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User-centered Smart Traffic Sign Development Study

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Flaggers protect workers by providing temporary traffic control and maintaining traffic flow through a work zone. They are often the first line of defense to stop distracted, inattentive, or aggressive motorists from intruding into the work area. This project aims to develop an automated intrusion detection system to alert drivers who are unsafely approaching or entering a flagger-controlled work zone. A human factors user needs assessment found maintenance workers preferred a modified traffic signal to feature the alert system due to flagger risks of being in the roadway and drivers failing to stop and remain stopped when presented with the STOP side of the flagger sign. A modified traffic signal that could be operated using a handheld remote was developed. The low-cost embedded electronics on the traffic signal enabled it to track trajectories of nearby vehicles, detect potential intrusions, and trigger audio-visual warnings to alert the intruding driver. Usability testing in a simulated driving test found poor 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. Furthermore, some drivers corrected their initial stopping error after triggering the auditory alarm of the traffic signal. A follow up test found improved performance with the alert system incorporated into an audiovisual enhanced STOP/SLOW flagger paddle. Testing of the developed sensor system found the system capable of simultaneous multi-vehicle tracking (including estimation of vehicle position, velocity, and heading) with a range of up to 60 meters and angular azimuth range of 120 degrees and correctly detecting all test intruding vehicles.

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LIST OF ABBREVIATIONS

CTP: Constant (coordinated) Turn Model with Polar Velocity

FoV: Field of View

IMM: Interacting-Multiple-Model

MCC: Maximum Correntropy Criterion

RMSE: Root-Mean-Squared-Errors

RSME: Rating Scale of Mental Effort

SNR: Signal to Noise Ratio

SUS: System Usability Scale

UKF: Unscented Kalman Filter

EXECUTIVE SUMMARY

From 2011 through 2020, 577 U.S. workers were killed by a moving vehicle at a road work site, accounting for 63% of all worker deaths (Bureau of Labor Statistics, 2022). Flaggers are often the first line of defense to stop distracted, inattentive, or aggressive motorists from intruding into the work area, but they are placed at risk through this role. Preventing these crashes by designing safer work zones through automated devices for flaggers and work zone intrusion notification systems were identified in *Minnesota's 2020-2024 Strategic Highway Safety Plan's Strategic Focus Areas* (MnDOT, 2020). Developing automated systems to better protect workers from drivers who intrude into the work zone will improve the safety of work zones and reduce worker risks. This project aimed to develop an automated intrusion detection system to alert drivers who are unsafely approaching or entering a flagger-controlled work zone.

The originally proposed design of this system planned to incorporate low-cost sensors, processors, and an audio-visual warning system on a modified STOP/SLOW sign supported by a rolling platform. At the beginning of this project, the human factors team conducted a user needs assessment with maintenance workers to identify workers' needs and expectations of a safety system, such as the one being proposed in this project. Maintenance workers expressed a strong desire to replace the system's STOP/SLOW sign with a modified traffic light due to the perception that drivers do not understand that the STOP sign requires them to "stop and remain stopped" and places flaggers in the roadway, subjecting them to risk.

In response to the worker feedback, the engineering team modified the sign prototype design to a new portable traffic signal to convey a red ball for STOP, flashing yellow ball for YIELD, and steady yellow ball for SLOW, which could be controlled remotely by a nearby worker on the side of the road. The system was designed to include a low-cost radar sensor chip and estimation algorithms on an embedded microprocessor capable of monitoring lateral and longitudinal distances and speeds, detecting the danger of an intrusion, an audio warning to capture the attention of errant drivers, a camera to capture the events via video stream, and batteries to power the unit. Further, this visual design of the engineering prototype signal was matched in the simulated usability test aimed at measuring drivers' understanding and response to the system.

The human factors team conducted two rounds of usability testing of the system in an immersive driving simulator to measure driver responsiveness and compliance to the experimental traffic signal with the alarm system compared to a traditional flagger. The results found drivers had more stop failures and late stops with the experimental signal but were less likely to remain stopped than with the traditional flagger as suggested by workers in the user needs assessment. The alarm of the experimental signal did show some indication that it helped to stop some drivers who initially failed to notice the signal. Post-test discussions found that participants reported higher expectancies and perceived authority for the flagger than the signal, but they preferred the signal concept due to its safety benefits.

The second iteration of the study increased the conspicuity of the experimental traffic signal with high visibility border signage to provide clarity about stopping expectations, and a nearby simulated maintenance worker. An audiovisual alarm component was added to the flagger by adding a simulated red LED border to the STOP/SLOW sign that would flash when the audio alarm was activated by a detected intruding driver. The results of the revised simulation study revealed positive results for the modified STOP/SLOW flagger design with the alarm system. No initial stop failures were observed with the alert flagger system among drivers who were presented with it in the first drive and only one initial stop failure was observed among drivers who were presented with it in the second drive. These results suggest that the alert flagger system may be more compatible with driver signage expectations and responsiveness for work zone presence. Additionally, whereas 22.8% of drivers exposed to the traditional flagger without the alarm system stopped *but did not remain stopped*; however, only 10% of drivers presented with the alert flagger system committed the same failure. This suggests that the automated alert system may be successful in helping to address some of the observations raised by workers in the initial interviews about driver confusion with the STOP signs used in work zones.

The engineering team developed and demonstrated the capabilities of the sensing system, integrated into the modified, high-conspicuity traffic signal prototype for demonstration purposes. Test demonstrations found the system capable of simultaneous multi-vehicle tracking (including estimation of vehicle position, velocity, and heading) with a range of up to 60 meters and angular azimuth range of 120 degrees. This intrusion detection algorithm was based on a safe speed versus distance curve, with an assumed value of maximum safe deceleration. The vehicle trajectory tracking accuracy was validated with a high-density lidar. Twenty-four vehicle runs were conducted during a testing session for vehicle intrusion detection. These runs included 11 vehicles staged to intrude the test area and 13 staged to safely stop or to quickly approach but to stop before intruding. All intruding vehicles were correctly detected. Warnings were provided during both modes if the vehicle was too fast, and no warnings were activated if the vehicle approached sufficiently slowly.

Recommendations

The findings and outcomes of this work advance the development of a worker-centered smart traffic sign device to automatically detect potential intruding vehicles near work zone flaggers and automatically alert the threat driver and surrounding crew. The advancements of the engineering team to use low-cost sensors and processors to detect threat vehicles was deemed successful and is recommended to be advanced to an implementation study to test its efficacy in a pilot study. Further, future research using the experimental sensor system and algorithms for extension to other work zone layouts and roadway speeds was also recommended.

The sign system on which this alarm system should be integrated is recommended to be an audio-visually enhanced (i.e., LED border and warning alarm) STOP/SLOW flagger system rather than the modified traffic signal. The alert STOP/SLOW flagger system should be advanced in the implementation study to determine its worker acceptance and whether the driver behavior observed in the simulation study extends to real work zone settings. Additionally, examining the signal-to-noise ratio and vehicle penetration of the auditory alarm in the work environment, along with worker hearing protection, should be a focus of this future recommended study.

CHAPTER 1: INTRODUCTION

1.1 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 (*Work Zone Data*, n.d.). Making Minnesota's work zones safer 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 (NIOSH, 2022). While a 2019 law empowered flaggers to report dangerous drivers who intrude into their workspace to 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 INTELLIGENT WORK ZONE SIGNAGE

A primary way of increasing that safety is by developing smart signage systems that are effective in reducing work zone intrusions or alerting workers of intrusions. Smart signage systems have the potential to significantly reduce fatalities among road workers (Finley, 2013; Nnaji et al., 2018; Sohlo, n.d.). 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 (Awolusi & Marks, 2019; Thapa & Mishra, 2021). This noise has the additional benefit of potentially alerting intruding drivers that they are illegally entering a work zone or approaching dangerously (Martin et al., 2016).

However, there are also many systems that provide clearer and more direct instructions to drivers with regard to stopping and work zone safety (Cottrell et al., 2006; Finley, 2013; Nnaji et al., 2020). 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 communication safety instructions with drivers and effectively warning workers of work zone intrusions (Cottrell et al., 2006). Those systems that attempt to control traffic do so through a variety of different signage. Some use a stop/slow sign (Cottrell et al., 2006; Debnath et al., 2017; Finley, 2013; Sohlo, n.d.; Trout et al., 2013). A slow/stop sign is useful for its familiarity, but when not accompanied by a flagger, drivers may treat the stop sign as indicating that they simply come to a complete stop before continuing, as opposed to stopping and waiting for the sign to change (Trout et al., 2013). Other systems use a light similar to a stop light (Debnath et al., 2017; Finley, 2013; Trout et al., 2013). This kind of signage conveys clearly that the driver should stop and stay stopped (Debnath et al., 2017; Finley, 2013). 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 some drivers in some situations (Debnath et al., 2017). However, other signs often accompany such signage systems. These additional signs often convey instructions such as “stop here on red” or “go on slow” (Debnath et al., 2017; Finley, 2013; Trout et al., 2013). Such signs have been shown to be effective in getting drivers to stop and stay stopped (Trout et al., 2013). Another function some signage systems employ is a raising and lowering stop arm (Finley, 2013; Trout et al., 2013). 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 (Trout et al., 2013).

Many of these systems 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/or remove (Awolusi & Marks, 2019; Thapa & Mishra, 2021). 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 to the work zone site. However, in more rural areas or roads with two lanes traveling in opposite directions, such systems are not as practical. This is good for construction operations that need such large and visible devices, but not all road work zones do. On top of that, the price of some systems can be prohibitive (Cottrell et al., 2006). Therefore, a portable, cheap, and easy to use device needs to be developed to provide both adequate signaling to other drivers and warnings to employees in the work zone when an intrusion or dangerous activity is occurring. A safety device that could be quickly and painlessly set up by a single flagger and transported in a 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.

