleration of 0.2 g was applied to define the warning curve on the downstream device, while a more lenient threshold of 0.08 g was used for the upstream device, as illustrated in Fig. 5.12. Over a data collection period of approximately 1.5 hours, 37 vehicles were successfully tracked. Of these, 20 passed through in SLOW mode, where no warnings were required. The remaining 17 vehicles were tracked in STOP mode, with no violations observed. To further confirm this outcome, Figs. 5.13 and 5.14 illustrate that all radar points for both the downstream and upstream devices lie below their respective warning thresholds. While a small number of isolated points appear above the threshold, they do not correspond to the same vehicle across consecutive frames. Since a vehicle is classified as a violator only if it remains above the warning threshold for three consecutive radar frames (0.1 s total), no audio–visual warnings were issued during this test. As a positive outcome, no false alarms were triggered over the 1.5

hours of testing.

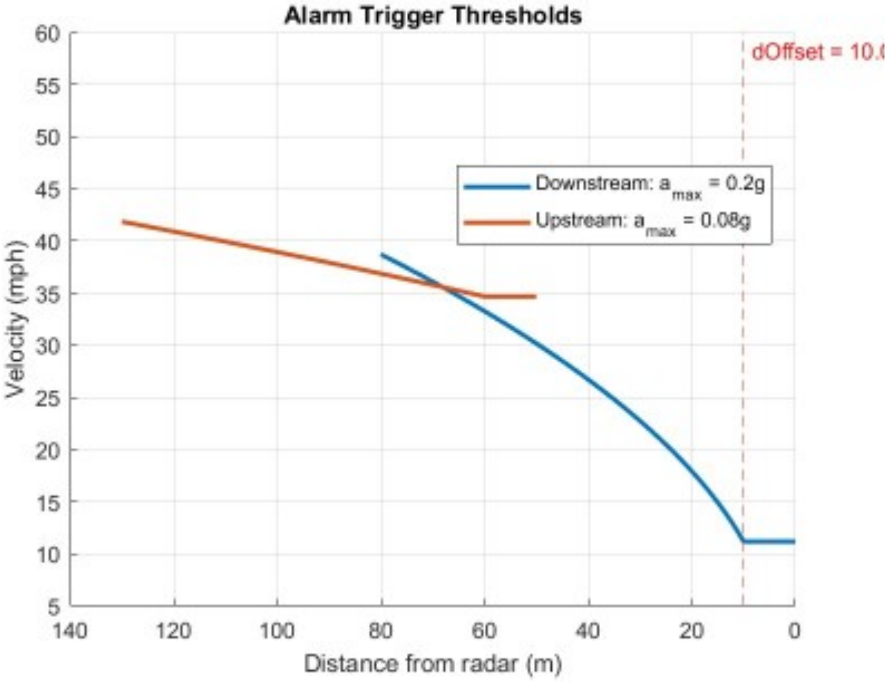


Figure 5.12 Downstream/upstream alarm thresholds.

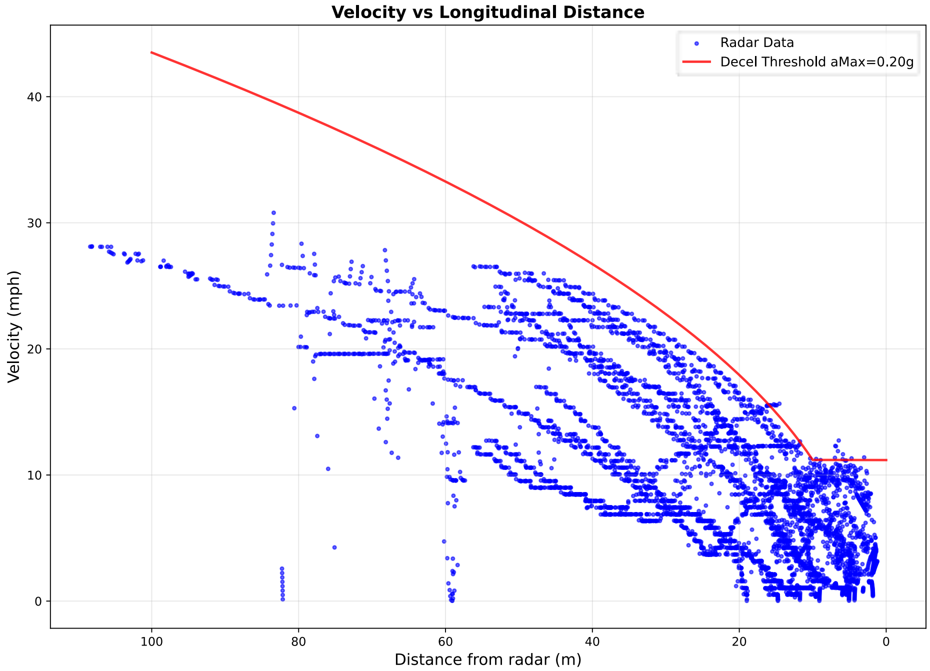


Figure 5.13 Downstream radar points vs. threshold.

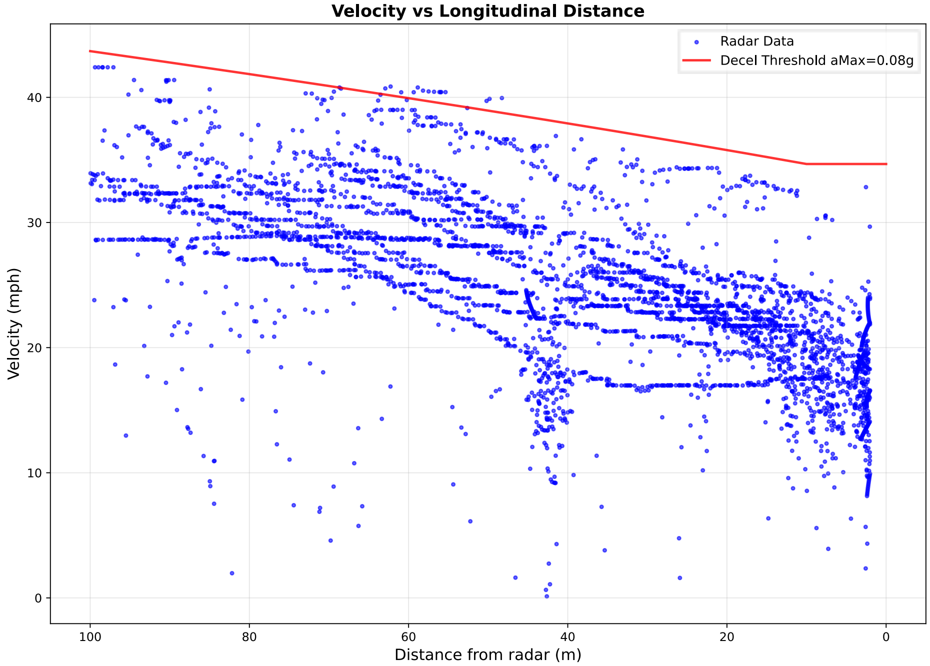


Figure 5.14 Upstream radar points vs. threshold.