1.2 RADAR BASED VEHICLE TRACKING

Millimeter wave technology on industrial/automotive radar systems has come a long way since its introduction (Waldschmidt et al., 2021; Dickmann et al., 2016). Radar can be a relatively low-cost solution to detecting on-road objects such as vehicles and pedestrians. It’s 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-object and intra-object data association (Koch, 2008; Granström et al., 2017; Cao et al., 2002; Scheel & Dietmayer, 2019). In the work done 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 brings the possibility for better estimation performance when the information from multiple points is strategically used (Kellner et al., 2014; Kellner et al., 2016). For example, Kellner and colleagues (2014) computed vehicle orientation from a single frame by analyzing the velocity profile from multiple detection points. Unlike Kellner et al. (2014), which uses Random Sample and Consensus (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 (Yao et al., 2021; Aftab et al., 2019; Wyffels & Campbell, 2017). In this work, the length and width of vehicles are estimated with a simple rectangular model, which is robust to different radar resolutions and noise levels. The vehicle extent model is coupled with vehicle kinematics, both of which are jointly estimated by the proposed vehicle tracking framework.

1.3 PROJECT DESCRIPTION

This project proposes to develop a smart traffic sign device using low-cost sensors that can automatically detect potential intruding vehicles and provide an audio-visual alert to warn both the driver and workers of the impending event. For the success of such a system, it is critical that the design team take a human-centered approach to fully account for the needs and demands of flaggers and design the system in partnership with workers. The objectives of this project are to develop and validate a smart portable stop sign that can electronically monitor the danger of potential intrusions into a designated work zone and provide automatic audio-visual alerts to the potentially intruding car driver.

1.4 PROJECT OVERVIEW

This project brought the combined efforts of the HumanFIRST lab and the Laboratory for Innovations in Sensing, Estimation, and Control (LISEC) lab to produce an effective and functional smart traffic sign device. The LISEC lab tackled the challenge of developing an intrusion detection system, while the HumanFIRST lab investigated the most understandable way to communicate with drivers.

For development of the intrusion danger detection system, a preliminary design was proposed during the proposal preparation stage. Subsequently, the design was modified based on feedback obtained during the user-requirements gathering at the beginning of this project. While the design (or form factor) of the system changed, one of the core technologies in it remained the same, namely a vehicle trajectory tracking system. Such a system enables detection of vehicles automatically and tracks variables such as position, velocity and orientation of the vehicle. These variables help predict whether there is a danger of the vehicle intruding into the work zone. The vehicle trajectory system using a low-cost sensor is developed and extensively tested as a part of this project.

Understanding which sign design was understood by drivers and addressed the needs and concerns of the road workers required multiple steps. Senior roadway maintenance employees were interviewed and asked what features and aspects were important to them for ease of use and maximum effectiveness. After incorporating their feedback, a driving simulation study was conducted in which data was gathered about the effectiveness of the alarm signal compared to a regular flagger. The alarm signal design and flagger design were then iterated on in a second simulation usability study. Overall findings concluded the signal was poorly suited to house the alarm system and an enhanced STOP/SLOW flagger sign with the alarm better met driver expectancies and better achieved safe stopping rate. Further examination of the signage is recommended in an implementation study.

CHAPTER 2: PROTOTYPE INTRUSION DETECTION SYSTEM

2.1 INITIAL CONSIDERATIONS FOR PROTOTYPE DEVICE EMBODIMENT

The original engineering aim of this project was to develop an automated intrusion detection system that could be used by flag workers to alert drivers who are unsafely approaching and therefore in danger of intruding into a flagger-controlled work zone.

Since a STOP/SLOW paddle is the most popular traffic control device used by flag workers, the originally proposed device design was to incorporate low-cost sensors, processors and electronics on a modified STOP/SLOW sign supported by a rolling platform, see Figure 2.1. The electronics would include a pair of laser scanners capable of monitoring lateral and longitudinal intrusions, a microprocessor capable of estimating trajectories of nearby vehicles in real-time and predicting potential intrusion, an audio-visual warning system to capture the attention of errant drivers, a camera to capture the events via video stream, and batteries to power the unit. Given the modification of the standard STOP/SLOW sign with the additional electronics and the added weight due to the battery, the team expected that the system would need to be designed with wheels to support workers in the manual rotation of the STOP/SLOW sign.

Figure 2.1 Proposed initial work zone traffic control device.

The enhanced wheeled STOP/SLOW traffic control device would be used in a very similar way to the traditional paddle, except it would be placed on the road and rotated to either the STOP or the SLOW side by the flag worker.

2.2 REVISED DEVICE EMBODIMENT AFTER USER-REQUIREMENTS GATHERING

As described in Chapter 3 on User-Requirements Gathering, the Human Factors team found that many users expressed a preference for a remote-controller traffic light rather than a STOP/SLOW paddle. This was motivated by the fact that a remote-controlled traffic light would allow the flag worker to be located in a safer spot behind the light and the light may better indicate of whether drivers in the traffic are expected to stay stopped or to just stop and then go.

A prototype based on a remote-controlled traffic signal was therefore developed for use by flag workers. The desired functions for the device were carefully considered in developing the prototype. A photograph of the developed prototype device is shown in Figure 2.2. The final version of the prototype has enhanced visual appearance, including wide high-visibility yellow borders on the signal lights for better visibility at distance, and a “Stop here on red” sign for better driver understanding of the signal. These enhancements were made after updated recommendations from the human factors team.

Figure 2.2 Photograph of the implemented smart work zone traffic signal.

The main functions implemented on the prototype work zone traffic signal are summarized below:

1) It can be remote-controlled by a flag operator who can choose its mode of operation (red, flashing yellow, or other desired operation).
2) It incorporates sensors, algorithms and electronics to track the trajectories of all nearby vehicles and detect if there is a danger of a vehicle intruding into the work zone.
3) It incorporates rechargeable batteries and allows for hot battery swapping so that a full 8 hours of operation can be obtained, as discussed further in section 2.3
4) It incorporates audio-visual warnings to alert an errant driver, if the danger of their vehicle potentially intruding into the work zone is predicted. Mathematical details of the algorithm used to predict intrusion danger are provided in Chapter 6 of this report.
5) The traffic signal can be disassembled into two parts and carried in a pick-up truck.

2.3 FEATURES OF THE PROTOTYPE DEVICE

The prototype traffic signal is programmed to have two modes of operation: flashing yellow (at 1 Hz) and solid red. The mode of the signal can be controlled by a long-range remote. A photograph of the remote controller is shown in Figure 2.3.

Figure 2.3 Remote controller for operating smart traffic signal.

Pressing buttons on the remote changes the state of a relay onboard, which is read by the Raspberry Pi to confirm which mode the user wants to set. Currently, one of two modes can be selected: steady red or flashing yellow. Depending on the mode of operation, different warning conditions (speed limit as a function of distance curves) can be designed and applied for the two different modes of the traffic light.

The two modes have different warning triggering conditions. Under flashing yellow, vehicles are required to proceed with caution, slow down to below and stay below the speed limit. Under solid red, vehicles are required to stop in front of the signal safely, i.e., with moderate deceleration. If these requirements are not satisfied by the vehicle, a warning will be provided. When the mode is switched from solid red to flashing yellow, during the transition, the signal will display a solid yellow. The duration of the solid yellow depends on the speed limit and can be calculated following the guidelines from the Institute of Transportation Engineers (ITE).

The prototype traffic signal has a traffic-sensing radar chip and antenna device for sensing vehicles in the vicinity of the signal. A photograph of a printed circuit board with the radar chip and antenna is shown in Figure 2.4. The radar chip used is the Texas Instruments IWR6843ISK mm wave radar chip containing 3-transmitters and 4-receivers radar with a 120-azimuth field of view (FoV) and a 30° elevation FoV. The measurement range is up to 60 meters and the market single-item price was approximately $175.

Estimation algorithms for reliably tracking the trajectories of all nearby vehicles using the radar chip have been developed and have been implemented on an embedded microprocessor which is installed on the traffic signal. Further details of the estimation algorithm are provided in Chapter 6.

Figure 2.4 Low-cost radar chip and antenna on a printed circuit board.

The electronic box and the audio alert speaker installed on the traffic signal are shown in Figure 2.5.

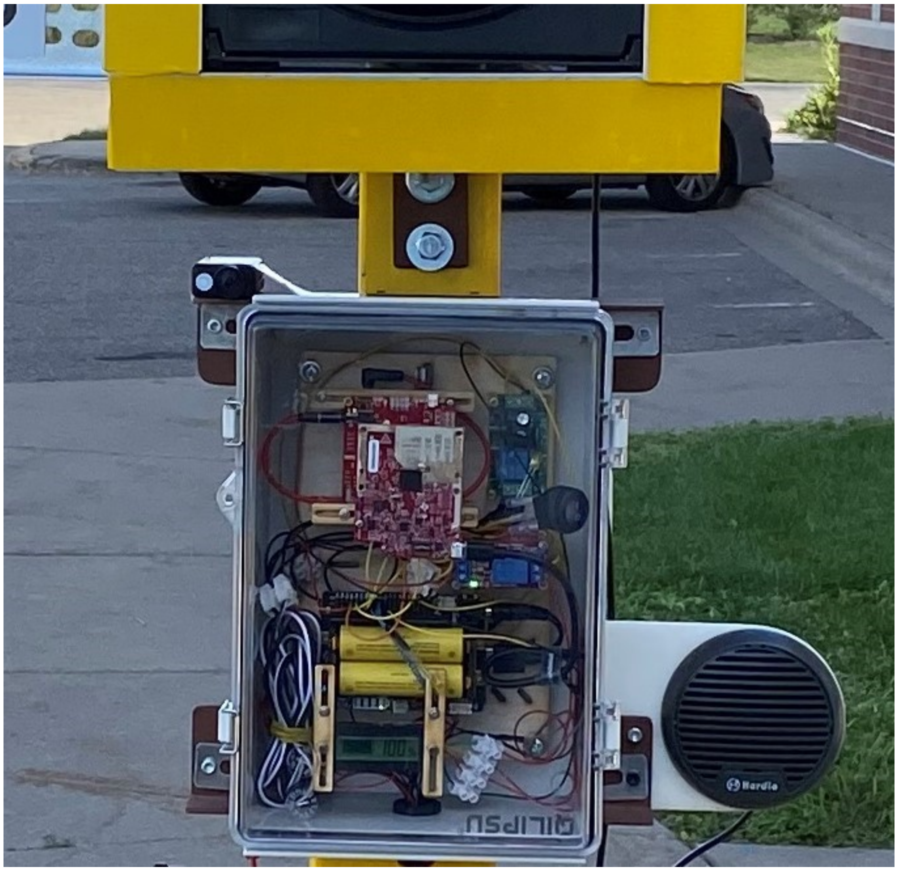


Figure 2.5 Photograph of electronics box and speaker on the smart work zone traffic signal.

The electronic components implemented in the box include:

1) Raspberry Pi and UPS hat (with Li-ion 18650 batteries)
2) Radar sensor (Texas Instruments IWR6843ISK)
3) Light control relays (3 sets, each control one light)
4) Remote control (315 Mhz) relay
5) Audio wave trigger
6) Audio amplifier
7) Speaker (70W)
8) Voltage converter (12V to 5V)
9) 12V LiFePO4 battery (with SAE cable connection)
10) Battery voltage meter
11) A camera for video recording.

The 12V LiFePO4 battery used is shown in Figure 2.6. Hot battery swapping is possible, even with the sensor and microprocessor continuously running. The traffic light and the speaker warning will not function when the main battery is disconnected (being swapped). However, once the main battery is connected, the traffic light and the speaker warning will function immediately without the need for a system reboot.

Figure 2.6 Photograph of hot swappable 12V 7AH battery on the smart work zone traffic signal.

The images below in Figure 2.7 show the traffic sign operating in the two primary modes (i.e., solid red and flashing yellow).

Figure 2.7 Photographs of the two modes on the smart work zone traffic signal.

2.3.1 Prototype Device Summary

In summary, a smart remote-operated traffic signal has been designed and fabricated for use by flag operators in construction work zones. The traffic signal includes the desired features specified by members of the Technical Advisory Panel for this project. It is remote operated, removes the flag worker from the direct path of vehicles, can encode protection so that only one of a pair of signals will allow traffic flow (flashing yellow) at any given time, provides warning of vehicle intrusion to the intruding vehicle and to the work zone workers, can be carried on a pickup truck and can operate for many hours (using hot battery swapping). The low-cost radar chip-based vehicle tracking system could have many other applications in the future. Vehicle tracking algorithms have been evaluated both in real traffic and in controlled tests and appear to work well.

CHAPTER 3: USER REQUIREMENTS GATHERING

3.1 PURPOSE

This chapter details the methods and key findings from the first set of user interviews with roadway maintenance workers discussing the initial prototype of the Intrusion Detection/Warning STOP/SLOW Sign developed by University of Minnesota Department of Mechanical Engineering researchers (see Figure 3.1). Future deployment of this sign is intended for standard flagging operations with two-way, two-lane roadways reduced to one-way roadways with alternating directions where it will replace flaggers' STOP/SLOW paddles. This sign is intended to reduce the risk of drivers illegally entering work zone roadway's single lane, which could lead to a crash. User interviews were held to discover possible improvements to the intrusion detection flagger station to ensure its final form meets the unique needs of the roadway workers who will use it.

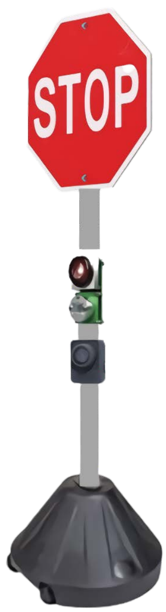


Figure 3.1 Initial Prototype of the Intrusion Detection Flagger Station Discussed During User Interviews

3.2 METHODS

3.2.1 Participants

User interviews were held remotely with eight senior level (supervisor or assistant supervisor) roadway maintenance employees. All interviewed have extensive relevant experience working in maintenance work zones. Six of the participants work for Minnesota's Department of Transportation (MnDOT) with three located in the 7-county metro area and three located in rural Minnesota. The remaining two work for Minnesota's Washington County Transportation Department.

3.2.1 Procedure

User interviews lasted 30 minutes to an hour. Prior to each interview, participants were emailed the initial prototype photo shown in Figure 3.1 and told that the discussion would focus on how the sign could be improved to better meet the needs of roadway maintenance workers. Semi-structured questions guided the conversation during interviews, allowing additional discussion or elaboration as needed. Key areas of improvement to the sign design discussed during interviews focused on the following topics:

- The sign's efficacy to direct traffic in all roadway scenarios as appropriately intended.
- The sign's ability to adequately alert both drivers and roadway workers to intrusions.
- The sign's physical build structure needs to be easily handled and deployed by a single maintenance roadway worker.
- The sign's required battery life and other battery considerations.

3.3 KEY FINDINGS

Detailed below in the "Requests" section are the build specification requests and considerations with relevant notes collected during the interviews. User requests are comments and recommendations expected to be implementable for the initial prototype of the sign and are expected to support meeting user expectations and needs for the system. However, not all requests are necessarily within scope of the project or the sign's initial design.

The following "Considerations" section are details of roadway work zones that may affect the sign's build. These design aspects have been considered as either not currently implementable or not sufficiently explored to qualify as a specific design request. Most requests and considerations listed here align with previous design discussions and have been added to the "Features of the Instrumented Sign" document, see Appendix A.

3.3.1 Requests

Request #1: Change from STOP/SLOW sign to Red/Green Stoplight

- The STOP portion of the STOP/SLOW sign can convey the wrong message to drivers, i.e., temporarily stop, look, and then immediately go.
- The Red Light in a Red/Green Stop Light sign might better communicate the desired driver behavior, i.e., stop and remain stopped.
- A full Stoplight is preferable but users did not feel it is mandatory to the sign's success. Reducing the components of the sign will reduce the overall weight of the sign (i.e., see Request #4), but may not comply with MUTCD requirements.

Request #2: Implement remote operation capability

- Allows flaggers to be placed further from incoming/outgoing traffic and further from harm's way.
- This functionality is viewed with roughly equal importance to the sign's automated intrusion detection/alarm capabilities.
- The sign's 20-foot remote operation specifications were viewed as acceptable.
- Having a flagger in a viewable but safe distance of the sign might better ensure appropriate drive behavior

Request #3: Make the sign's component parts detachable

- For handling and storing purposes, the sign and pole should be detachable from the base, but this feature is a lower implementation priority.

Request #4: Total weight ≤ 50LBS & individual component weight ≤ 30LBS

- While stated mandatory lifting requirements are higher, multiple users indicated that they would not deploy the unit if its operable weight were above 30 to 50 pounds per lifter.
- Should expect and plan on the unit being handled by only a single person.
  - Note: The final design should undergo NIOSH lifting analyses to ensure minimal lifting risks are not exceeded
- Proper coupling should also be introduced (i.e., two grab handles included on the base) to reduce lifting risks

Request #5: Provide larger wheels and a handle to grip on the sign's pole

- While the current prototype is being developed for "stationary" operations and not "mobile" operations, most "stationary" operations involve some movement. Also, bigger wheels with better grip handling would help with standard handling and placement.
- The bigger wheels are the more imperative/important part of this request as the pole can be gripped if needed.
- The unit will not be required to roll over any fresh pavement as repaving operations are typically contracted out to private agencies.

Request #6: Make the battery easily swappable

- Should plan and expect occasional lapses or failures in charging the main battery overnight, requiring interchangeable batteries and spare battery considerations and planning.
- Providing interchangeable batteries may also reduce the weight constraints on the sign to allow sufficient power across batteries (i.e., not all contained in the sign at once) for the entire workday.

Request #7: Make the battery's remaining charge easily noticeable

- Indicating the battery's current charge will increase the likelihood that the unit is adequately hooked up for recharge overnight and minimize surprise shutoffs.

3.3.2 User-Centered Design Considerations

Consideration #1: The intrusion alarm

- The near-term alarm requirements of the unit should be to alert both nearby workers and drivers of intrusions at the unit's station that triggered the alarm.
- A long-term goal should be to send an alert/signal to the work zone's opposing side's unit.
- Workers may not wear protective hearing equipment and the alarm should not be designed assuming workers are wearing protective hearing equipment.
  - Additional flashing alarm lighting could be considered to compensate for maximum volume safety requirements.
  - NIOSH safety guidelines should be considered in designing the intensity of the alarm based on expected alarm duration, sound attenuation, and sound frequency.
- Alarm sensitivity and specificity should be examined in the future to determine the degree to which false alarms and misses meet worker expectations and safety requirements.

Consideration #2: Battery duration

- A two-hour max battery operation time is expected to be too short to meet worker needs.
- A minimum runtime of 4 hours and the desired maximum runtime of 8 to 10 hours.

Consideration #3: Possible communication distance requirements

- If cellular technology is incorporated to allow communication between two units stationed on opposing ends of a work zone, the average distance needing to be communicated over ranges from 50 to 333 yards (150 to 1000 ft.) with a maximum distance of 2 to 3 miles.

CHAPTER 4: INITIAL DESIGN AND USABILITY TESTING

The results of User Requirements Gathering activities described in Chapter 3 found that maintenance workers preferred the STOP/SLOW sign to be replaced with a modified traffic light (e.g., with only a red and green light) to allow better communication with drivers that they should stop and remain stopped and would allow the flagger to be placed further away from incoming/outgoing traffic. In response to user needs, the engineering team modified the original design of the sign (see Figure 4.1 left) to a new portable traffic signal (see Figure 4.1 right) which can convey a red ball, yellow ball (flashing and steady).