For further analysis of driver behavior relative to the posted 30 mph speed limit, we inspected velocity distributions at a distance of 50 m from both the downstream and upstream devices. As shown in Fig. 5.15, the downstream device recorded lower approach speeds, with most vehicles traveling between 10–20 mph. This indicates that drivers approaching the work zone were generally slowing well below the speed limit, consistent with the presence of the flagger and work zone activity.

In contrast, the upstream device (Fig. 5.16) captured higher approach speeds, with the majority of vehicles clustered between 25–35 mph. This distribution suggests that while most drivers adhered to or stayed near the 30 mph limit when approaching from upstream, substantial speed reductions occurred only closer to the flagging station, as reflected in the downstream measurements.

5.2.6 Suburban greater Minnesota work zone (North Shore Dr, Mound, MN)

This testing was conducted along North Shore Drive, Mound, Minnesota. Since the posted speed limit was 30 mph, the same warning thresholds used in the Eden Prairie site were applied to both the upstream and downstream devices. The setup configuration for this testing is illustrated in Fig. 5.17.

During the 1.5-hour data collection period, a total of 66 vehicles were tracked. Among them, 11 drivers received warnings from the upstream device which corresponds to a significantly higher percentage compared to previous testings. In this road the speed limit reduces from 35 mph to 30 mph right before the workzone, This might be a contributing factor to the substantial increase in number of violators. The 11 violators were subsequently tracked by the downstream device after receiving the initial upstream warning to assess their behavioral response. As shown in Fig. 5.18, vehicles were tracked by the upstream device until approximately 60 m upstream of the downstream unit, and thereafter by the downstream device as they passed. The results revealed that 6 vehicles reduced their speed following the upstream warning, while 5 drivers failed to respond adequately and received a second alert from the downstream device. Among these, 4 drivers decelerated after the second warning, and only one driver disregarded both warnings and

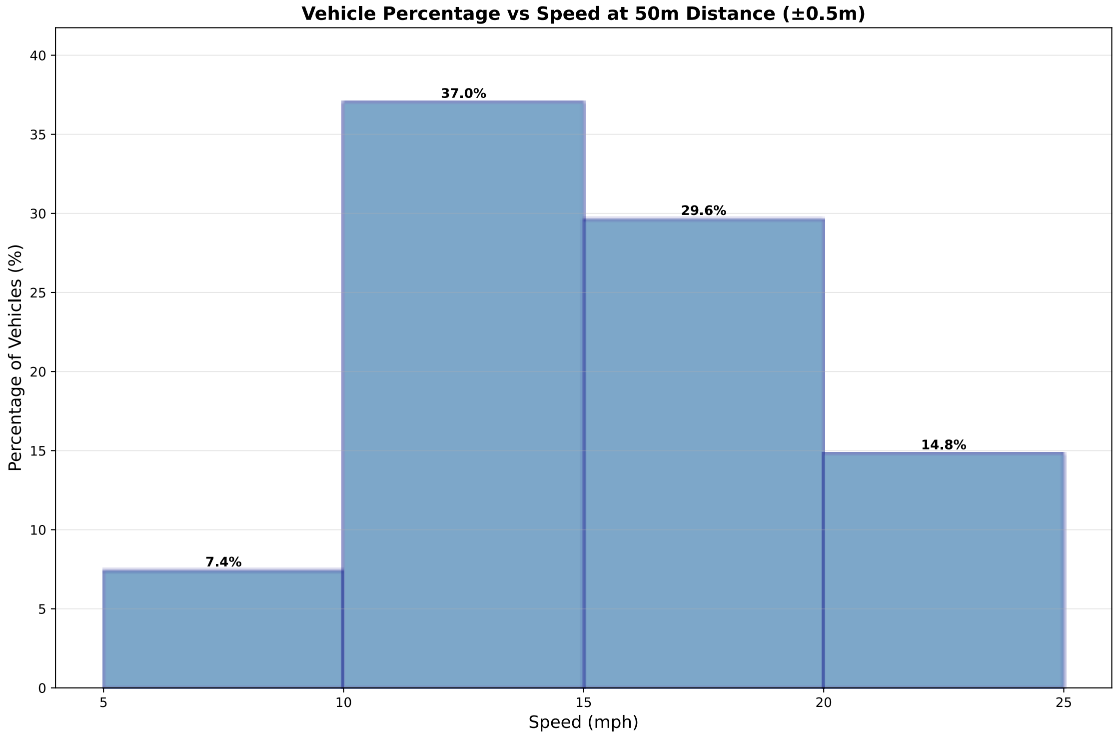


Figure 5.15 Vehicle speed distribution at 50 m (downstream device).

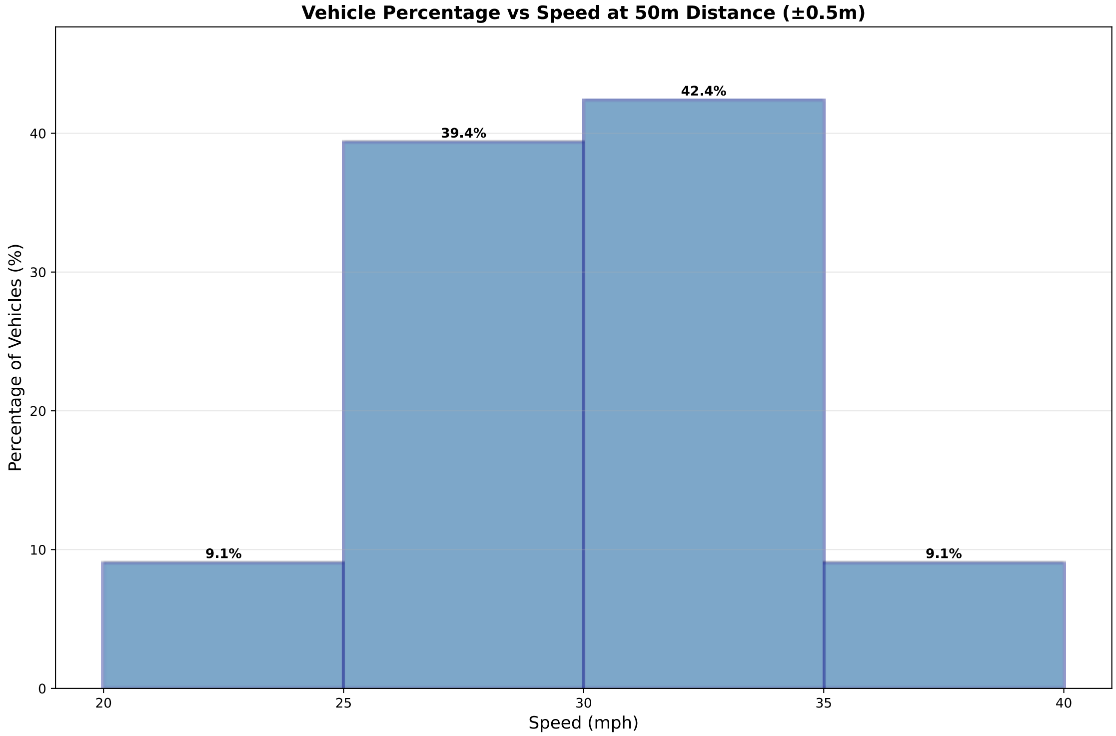


Figure 5.16 Vehicle speed distribution at 50 m (upstream device).

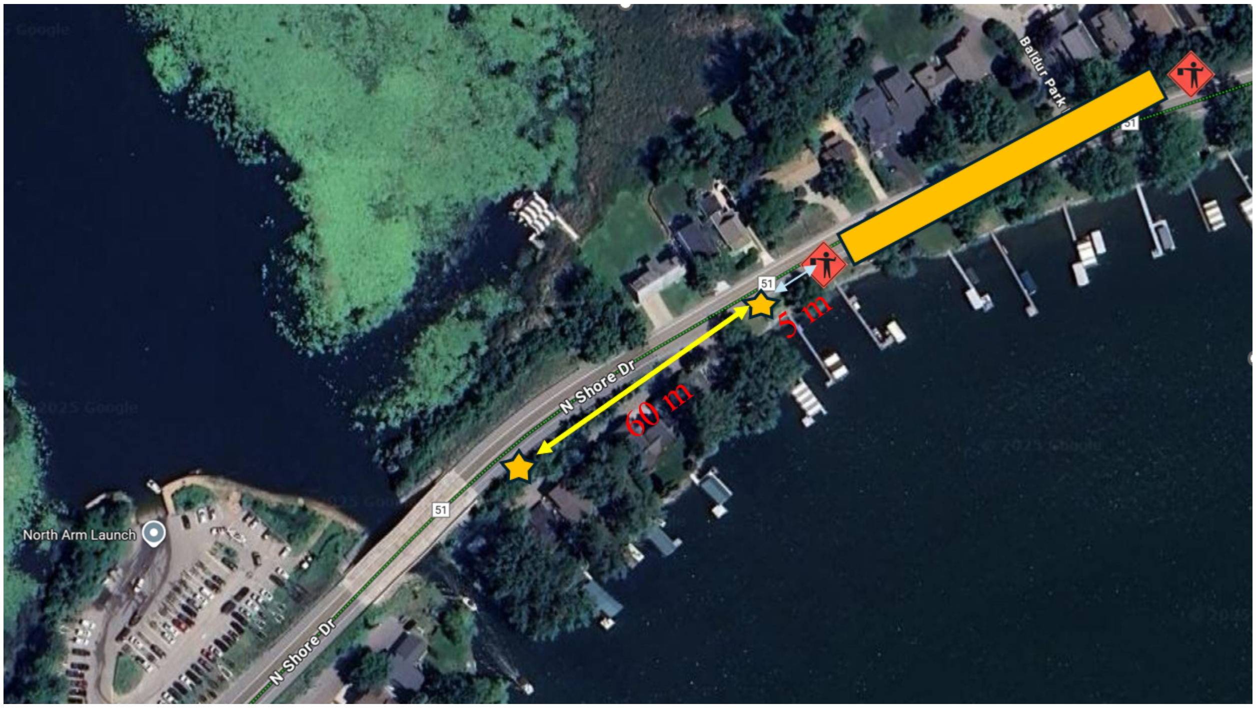
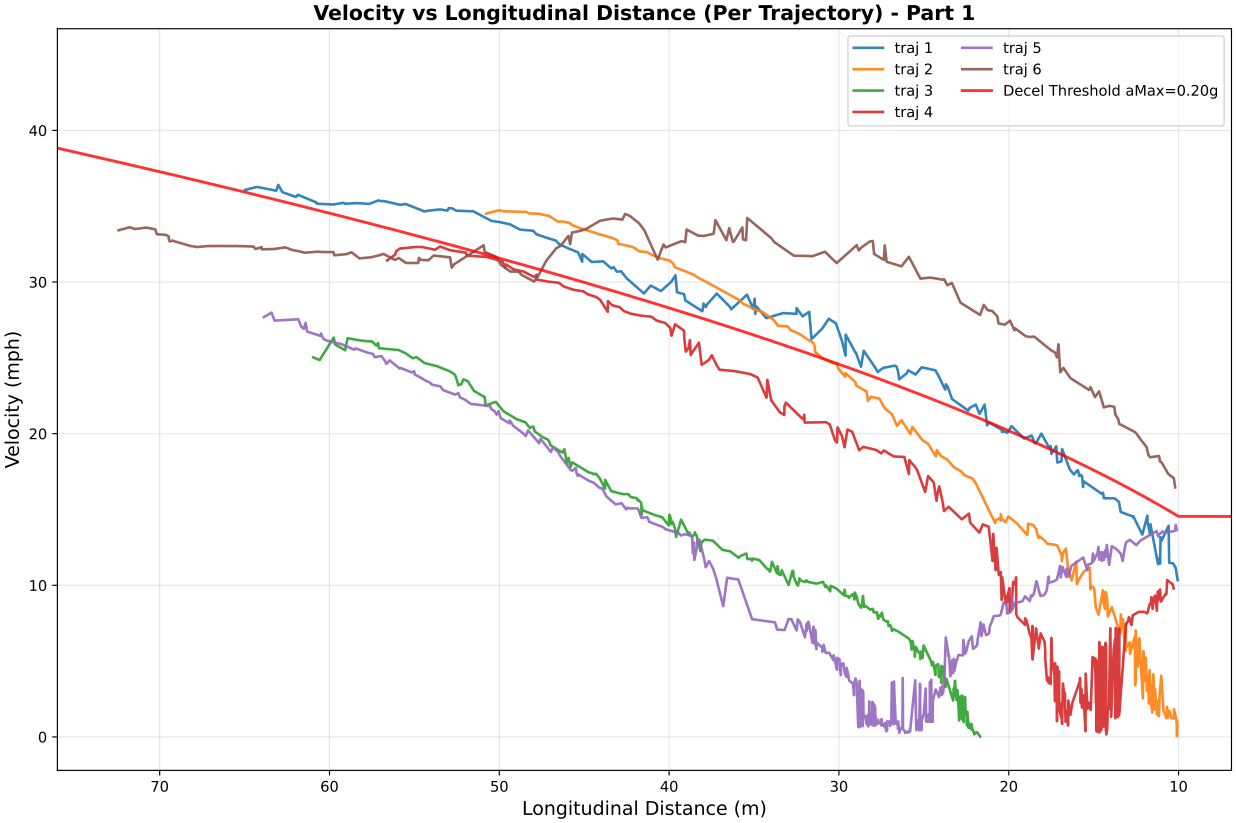