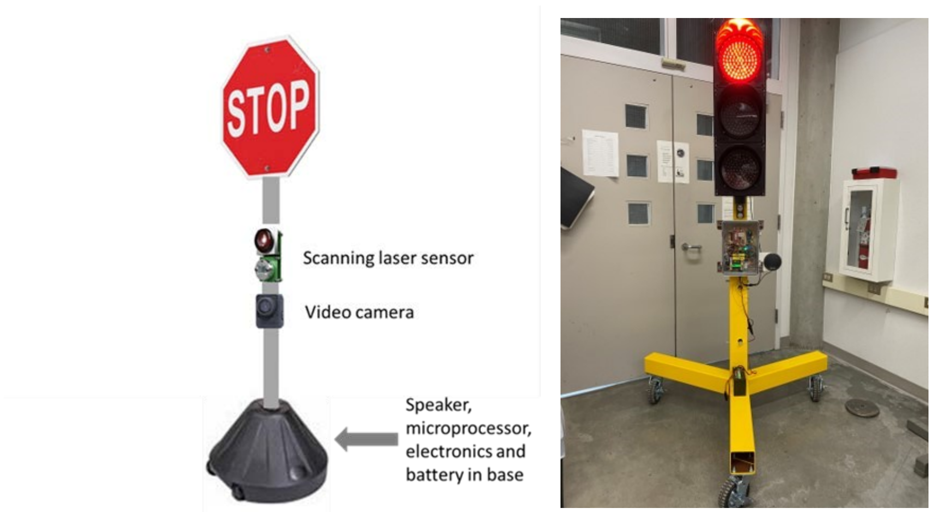


Figure 4.1 Smart portable traffic sign with battery powered electronics, sensor and video camera (left) and updated traffic light design (right)

4.1 RESEARCH QUESTIONS

This research aimed to conduct an initial usability test of the smart sign warning system to examine the human machine interaction (HMI) between drivers and the proposed system design. Given the potential risks and specific conditions that typically exist for a work zone intrusion event, the test was conducted in the HumanFIRST immersive simulator to ensure the conditions were safe and controlled. The key research questions of the study were:

1. Is driver stopping behavior at a work zone with the experimental traffic signal equivalent, or safer, to a traditional flagger?
2. Is driver stopping duration at a work zone with the experimental traffic signal equivalent, or safer, to a traditional flagger?
3. Do drivers report appropriate trust, acceptance, and understanding of the experimental traffic signal compared to the traditional flagger?

4.2 METHODS

4.2.1 Participants

A total of 36 participants (66% male, 33% female) were recruited to participate in the study. Participants' ages range between 20 and 78 (*M* = 46.9, *SD* = 16.7). Participants all reported some level of college education and 75% reported a bachelor's degree or higher (see Table 4.1). The majority of participants self-reported as white and not Hispanic. Participants reported predominantly living in urban (50%) or suburban (39%) areas; however, a greater percentage reported to frequently drive in rural areas (19%) than live in them (11%).

Table 4.1 Participant Demographics

What is your highest level of education?	
Some high school	0
High school diploma or GED	0
Associate degree	4
Some college, no degree	5
Bachelor's degree	16
Graduate or professional degree	11
What is your ethnicity?	
Hispanic or Latino	0
Not Hispanic or Latino	36
What is your racial background?	
American Indian or Alaska Native	1
Asian	2
Black or African American	1
Hawaiian or Other Pacific Islander	0
White	31
Multiracial	1
Do you consider yourself to live in an urban, suburban, or rural area?	
Urban	18
Suburban	14
Rural	4
In which area(s) do you drive the most often?	
Urban	19
Suburban	10
Rural	7

Eligible participants included licensed drivers with no cognitive or physical constraints that might limit their performance, drive minimum of 4,000 miles driven each year, normal or corrected-to-normal vision (20/40 or better, normal color vision), normal hearing function, and normal cognitive function. Participants were excluded from the study if they had a history of hearing loss that inhibits everyday conversation, health problems that affect driving, inner ear or balance problems, history of motion (or sea) sickness, lingering effects of stroke, tumor, head trauma, or infection, and history of migraines or epileptic seizures.

The participants were recruited via email distributed to 707 potential participants who had previously indicated they wished to be contacted about study opportunities from the HumanFIRST Laboratory. Prior to enrollment in the study, participants will be asked questions from a screening questionnaire (see Appendix B) to ensure they meet the age, driving, and visual requirements of the study as well as ensure those prone to motion sickness were not included in the study. Of the 707 potential eligible participants, 112 responses were received as of July 7th, 2022. A total of 81 eligible participants were contacted for potential participation and asked if they were capable and willing to travel to the University of Minnesota East Bank Campus. Participants were paid $50 cash at the time of the simulation and the experiment lasted approximately 1 hour.

4.2.2 Driving Environment Simulator

The simulated driving performance test was conducted in the HumanFIRST immersive, motion-based driving simulator manufactured (see Figure 4.2) by Realtime Technologies, Inc. The simulator consists of a 2013 Ford Fusion full vehicle cab with realistic operation of controls and instrumentation including force feedback on the steering and realistic power assist feel for the brakes. The simulator is powered by the latest generation PCs with the latest generation simulation creation software that provides high fidelity simulation for all sensory channels to generate a realistic presence within the simulated environment. The visual scene is projected through three new, high lumen, high-resolution projectors and a seamless, cylindrical screen which will maximize the 210-degree forward horizontal field of view. Complimentary right and left LCD mirrors are embedded into the standard mirror housing of the chassis for an OEM look. A custom-fitted glass cockpit includes a dashboard cluster panel that can replicate any configuration of vehicle gauges and display. Auditory feedback pertaining to the driving world is provided by a 3D surround sound system.

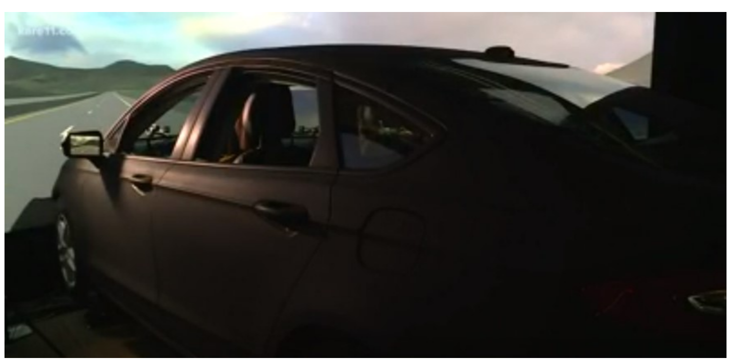


Figure 4.2 HumanFIRST immersive driving simulator and intake practice drive

The Smart Eye Pro camera system (i.e., Smart Eye AB, Gothenburg, Sweden) was utilized for collecting video of the participant’s face, head, and upper torso during each drive. The system consists of four in-vehicle digital infrared cameras (three on the dash and one below the center console touch screen, see

Figure 4.3, that enabled multiple perspectives of the participant to be captured. The live stream of the participant's face from the four cameras was recorded for later analysis of observable movements, facial expressions, or positional indicators.

Figure 4.3 Screenshot of four cameras capturing participant and forward view of simulation

The simulated world will consist of work zones on a rural Minnesota highway, Scott County Highway 81 in Spring Lake Township. The area is rural residential and agricultural that bears the characteristics of rural roadways such as two-lane undivided roadways, wooded areas, shoulders, etc. (see Figure 4.4). This roadway segment was selected for use in this study because it provided opportunities for blind curves leading up to a small, short duration work zone in two places (see Figure 4.5 and Figure 4.6). The length of the roadway allows for acceptable route duration (~five-minute duration for 5 miles of roadway) with few curves to minimize the effect of simulation sickness. It features a divided 2-lane roadway which can be simulated to include shoulder work and lane closures.

Figure 4.4 Aerial view of topographical map with work zone locations

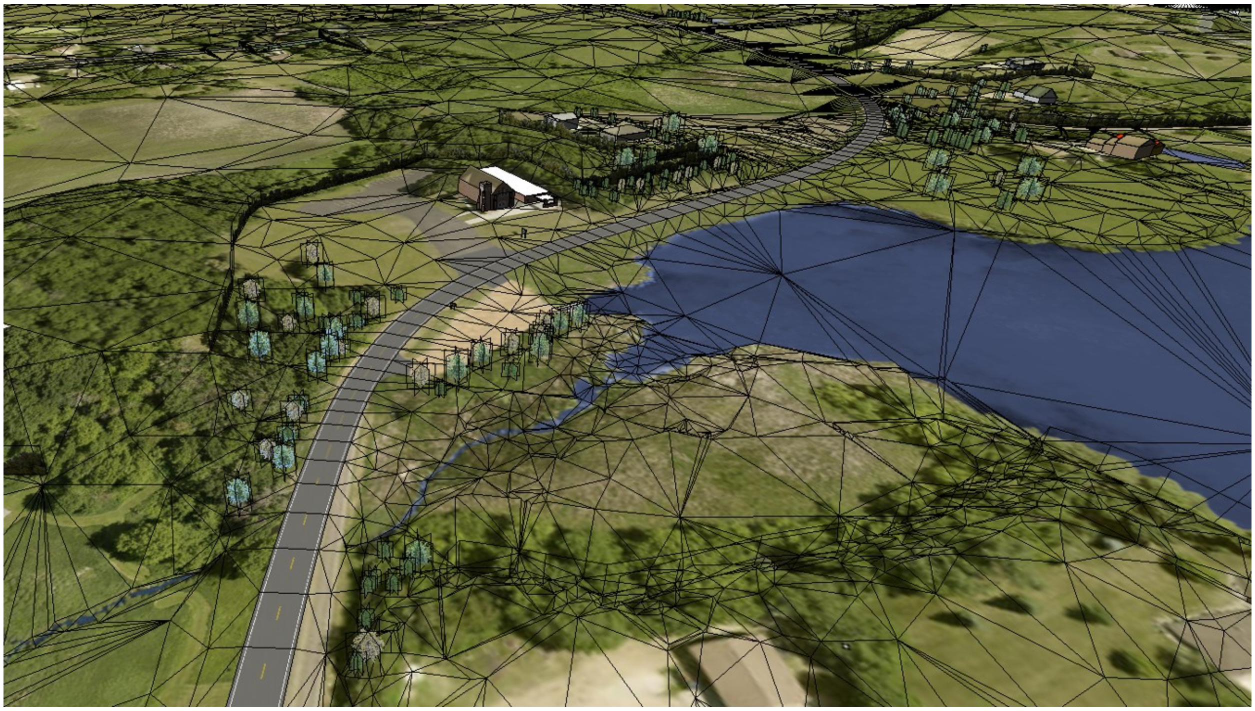


Figure 4.5 Aerial view of simulation rendering of curve for work zone #1 placement