Figure 5.17 Satellite view of the North Shore Drive, Minnesota, field testing site. The yellow strip represents the designated work zone area, while the two stars mark the positions of the deployed upstream and downstream warning devices.

overshot the flagger. Table 5.2 summarizes the warning trigger points and the corresponding time required for each vehicle to reduce its speed by 10 mph, which includes both driver reaction and vehicle deceleration time. Most warnings were issued at distances between 100 m and 130 m from the downstream device, with velocities typically ranging from 35 mph to 40 mph which is above the posted speed limit 30 mph. The speed reduction time Δt_{10}, were generally between 2 s and 4 s for the upstream warnings and 1.5-3 s for the downstream warnings. Assuming the reaction time is 1 s on average. The deceleration rate of the violators after receiving a warning from the the upstream device is -2.25 m/s^2 on average, and for the downstream unit this value is -3.58 m/s^2, which is reasonable as the downstream device is closer to the flagger and people most likely break more aggressively in this case.

As illustrated in Fig. 5.19, most drivers began decelerating shortly after receiving the first warning, while some only responded after the second alert. A similar trend can be observed in Fig. 5.20, where the slopes of the longitudinal distance curves gradually flatten following the warnings, indicating smoother and progressive deceleration behavior as expected.

The same analysis was performed on the downstream device, revealing that in addition to the five incidents where drivers received warnings from both devices, four drivers were exclusively warned by the downstream device. Figure 5.21 illustrates these four trajectories along with the warning threshold. It can be observed that all targets were reliably tracked from approximately 60 m away and promptly alerted if violating the threshold. Table 5.3 presents the measured warning trigger points and corresponding driver response times for vehicles that received alerts exclusively from the downstream device. All warnings were triggered at distances ranging from 40 m to 60 m, with velocities between 30 mph and 34 mph. The observed reaction plus deceleration times, $\Delta t_{10\ mph}$, ranged from 1.5 s to 2.2 s, indicating that drivers responded promptly after receiving the downstream warnings.



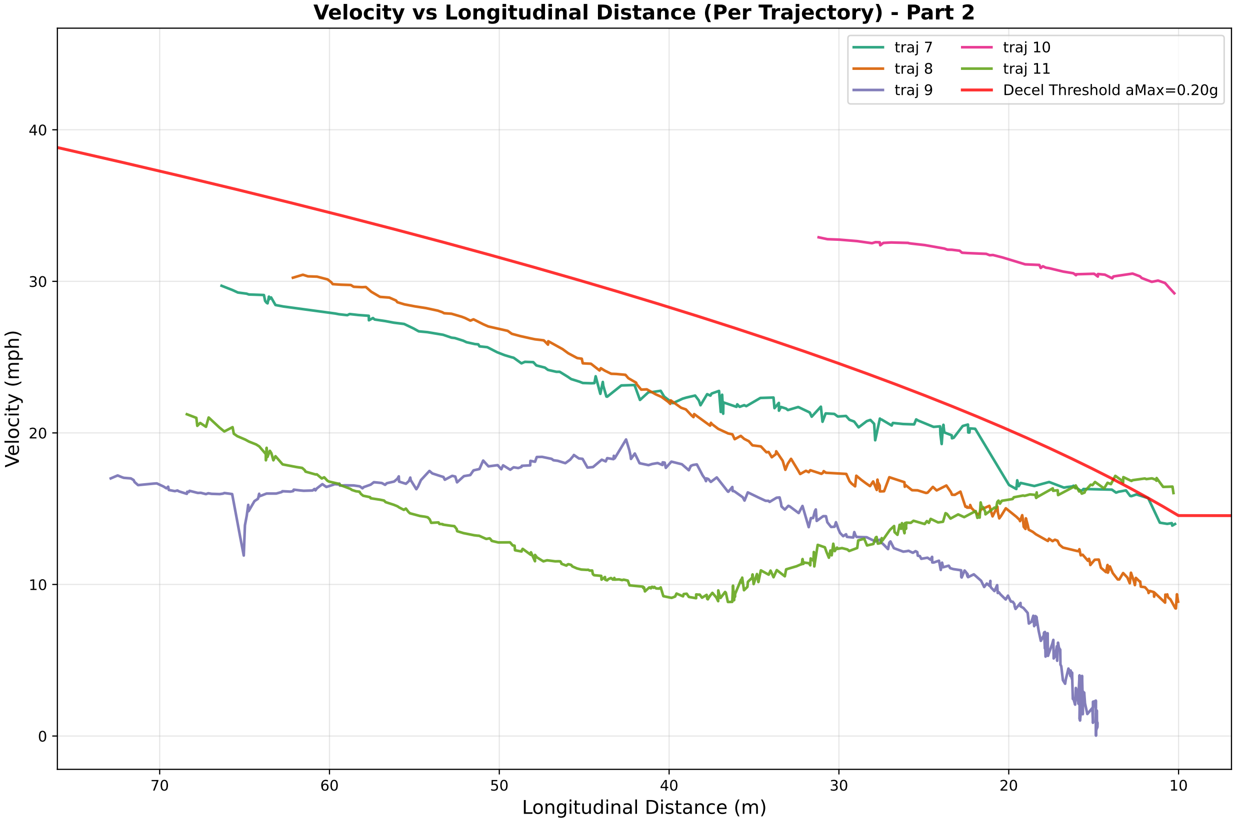
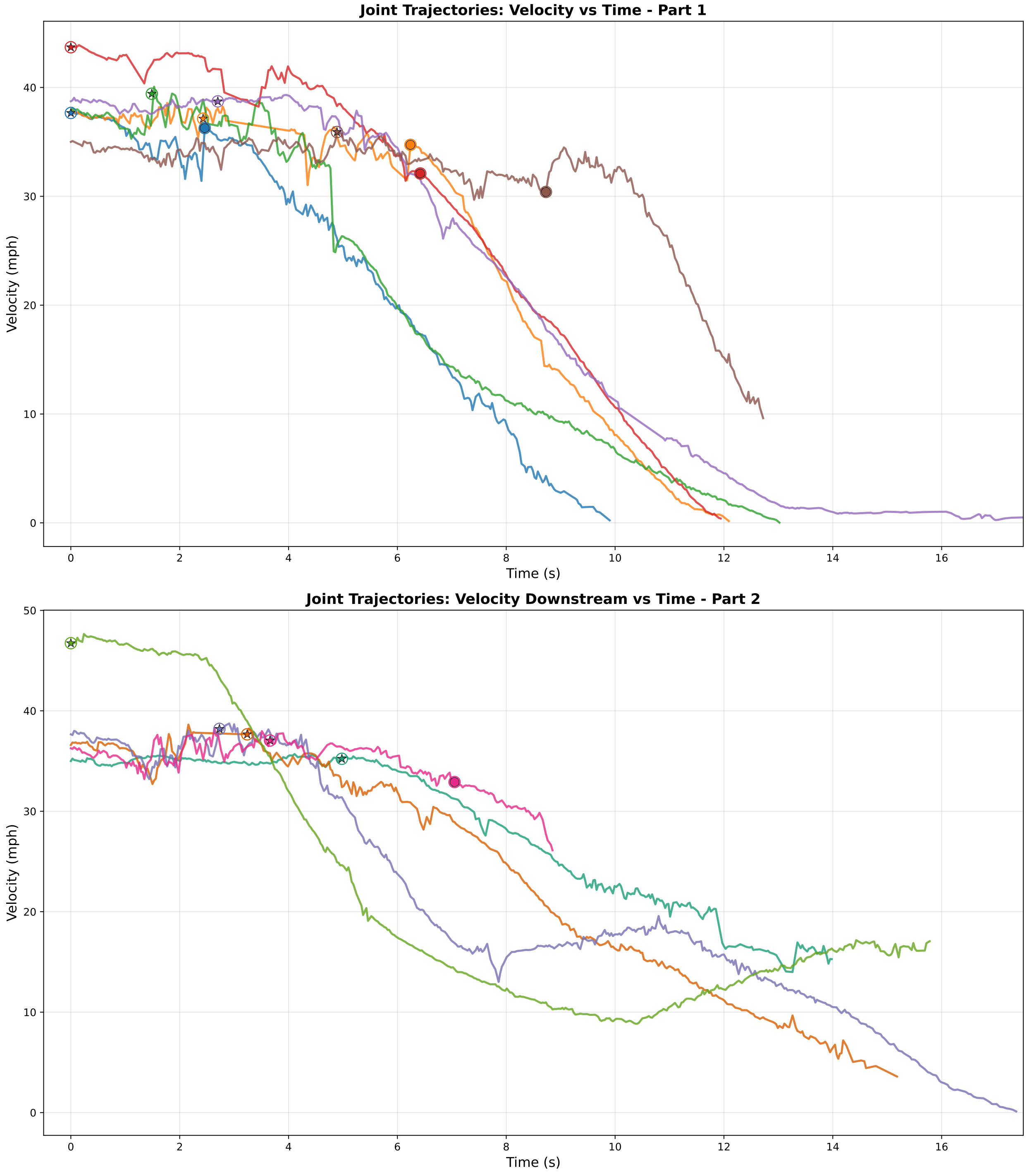


Figure 5.18 Joint vehicle trajectories recorded during the North Shore Drive field testing, showing velocity profiles with respect to longitudinal distance from the downstream radar point of view.



Joint Trajectories: Velocity vs Time - Part 1

Joint Trajectories: Velocity Downstream vs Time - Part 2

Figure 5.19 Joint vehicle velocity profiles over time for the North Shore Drive field test. The top and bottom plots correspond to two subsets of the eleven tracked trajectories that triggered warnings. Star markers denote the time instants when upstream warnings were issued, while circular markers indicate downstream warnings.