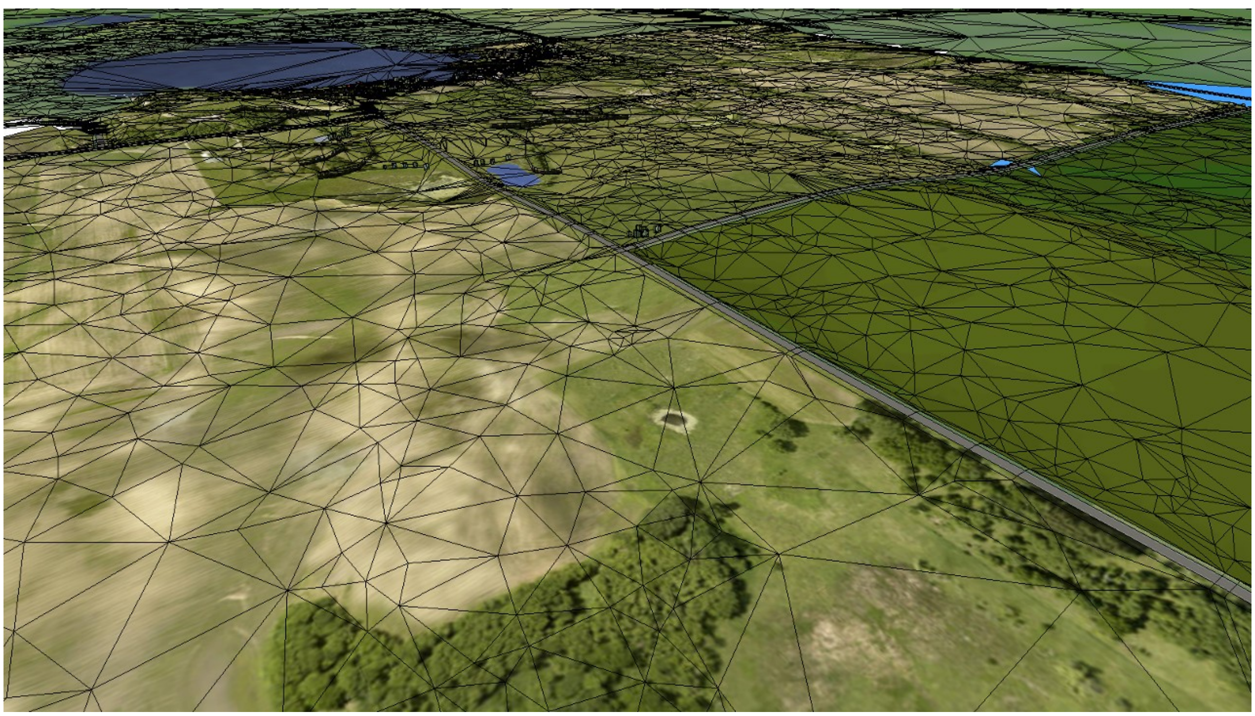


Figure 4.6 Aerial view of simulation rendering of straight segment for work zone #2 placement

4.2.3 Car Following Task

During all drives, participants were instructed to follow a FedEx truck which maintained a 50-mph speed on a rural, two-lane roadway, see Figure 4.7. They were given the following instructions (see Appendix C for entire script) about this car following task:

> *"During the drives, we ask that you attempt to drive exactly 50 mph and follow at a two-second or two-car lengths following distance as exactly as you can. You may exceed 50 mph for a short time if you fall behind and need to catch up to the truck. Most importantly, follow all rules of the road over all else."*

The intent of this task was to create a scenario in which the driver may become hyper focused on the car following task (e.g., focusing on maintaining the 2-second following distance) which may limit visual scanning and a failure to notice they are approaching a work zone. Additionally, the task may create an artificial pressure to remain with the FedEx truck and violate signage of the inactive work zone despite being instructed to "follow all rules of the road over all else".

Figure 4.7 Image of participant following FedEx truck on Scott County Highway 81

4.2.4 Work Zone Description

4.2.4.1 Layout

Each participant, after finishing the practice drive, completed two additional drives in which they completed the car following task behind the FedEx truck while instructed to follow all traditional traffic signs, laws, and general rules of the road. The drive began with the vehicle behind the FedEx truck. When the participant began to accelerate the FedEx truck would accelerate up to and maintain a speed of 50mph. During each of these drives the participant would approach a work zone where traffic is controlled by either the traditional flagger or the experimental traffic signal. In order to avoid potential anticipation of the work zone by participants, the work zone location was moved between driving scenarios as well. Both work zone location (north/south) and traffic control (control - traditional flagger/treatment - experimental traffic control) are counterbalanced among participants creating four potential combinations of drives outlined in Table 4.2. Additional images for the work zone conditions can be found in Appendix H.

Table 4.2 Drives and Conditions Counterbalanced Orders

Counterbalanced Order	Drive #1	Drive #2
A	South drive/Flagger	North drive/Signal
B	South drive/Signal	North drive/Flagger
C	North drive/Signal	South drive/Flagger
D	North drive/Flagger	South drive/Signal

In both the treatment and control scenarios, the participants were signaled to stop and wait for confirmation to proceed at the work zone. In the control scenario the flagger rotated the sign to the "STOP" side, signaling to the driver to stop, and hold this position for one minute before turning the side back to show "SLOW". In the treatment scenario, the light first turns to solid yellow for a brief period then turn to solid red signaling to the participant to stop. After one minute, the light changes from red to flashing yellow, signaling to the participant to proceed. In both scenarios the participant should stop and wait for one minute total before being signaled to proceed with caution through the work zone. The drives ended shortly, after roughly 30 seconds of driving following the participants passing through the work zone.

4.2.4.2 Flagger (set up and timing)

Both scenarios were designed such that the lead FedEx truck was just allowed to drive through the work zone, but the participant was signaled to stop before the work zone. During this scenario, the animation in which the flagger turns the sign from "SLOW" to "STOP" was triggered the instant the participant was 30m from the sign. The animation took 1.2s to fully transition from "SLOW" to "STOP". The sign remained in the "STOP" position (see Figure 4.8) for 60s before turning back to "SLOW" (see Figure 4.9) to allow the participant to proceed. It is important to note that the sign dimensions used in this simulation were based on the standard flagger sign design and average worker height and weight which are provided below:

- The sign is an octagon with height and width of 40 inches
- The sign pole height is 67 inches
- The flagger height is approximately 65 inches

Figure 4.8 Image of flagger displaying STOP sign at work zone

Figure 4.9 Image of driver's perspective of flagger displaying SLOW sign at work zone

4.2.4.3 Experimental Traffic Signal (set up and timing)

The experimental traffic signal event was designed similar to that of the flagger event in regard to when the event is triggered and overall duration. At steady state the traffic signal remained flashing yellow at 1hz indicating to proceed with caution until the participant is 30m from the sign. At that instant the light then changed to a flashing steady yellow light for 2.0s, then turned to a solid red light signaling (see Figure 4.10) the participant to stop at the light. The red light remained for 60 seconds before returning to a flashing yellow to signal to the participant to proceed with caution (see Figure 4.11).

- The lamp assembly was 10 inches wide and 30 inches tall.
- The diameter of the LEDs was 7.25 inches.
- The top of the pole and the overall height of the system was 7 feet.
- The carriage legs and the upright were all 24-inch-long pieces of 4-inch square steel tubing.
- The pole was a piece of 3-inch square tubing.
- The casters were 7.5 inches high.
- The overall width of the carriage (between the ends of any two legs) was 47 inches.

Figure 4.10 Image of driver's perspective of signal displaying red light at work zone

Figure 4.11 Image of driver's perspective of signal displaying flashing yellow light at work zone

4.2.5 Procedure

Once participants read and signed an informed consent form, they were screened for color blindness with the Ishihara's color test. Participants next completed a Demographic and Driving History Questionnaire (see Appendix D) that asks questions about their age, years licensed, frequency and type of driving, and other related driving behaviors. Participants were also asked if they had recently been in a crash or near crash at the start of each testing session. Participants were provided with a general background of the project and a detailed explanation of the purpose of their participation.

Participants completed a practice drive which served dual purposes. The initial purpose was to acclimate drivers to the dynamics of the simulator vehicle (e.g., speed, steering, braking, etc.). The second purpose was to acclimate the driver to the car following task. Following the practice drive, participants completed a wellness questionnaire (Appendix E) to check for any symptoms of simulation sickness. Slight symptoms were flagged for monitoring and additional measures may be taken to mitigate them (e.g., break, cold beverage). Moderate or greater symptoms necessitated a halting of the experiment to protect the safety of the participant who was paid for their time (i.e., prorated payment) and excused from the study.

Following the practice drive, participants drove through two work zones for each within-subjects condition of message type (i.e., experimental traffic signal and standard flagger) for a total of three drives. Each work zone drive took approximately 3 to 5 minutes to complete depending on the work zone location in the simulated world (north/south). After completing a drive pairing, participants completed some brief questionnaires to survey their levels of perceived mental effort, system usability, and other subjective metrics, (Appendix F), along with repeated wellness assessments. Participants were interviewed and debriefed about the experiment upon completion of all drives (Appendix G).

4.3 EXPERIMENTAL DESIGN

The experimental design was a 2 x 2 mixed factorial with Signage Type (i.e., experimental traffic signal and standard flagger) as a within-subjects measure and Signage Order (i.e., experimental traffic signal first and standard flagger first) as a between-subjects measure, see Table 4.3. Participants were randomly assigned to an order of signage group with half of the participants receiving the experimental traffic signal first and the other half receiving the standard flagger first.

Table 4.3 Study conditions across the two participant groups.

	Within-Subjects Conditions	
Group 1	Experimental Traffic Signal	Standard Flagger
Group 2	Standard Flagger	Experimental Traffic Signal

4.4 DEPENDENT VARIABLES

Dependent variables for the study were grouped into the constructs of Driving Performance, Visual Attention, and Workload to better understand the extent to which the experimental traffic signal supports safe stopping and travel through work zones. A summary of the dependent variables is presented in Table 4.4.

Table 4.4 Dependent Variables.

Measure	**Description**
Driving Performance	
Overall signal compliance	(Y/N) - Did not pass through work zone during STOP/Red signal
Initial stop failure	(Y/N) - Failed to stop before the sign/signal
Failure to remain stopped	(Y/N); Did not remain stopped until signaled to proceed
Workload and Usability	
RSME	Rating Scale Mental Effort is a standardized Likert scale method to quickly assess mental workload (Appendix E).
SUS	System Usability Scale
Subjective Measures	Confusion, frustration metrics
Preference Metrics	Preference metrics between flagger and experimental flagger

4.5 DESIGN AND ANALYSIS

The analyses of the Driving Performance, Visual Attention, and Workload measures were carried out within 3 x 2 mixed model ANOVA with Message Type (Roadside, Audio Only, and Audio-visual) as a within-subjects measure and Smartphone Placement (Dash or Passenger Seat) as a between-subjects measure. Measures of Situational Awareness were analyzed using descriptive statistics.

4.6 RESULTS

4.6.1 Overall Signal Compliance

Participants traveling through the work zone against the signal/sign (i.e., either did not stop or did not remain stopped for the entire 60 second duration) was captured by the simulation software. Overall, drivers violated the light 39% of the time compared to fewer overall violations with the flagger (18%), see Table 4.5. However, nearly all of the violations of the signal (93%) were observed among participants who experienced the signal first compared to the violations being more similar across drivers who experienced the flagger at the first work zone compared to those who experienced it at the second work zone. A chi-square test of independence was performed and found the relationship between signal type and stopping behavior in the first drive was statistically significant, X^2 (2, *N*= 35) = 8.534, *p* = 0.014. The difference in stopping behavior in the second drive was not statistically significant, however (i.e., *p* = 0.185).

Table 4.5 Frequency count of stopping and signal violations for by signal type and work zone order.

	Drive #1				Drive #2			
Signal Type	**Complied**	**Violated**	**Unknown**	**Total**	**Complied**	**Violated**	**Unknown**	**Total**
Flagger	15 (88.2%)	**2 (11.7%)**	0	17	12 (70.6%)	**4 (23.5%)**	1 (5.9%)	17
Signal	4 (22.2%)	**13 (72.2%)**	1 (5.5%)	18	16 (94.1%)	**1 (5.8%)**	0	17

4.6.2 Initial Stop Failure

Participants initial stopping behavior upon signal or sign change was recorded. Failures to stop included both those that did not stop at all and those who did not initially stop but stopped late (i.e., after the sign or signal). Eleven participants failed to stop altogether upon being signaled to do so and all but one of these instances occurred with the signal and all in the first drive, see Table 4.6. Four participants (3 in drive #1) were observed to fail to initially brake with the signal (i.e., went past the signal), but did then fully brake and remained stopped after activating the signal's alarm.

Table 4.6 Frequency count of initial stopping failures by signal type and work zone order.

	Drive #1			Drive #2		
Signal Type	**No Stop**	**Late Stop**	**Total Stop Failures**	**No Stop**	**Late Stop**	**Total Stop Failures**
Flagger	1 (100%)	0	1	0	0	0
Signal	10 (90.9%)	1 (9.1%)	11	0	3 (100%)	3

4.6.3 Failure to Remain Stopped

Participants who came to a stop but did not remain stopped until the signal changed to flashing yellow or the flagger displayed the "SLOW" signal were analyzed by frequency and stopping duration. Participants were more frequently to fail to remain stopped when presented with the flagger than with the signal, see Table 4.7. This difference was not found to be statistically significant with a chi square test of independence for either the first or the second drive (p = 0.26 and p = 0.19, respectively), however, it may suggest there is insufficient power in the sample size to fully demonstrate the difference.

Table 4.7 Frequency count of disregarding signal after stopping and average stop time by signal type and work zone order.

	Drive #1		Drive #2		Overall	
Signal Type	**Failure Count**	**Avg Stop Duration**	**Failure Count**	**Avg Stop Duration**	**Total Failures Counts**	**Avg Stop Duration**
Flagger	4	18.5s	4	18.8s	8	18.6s
Signal	3	9.6s	1	2.7s	4	7.8s

4.7 SUBJECTIVE FEEDBACK

4.7.1 Mental Workload (RSME)

Following each drive, participants reported their perceived mental workload. While the overall reported mental effort was slightly higher for the flagger than for the signal (see Table 4.8), this difference was not found to be significant when considering sign type, drive number, or interaction between the two (i.e., $p > .05$).

Table 4.8 Average and standard deviation of reported mental workload by signal type and work zone order.

	Drive #1		Drive #2		Overall	
Signal Type	**Avg RSME**	**Standard Deviation**	**Avg RSME**	**Standard Deviation**	**Avg RSME**	**Standard Deviation**
Flagger	98.7	*24.6*	111.6	*18.3*	105.2	*22.9*
Signal	98.1	*23.3*	100.8	*24.7*	99.5	*24.4*

4.7.2 Clarity

Participants reported, both qualitatively through feedback and through the survey, that the flagger system was in general clearer to understand and follow compared to the portable stop light. The survey results, provided below in Table 4.9, show the general trend that most participants, 25 (69.4%), thought that the flagger with a sign was clearer. This sentiment was echoed through conversations with participants, where many participants stated that they were not familiar with the portable stop light and thus did not know what was expected of them based on the light. Through reflection after participating many also stated that the flashing yellow light transitioning to solid yellow to then solid red made intuitive sense to them; however, in the moment they did not know what the various lights signaled them to do. When discussing clarity participants often referred specifically to the flashing yellow light which they did not interpret to proceed initially but were expecting a green light.

Table 4.9 Participant survey responses comparing clarity of the flagger and signal systems

	Which signage system was clearer to understand and follow?				
	Flagger with sign		**Equal**		**Portable stop light**
Flagger First	7 (38.9%)	3 (16.7%)	4 (22.2%)	1 (5.6%)	3 (16.7%)
Stop Light First	13 (72.2%)	2 (11.1%)	2 (11.1%)	1 (5.6%)	0 (0.0%)
Total	20 (55.6%)	5 (13.9%)	6 (16.7%)	2 (5.56%)	3 (8.3%)

4.7.3 Visibility

Reported overall visibility of each system followed a similar trend to that of clarity from the participants. As shown in the survey results in Table 4.10 and through conversations with participants, a majority of participants stated that the flagger with sign was more visible than the signal. 21 (58.3%) participants reported via survey that the flagger with sign was more visible while 10 (27.7%) reported the signal being more visible and 5 (13.9%) reported them as equally visible. This sentiment was echoed through conversations with participants as well with my participants who reported the flagger with sign being more visible stating that it was because they are not accustomed to look for a stop light like system in a rural work zone setting.

Table 4.10 Participant survey responses comparing visibility of the flagger and signal systems

	Which Signage system was more visible?				
	Flagger with sign		**Equal**		**Portable stop light**
Flagger First	9 (50.0%)	1 (5.6%)	3 (16.7%)	2 (11.1%)	3 (16.7%)
Stop Light First	11 (61.1%)	0 (0.0%)	2 (11.1%)	0 (0.0%)	5 (27.8%)
Total	20 (55.6%)	1 (2.8%)	5 (13.9%)	2 (5.56%)	8 (22.2%)

4.7.4 Authority

Participants often reported that the flagger system has more authority to direct their driving compared to the signal system. As shown in Table 4.11, 27 (75.0%) participants reported that the flagger system had more authority than the signal system while 3 (8.3%) of participants reported that the signal system had more authority and 6 (16.7%) reported the two systems had equal authority. When discussing the systems, participants stated that this feeling of authority can be primarily attributed to the presence of a worker next to the flagger with sign. Many participants stated that the presence of a worker provides more direct human-to-human feedback interaction which has more authority than a system where no other person is present. When prompted further, those that did refer to the presence of a worker stated that if there were other workers present in the work zone during the simulation that the sign would have had more authority simply due to human presence.

Table 4.11 Participant survey responses comparing authority of the flagger and signal systems

	Which Signage system do you think has more authority to direct your driving?				
	Flagger with sign		**Equal**		**Portable stop light**
Flagger First	10 (55.6%)	1 (5.6%)	5 (27.8%)	1 (5.6%)	1 (5.6%)
Stop Light First	16 (88.9%)	0 (0.0%)	1 (5.6%)	1 (5.6%)	0 (0.0%)
Total	26 (72.2%)	1 (2.8%)	6 (16.7%)	2 (5.56%)	1 (2.8%)

4.7.5 Preference

While participants were primarily in agreement that the flagger system had more authority, was more visible, and was clearer, when asked whether they preferred the flagger or signal systems they were much more split between the two. Presented below, in Table 4.12 are the results for which system each participant preferred. For previous questions the results were relatively consistent between those that were exposed to the flagger first and those that saw the signal system first. When asked which system they prefer, there was a noticeable difference between the two groups. Participants that were exposed to the signal system with the stop light first preferred the flagger system more with 13 (72.2%) while only 3 (16.7%) preferred the signal. Those that were exposed to the flagger system first were much more split regarding preference with 9 (50.0%) participants preferring the flagger and 7 (38.9%) preferred the signal. When asked about this order effect, many participants who were exposed to the signal system first expressed feeling “caught off guard” more so than participants who were exposed to the flagger system first. This sense of surprise, coupled with those that saw the signal system second having a chance to experience a work zone already, likely created more of a negative connotation with the signal system for those that experienced that system first.

Table 4.12 Participant survey responses of preference between the flagger and signal systems

	Which signage system would you prefer to come across while driving?				
	Flagger with sign		**Equal**		**Portable stop light**
Flagger First	7 (38.8%)	2 (11.1%)	2 (11.1%)	2 (11.1%)	5 (27.8%)
Stop Light First	10 (55.6%)	3 (16.7%)	2 (11.1%)	1 (5.6%)	2 (11.1%)
Total	17 (47.2%)	5 (13.9%)	4 (11.1%)	3 (8.3%)	7 (19.4%)

4.7.6 Results Summary

As a result of the usability testing, the research team was able to assess each of the proposed research questions individually. Findings to each research question analyzing the proposed experimental traffic signal are as follows:

Is driver stopping behavior at a work zone with the experimental traffic signal equivalent, or safer, to a traditional flagger?