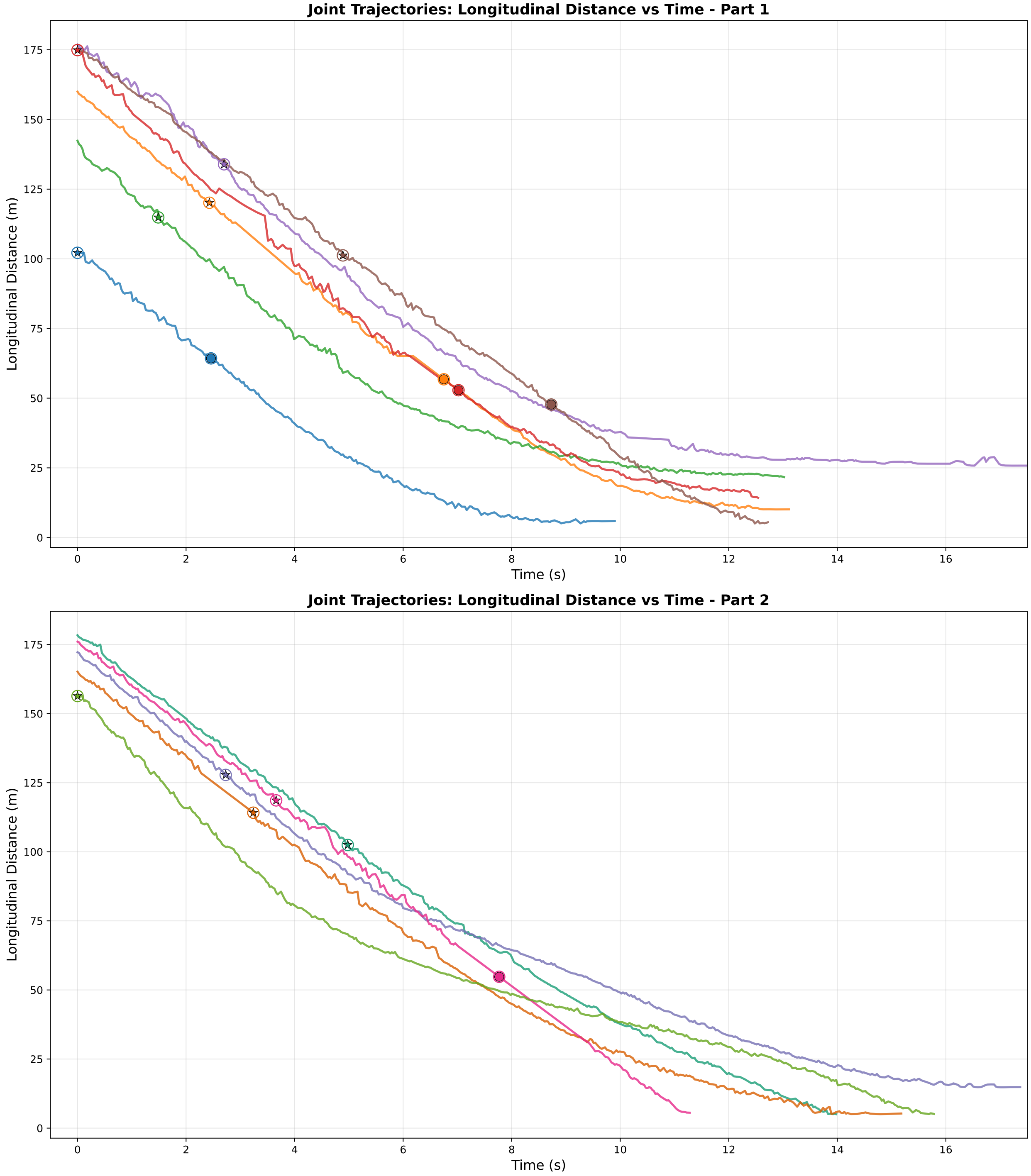


Figure 5.20 Joint Longitudinal distance profiles of the tracked vehicles during the North Shore Drive field testing. The top and bottom plots correspond to two subsets of the eleven trajectories that triggered warnings. Star markers denote the instants when upstream warnings were issued, while circular markers represent downstream warnings.

Table 5.2 Measured Warning Trigger Points and Corresponding Time to Reduce Speed by 10 mph

Traj	Up Dist (m)	Up Vel (mph)	Up Δt_{10} (s)	Down Dist (m)	Down Vel (mph)	Down Δt_{10} (s)
1	102.16	37.66	2.52	64.28	36.27	2.43
2	120.12	37.14	3.78	56.77	33.25	1.53
3	114.87	39.42	3.33	N/A	N/A	N/A
4	174.89	43.70	5.97	52.85	32.09	1.68
5	133.92	38.72	4.02	N/A	N/A	N/A
6	101.23	35.91	2.82	47.71	30.40	2.76
7	102.47	35.23	3.09	N/A	N/A	N/A
8	114.14	37.66	3.45	N/A	N/A	N/A
9	127.82	38.20	2.55	N/A	N/A	N/A
10	118.60	37.05	3.72	54.76	32.65	N/A
11	156.36	46.74	3.51	N/A	N/A	N/A