The experimental traffic signal, as a result of the usability testing, was found to be associated with statistically significant poorer stopping behavior compared to the traditional flagger. There was a statistically significant higher rate of violations and initial stopping failures of the experimental traffic signal compared to the traditional flagger. It should be noted that the frequency of violations of the experimental traffic signal greatly decreased among those that experienced the traffic signal *after* experiencing the traditional flagger (i.e., compared to those that experienced the traffic signal first).

Is driver stopping duration at a work zone with the experimental traffic signal equivalent, or safer, to a traditional flagger?

The experimental traffic signal had a lower observed count of stopping duration failures with overall shorter stopped duration of those participants that had stopping duration failures. These results, while not statistically significant, indicate that the appears to alleviate driver confusion regarding expected stopping behavior indicated by the traditional flagger. The lack of statistical significance is assumed to be due to the low stopping duration failure counts and overall frequency.

Do drivers report appropriate trust, acceptance, and understanding of the experimental traffic signal compared to the traditional flagger?

The experimental traffic signal generally received poorer feedback relative to the traditional flagger across all both participant groups. Participants indicated that the traditional flagger is clearer, more visible, has more authority to direct their driving, and is the preferred traffic control system at a work zone. It should be noted that participants that experienced the traditional flagger first followed by the experimental traffic signal indicated less intense preference toward the traditional flagger in each area while still ultimately leaning toward the traditional flagger.

CHAPTER 5: ITERATIVE DESIGN AND USABILITY TEST

The first round of user testing conducted in the driving simulator discovered that the original proposed traffic signal for work zones was not as effective at capturing distracted drivers' attention and instructing them to stop at the work zone compared to the traditional flagger system. The automated alarm system did appear to prevent some distracted drivers from fully entering the work zone if they missed the original signage, but the overall rate of violations remained higher than the traditional flagger. Based on user feedback, it was determined that this discrepancy between the two signage conditions was likely due to overall visibility of the portable traffic signal (i.e., lacked conspicuity) as well as sign clarity (i.e., instructions not clear). The research team made modifications to the traffic signal for the second round of user testing to determine if the modified changes made the traffic signal as effective as the flagger regarding the overall number of violations. Additionally, the research team tested an enhanced flagger condition to determine if the traditional flagger design is a more effective sign system to implement with the automated alarm system included. Through this second round of user testing the research team aimed to assess whether the modifications made to the experimental traffic signal improved driver behavior and acceptance of the signal, and whether the addition of the alarm system improved driver compliance to the flagger system.

5.1 METHODS

5.1.1 Participants

The original round of driver performance evaluation diving sim study recruited 36 participants. Based on feedback from the participants in the original round of testing a second round of user testing was conducted with 20 participants recruited. These participants completed the same set of driving scenarios; however, the signage (flagger and experimental traffic signal) was modified to improve driver performance and response. Provided below, in Table 5.1, is a summary of the demographic information of all participants across the original study and modified study.

Table 5.1 Participant demographics

	Original Study Population (*n* = 36)	**Modified Study Population (*n* = 20)**
What is your highest level of education?		
Some high school	0	1
High school diploma or GED	0	1
Associate degree	4	0
Some college, no degree	5	1
Bachelor's degree	16	12
Graduate or professional degree	11	5
What is your ethnicity?		
Hispanic or Latino	0	0
Not Hispanic or Latino	36	20
What is your racial background?		
American Indian or Alaska Native	1	1

Asian	2	3
Black or African American	1	0
Hawaiian or Other Pacific Islander	0	0
White	31	13
Multiracial	1	2
Other	0	1
Do you consider yourself to live in an urban, suburban, or rural area?		
Urban	18	11
Suburban	14	8
Rural	4	1
In which area(s) do you drive the most often?		
Urban	19	12
Suburban	10	8
Rural	7	0

Participant recruitment methods were identical across the original study and the modified study and were recruited via a screening survey distributed by email. Identical screening requirements were used to ensure eligibility and minimize sickness. The overall protocol between the studies was the same in regard to the simulated environment, car following task, and overall work zone descriptions. The key difference between the two studies, were modifications made to the flagger as well as the experimental traffic signal to improve visibility and potentially reduce the number of violations.

5.1.2 Flagger Modifications

Two major changes were made to the flagger system used in the simulator scenarios, both of which are related to the addition of the alarm system previously used in the original experimental traffic signal design. The alarm system, which flags drivers who are approaching the work zone above a time to collision (TTC) threshold or are within a set distance from the work zone, alerts the driver using both audible and visual warnings. The audible warning of the flagger is an identical sound to the audio that the experimental traffic signal uses. The visual warning added to the flagger system is a 5cm strip of LEDs around the outer edge of the stop sign. These LEDs are lit red when the STOP sign is shown and flashes red at a rate of 4hz, similar to that of the warning flash of the experimental traffic signal when either warning condition is triggered. An image of the modified flagger is provided below in Figure 5.1 followed by an image of the flagger displaying the STOP sign in the simulation in Figure 5.2.

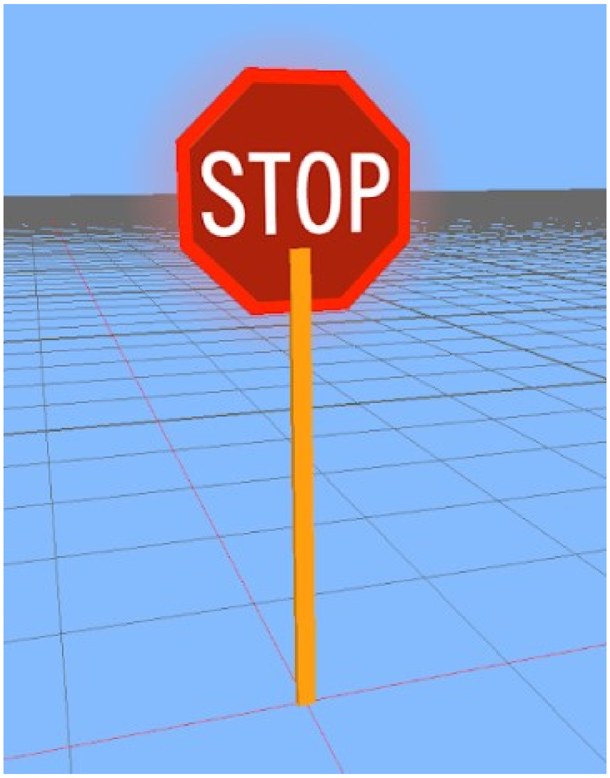


Figure 5.1 Image of modified flagger model

Figure 5.2 Image of flagger displaying STOP sign at work zone

5.1.3 Experimental Traffic Signal Modifications

Three changes to the experimental traffic signal scenario were implemented for the second round of driving simulator performance evaluation, each of which aimed to increase the visibility of the signal based on user feedback. A majority of the criticism of the experimental signal system was that the participants “did not see” the signal and that they “were not used to looking for” that type of signage in a work zone. The first change made to the traffic signal scenario was the inclusion of a worker, identical to the worker flagger, near the traffic signal. Adding this worker creates a scenario more comparable to the flagger scenario and creates a sense of an active work zone which previous participants stated was a potential reason they did not notice the work zone or the traffic signal in the original study. A 3cm yellow border was added to the traffic signal as well to gain the attention of drivers toward the sign. The final change made to the traffic signal scenario was the addition of a 40cm by 60cm “Stop Here on Red” sign indicating where drivers should stop at the signal. Feedback given to the research team was that many participants were not familiar with this style of traffic signal at a work zone and were unsure what the lighting configurations meant in this setting. The purpose of this sign is to increase traffic signal clarity as well as increase the overall size and visibility of the traffic signal. These three changes to the scenario should increase visibility of the traffic signal and work zone as well as provide added instruction to the participants. In turn, the research team anticipates increased compliance with the modified experimental traffic signal from the original study. An image of the modified traffic signal model is provided below in Figure 5.3, followed by two images of the traffic signal in the simulation in Figure 5.4 and Figure 5.5.

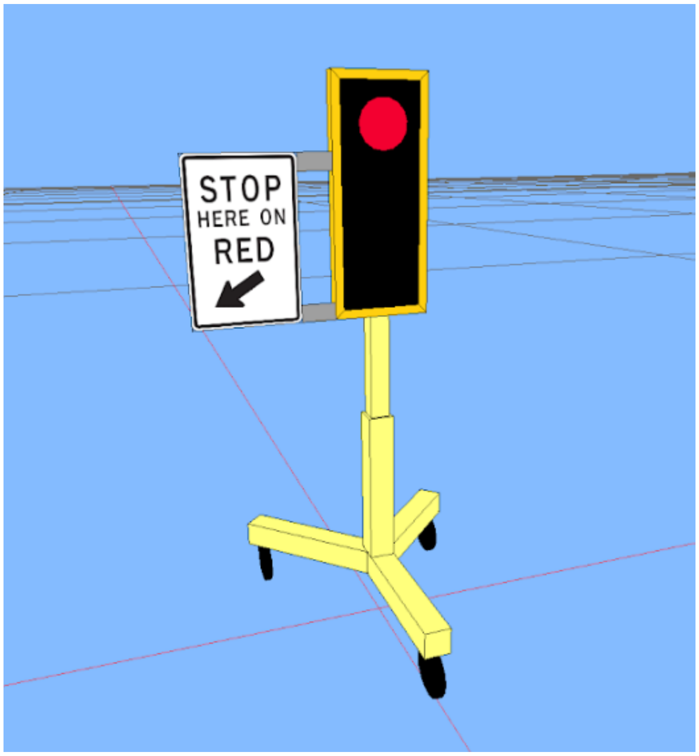


Figure 5.3 Image of modified experimental traffic signal model

Figure 5.4 Image of experimental traffic signal signaling to stop at work zone

Figure 5.5 Image of experimental traffic signal signaling to proceed at work zone

5.2 RESULTS

5.2.1 Driver Performance

5.2.1.1 Overall Signal Compliance

Participants traveling through the work zone against the signal/sign (i.e., either did not stop or did not remain stopped for the entire 60 second duration) was captured by the simulation software. When testing the original systems, it was found that drivers violated the traffic signal at a higher rate (39%) compared to the flagger (18%), with nearly all of the signal violations occurring during the first drive and violations of the flagger split across both drives. When testing the modified systems, there were 3 (15%) violations of the flagger system across 20 exposures and 8 (40%) violations of the traffic signal. It is important to note that a majority of the violations of the modified traffic signal (87.5%) occurred among the group that experienced the traffic signal in their first drive, see Table 5.2.