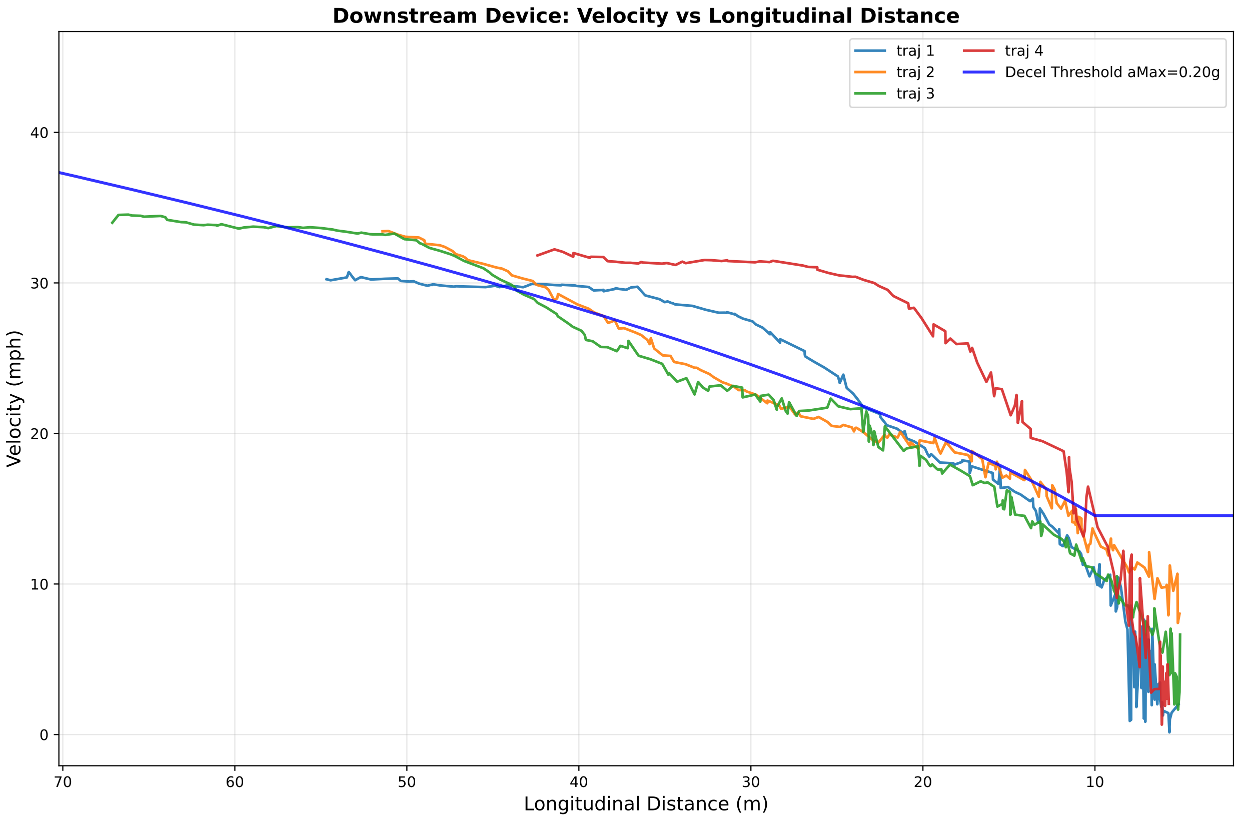


Figure 5.21 Velocity–distance profiles from the downstream device captured during the North Shore Drive field testing.

Table 5.3 Measured Warning Trigger Points on the downstream device and Corresponding Time to Reduce Speed by 10 mph

Trajectory	Downstream Dist. (m)	Downstream Vel. (mph)	Downstream $\Delta t_{10\ mph}$ (s)
1	44.15	29.84	1.98
2	51.41	33.43	1.53
3	56.92	33.69	1.68
4	42.41	31.82	2.16

As illustrated in Fig. 5.22 the velocity-time profiles show a noticeable drop in velocity shortly after the warning trigger points, indicating prompt deceleration behavior following the alerts. The varying steepness of the curves demonstrates differences in driver reaction times and braking aggressiveness. In Fig. 5.23 the profiles show a smooth decrease in distance, with the slope gradually flattening after the warnings, confirming that vehicles decelerated to a stop as they approached the flagger. These results validate that the warning system effectively influenced driver behavior, reducing vehicle speeds and improving safety in proximity to the work zone.

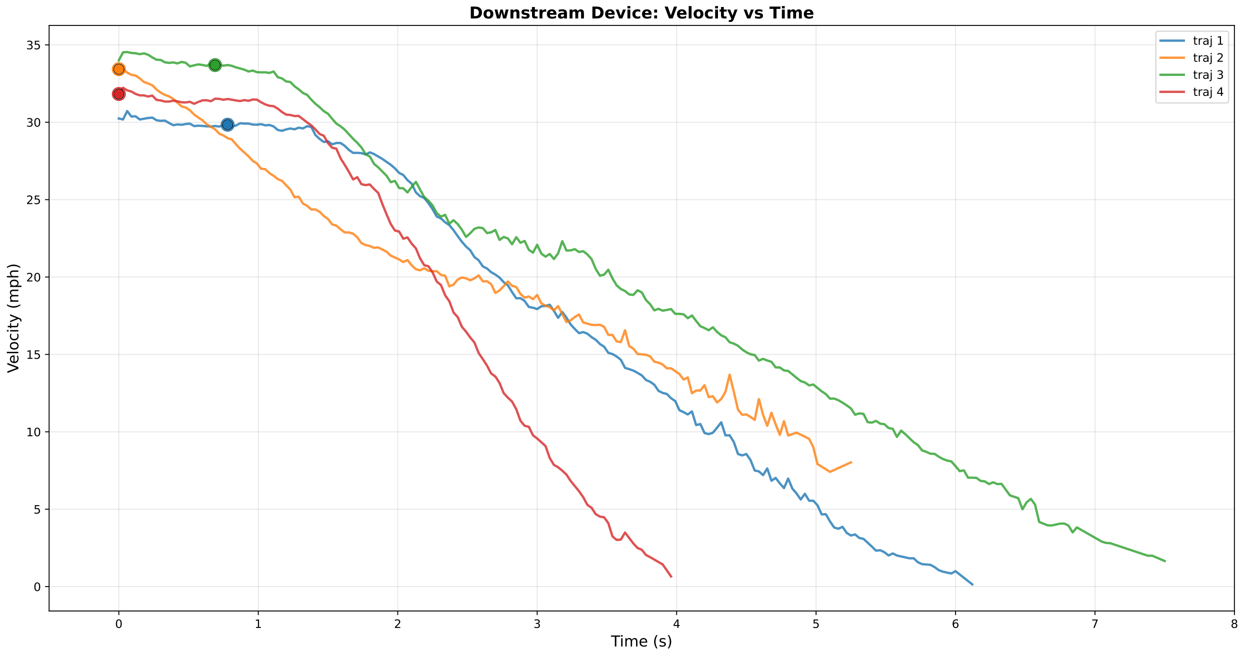


Figure 5.22 Velocity–time profiles from the downstream radar device during the North Shore Drive field testing. Each trajectory represents a vehicle that received a downstream warning, with circular markers indicating the moments when warnings were triggered.

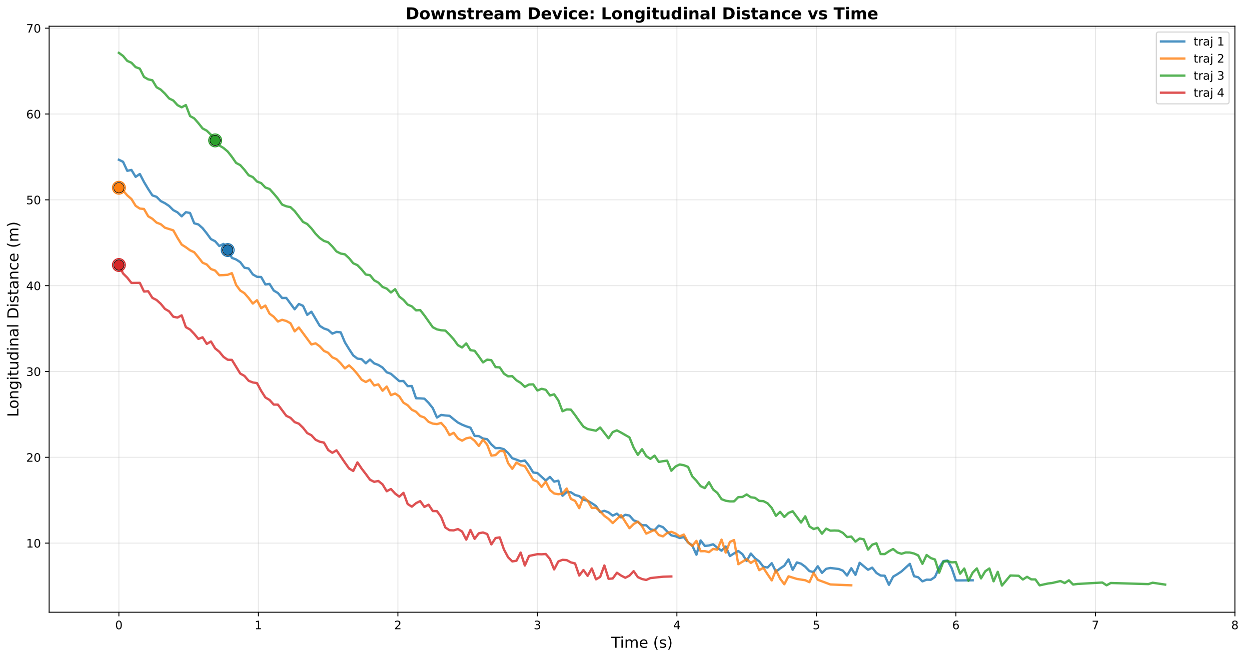


Figure 5.23 Longitudinal distance–time profiles recorded by the downstream device during the North Shore Drive field testing. Each curve corresponds to a vehicle trajectory, with circular markers indicating the moments when warnings were triggered.

Chapter 6: Conclusion

Flaggers keep traffic moving through work zones even when lanes are closed by providing temporary traffic control. Their work is also among the most hazardous in transportation, with an estimated 41 out of every 100,000 workers killed on the job each year. This project set out to reduce that risk by building and testing a low–cost, portable system that automatically tracks approaching vehicles, detects potential near–intrusions into flagger–controlled areas, and issues audio–visual alerts to warn drivers who might endanger workers.

The device evolved through several design iterations in direct response to feedback from roadway agencies. We began with a flagger–operated traffic signal with embedded radar, moved to a wheeled STOP/SLOW unit, and ultimately converged on a compact toolbox–style package weighing about 15 lb. The final design deploys quickly with fold–out brackets and a telescoping pole, uses automotive radar for lane–level tracking, and runs real–time trajectory estimation (distance, speed, lane) on a Raspberry Pi. Field work spanned six real–world scenarios: one rural site (Cook County), three urban sites (Saint Paul, White Bear Lake, Eden Prairie), a staged pedestrian crossing (Saint Paul), and a suburban/rural corridor (North Shore Dr, Mound). In four deployments we logged data only to validate tracking and warning logic; in two deployments we enabled audio–visual alerts. In the first alert–enabled test, no vehicles posed a risk, so no alarms were issued. In the other, 11 upstream alerts were triggered; six drivers slowed after the first warning and five later triggered a reinforcing downstream alert—evidence that a two–device, upstream–downstream strategy can shape approaching traffic before it reaches the flagger.

The final test on North Shore Drive (posted at 30 mph, with a reduction from 35 mph just before the work zone) offered the clearest picture of driver responses under the refined configuration. Over 1.5 hours, the system tracked 66 vehicles and issued 11 upstream warnings—a higher share than previous sites, likely due to the late speed-limit reduction on this road. Of the 11 drivers warned upstream, six slowed after the first alert; five required a downstream alert, and four of those slowed after the second. Only one driver ignored both warnings and overshot the flagger.

Most upstream warnings occurred 100–130 m from the downstream device at 35–40 mph (above the 30 mph limit), with times to reduce 10 mph typically 2–4 s upstream and 1.5–3 s downstream. Assuming a reaction time of 1 s, the implied average deceleration upstream was -2.25 m/s^2. If vehicles travel at 40 mph, which is 10 mph over the limit, they require approximately 30 m to slow down to 30 mph. Since they were warned about 60 m in advance by the upstream device, this is double the required distance, indicating adequate distance for driver reaction.

The average downstream deceleration was -3.58 m/s^2, consistent with stronger braking closer to the flagger. Four drivers were warned by the downstream unit only (from 40–60 m at speeds of 30–34 mph) and decelerated within 1.5–2.2 s. Assuming a speed of 30 mph, a full stop would require about 25 m with this deceleration rate. Since the warnings occurred around 50 m away, this again provides twice the necessary distance, confirming the effectiveness of device placement.

Taken together, these results show that: (i) lane-level tracking and speed–distance warnings function reliably; (ii) upstream alerts prompt many drivers to decelerate before reaching the work zone; and (iii) separate STOP/SLOW thresholds (remotely adjustable) help avoid false alarms while maintaining sensitivity to genuinely risky approaches. With these capabilities demonstrated in the field, the system is ready for broader deployment, alongside refinements such as GPS-informed dynamic thresholds, finalized strobe patterns for better visibility, and practical deployment guidance on mounting height and device spacing.

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Appendix A Interview Template

Introduction Questions

1. What is your title and role/position within MnDOT?
2. Can you walk me through what your job is in regard to work zones?
3. How often are you at a work site that is using flaggers (traditional or AFADs)?

Proposed Flagger System Questions (walkthrough of current design first)

4. Where would the proposed sign work well? Where would it not?
5. Is the design feasible to use in terms of transportation, setup, and maintenance?
6. What issues are not captured via the current design that you think could be?
7. What kind of alerting is the most effective or preferred, visual or audio?
8. Is there a difference in the alarm you would prefer when presenting STOP versus when presenting SLOW (i.e., audio or visual or no warning)?
9. How important is it that the system is freestanding and allows for the worker not to be standing next to the sign?

Other Flagger Related Questions

10. Do you have any experience using different kinds of flagging systems (i.e., automated lights)?
    a. If so, where was this used, how, and why?
    b. How would you compare it to using a traditional flagger—thinking about both worker safety and the driver’s perspective?
11. What size signs do you typically use, and would it be beneficial to have various sizes?

Questions For Supervisors

12. Are there other staff that we could reach out to for additional similar interviews?
13. Are there any upcoming flagger-controlled work zones that we could visit/observe?
14. Can we test a non-alarm system to validate data collection (e.g., false alarms) and general usability?