A chi-square test of independence was performed and found the relationship between signal type and stopping behavior in the first drive for the modified signal types was statistically significant, X^2 (1, *N*= 20) = 5.05, p = 0.025, similar to the relationship observed during the original round of testing. Additionally, there was no observed differences in stopping behavior between the original and modified designs for either the flagger or the signal (p = 0.26 and p = 0.67 respectively). The difference in stopping behavior across any combination of second drives was not statistically significant, however (i.e., $p > 0.05$).

Table 5.2 Frequency count of stopping and signal violations for by signal type and work zone order.

	Drive #1				Drive #2			
Signal Type	**Complied**	**Violated**	**Unknown**	**Total**	**Complied**	**Violated**	**Unknown**	**Total**
Original Flagger	15 (88.2%)	**2 (11.7%)**	0	17	12 (70.6%)	**4 (23.5%)**	1 (5.9%)	17
Original Signal	4 (22.2%)	**13 (72.2%)**	1 (5.5%)	18	16 (94.1%)	**1 (5.8%)**	0	17
Modified Flagger	8 (80%)	**2 (20%)**	0	10	9 (90%)	**1 (10%)**	0	10
Modified Signal	3 (30%)	**7 (70%)**	0	10	9 (90%)	**1 (10%)**	0	10

5.2.1.2 Initial Stop Failure

Participants initial stopping behavior upon signal or sign change was recorded and failure to stop were separated into late stop and no stop categories. The first round of user testing found that a majority of violations at the traffic signal were no stops (10 - 90.9%), all of which occurred during initial exposures; while the few participants who violated the traffic signal during their second drive stopped late (3 - 100%), Table 5.3. While testing the modified signage systems, there was a single (5%) no stop stopping failures of the flagger, and the only failures or violations of the traffic signal occurred among participants who experienced the traffic signal in their first drive. Of those participants that failed to stop at the modified traffic signal, only 2 (33.3%) failed to stop while the other 4 (66.7%) stopped after the traffic signal. A chi-square test of independence was performed and found the relationship between stop failures between for the original and the modified signals was statistically significant, X^2 (1, *N*= 20) =

6.20, p = 0.013. The result of this test indicates that the modifications to the signal were effective in reducing the overall number of stop failures and of those areas a higher rate were late stops rather than no stops.

Table 5.3 Frequency count of initial stopping failures by signal type and work zone order.

	Drive #1			Drive #2		
Signal Type	**No Stop**	**Late Stop**	**Total Stop Failures**	**No Stop**	**Late Stop**	**Total Stop Failures**
Original Flagger	1 (100%)	0	1	0	0	0
Original Signal	10 (90.9%)	1 (9.1%)	11	0	3 (100%)	3
Modified Flagger	0	0	0	1 (100%)	0	1
Modified Signal	2 (33.3%)	4 (66.7%)	6	0	0	0

5.2.1.3 Failure to Remain Stopped

Participants failure to remain stopped behavior from the original round of user testing discovered that, while not statistically significant due to insufficient power in the sample size, participants more frequently failed to remain stopped at the flagger than the experimental traffic signal. In the second round of user testing, it was discovered that the inclusion of the alarm system in the modified flagger system brought the failure rate down from 24% in the original round of user testing to 10%. It should be noted that this reduction is not statistically significant via a chi square test of independence (p = 0.23), however, this is likely due to insufficient power in the sample size and overall low failure rates. Additionally, there is a marginal difference (p = 0.068) between the failure to remain stopped rates between the modified flagger condition and the modified traffic signal conditions, indicating that the modified flagger system has a marginally lower rate of failure to remain stopped violations.

Table 5.4 Frequency count of disregarding signal after stopping and average stop time by signal type and work zone order.

	Drive #1		Drive #2		Overall	
Signal Type	**Failure Count**	**Avg Stop Duration**	**Failure Count**	**Avg Stop Duration**	**Total Failures Counts**	**Avg Stop Duration**
Original Flagger	4	18.5s	4	18.8s	8	18.6s
Original Signal	3	9.6s	1	2.7s	4	7.8s
Modified Flagger	2	9.9s	0	N/A	2	9.9s
Modified Signal	5	8.1s	1	13.3s	6	9.4s

5.2.2 Subjective Feedback

5.2.2.1 Mental Workload (RSME)

Following each drive, participants reported their perceived mental workload. While the overall reported mental effort was slightly higher for the original and modified flaggers than for the signal (see Table 5.5), this difference was not found to be significant when considering sign type, drive number, or interaction between the two (i.e., $p > .05$).

Table 5.5 Average and standard deviation of reported mental workload by signal type and work zone order.

	Drive #1		Drive #2		Overall	
Signal Type	**Avg RSME**	**Standard Deviation**	**Avg RSME**	**Standard Deviation**	**Avg RSME**	**Standard Deviation**
Original Flagger	98.7	*24.6*	111.6	*18.3*	105.2	*22.9*
Original Signal	98.1	*23.3*	100.8	*24.7*	99.5	*24.4*
Modified Flagger	103.3	*22.7*	115.4	*14.1*	109.4	*19.9*
Modified Signal	105.7	*14.4*	103.1	*23.9*	104.4	*19.8*

5.2.2.2 Clarity

Participants reported, both qualitatively through feedback and through the survey, that the flagger system was in general clearer to understand and follow compared to the portable stop light. Participants from the original study indicated that they believed the flagger was clearer to understand and follow than the traffic signal, with those who experienced the traffic signal first trending more in favor of the flagger system. These same trends, both as a whole and for those experiencing the traffic signal first, remained true across the participants from the second round of user testing. Those that experienced the traffic signal first all stated that the flagger was clearer while those that experienced the flagger first generally saw the systems as more equally clear, leaning slightly towards the traffic signal, see Table 5.6.

Table 5.6 Participant survey responses comparing clarity of the flagger and signal systems

	Which signage system was clearer to understand and follow?				
	Flagger with sign		**Equal**		**Portable stop light**
Original Flagger First	7 (38.9%)	3 (16.7%)	4 (22.2%)	1 (5.6%)	3 (16.7%)
Original Signal First	13 (72.2%)	2 (11.1%)	2 (11.1%)	1 (5.6%)	0 (0.0%)
Original Total	**20 (55.6%)**	**5 (13.9%)**	**6 (16.7%)**	**2 (5.56%)**	**3 (8.3%)**
Modified Flagger First	1 (10%)	3 (30%)	2 (20%)	1 (10%)	3 (30%)
Modified Signal First	6 (60%)	3 (30%)	0	0	1 (10%)
Modified Total	**7 (35%)**	**6 (30%)**	**2 (10%)**	**1 (5%)**	**4 (20%)**

5.2.2.3 Visibility

Reported overall visibility of each system followed a similar trend to that of clarity from the participants from the first round of user testing with the original systems. A similar trend was observed among the participants who participated in the second round of user testing with the modified signage systems; however, the participants that experienced the flagger system first were generally most split in regard to visibility between the two systems, leaning slightly toward the flagger, see Table 5.7. Those that experienced the modified traffic signal first reported that the flagger was much more visible than the traffic signal/portable stop light. Ultimately, the modifications made to the traffic signal marginally improved overall visibility of the system; however, participants reported that the flagger was more visible than the traffic signal.

Table 5.7 Participant survey responses comparing visibility of the flagger and signal systems

	Which Signage system was more visible?				
	Flagger with sign		**Equal**		**Portable stop light**
Original Flagger First	9 (50.0%)	1 (5.6%)	3 (16.7%)	2 (11.1%)	3 (16.7%)
Original Signal First	11 (61.1%)	0 (0.0%)	2 (11.1%)	0 (0.0%)	5 (27.8%)
Original Total	**20 (55.6%)**	**1 (2.8%)**	**5 (13.9%)**	**2 (5.56%)**	**8 (22.2%)**
Modified Flagger First	1 (10%)	6 (60%)	0	0	3 (30%)
Modified Signal First	4 (40%)	2 (20%)	2 (20%)	1 (10%)	1 (10%)
Modified Total	**5 (25%)**	**8 (40%)**	**2 (10%)**	**1 (5%)**	**4 (20%)**

5.2.2.4 Authority

Participants from the first iteration of user testing reported that the flagger system has more authority to direct their driving compared to the signal system, with a majority of participants in both groups selecting the option signifying the most authority to the flagger with sign, see Table 5.8. This trend of stating that the flagger has more authority than the signal was exhibited among the participants during the second round of user testing as well. Participants who experienced the modified flagger during their first drive claimed that the authority was more equal between the two signage systems marginally trending toward the traffic signal while participants who experienced the traffic signal first trended further toward the flagger. Based on self-reported levels of authority, as well as through informal discussions with the participants, that the addition of a worker present near the modified traffic signal did not seem to greatly affect how the work zone was perceived, and that the perceived authority is directly related to the flagger rather than the worker present.

Table 5.8 Participant survey responses comparing authority of the flagger and signal systems

	Which Signage system do you think has more authority to direct your driving?				
	Flagger with sign		**Equal**		**Portable stop light**
Original Flagger First	10 (55.6%)	1 (5.6%)	5 (27.8%)	1 (5.6%)	1 (5.6%)
Original Signal First	16 (88.9%)	0 (0.0%)	1 (5.6%)	1 (5.6%)	0 (0.0%)
Original Total	**26 (72.2%)**	**1 (2.8%)**	**6 (16.7%)**	**2 (5.56%)**	**1 (2.8%)**
Modified Flagger First	2 (20%)	1 (10%)	3 (30%)	0	4 (40%)
Modified Signal First	6 (60%)	2 (20%)	1 (10%)	0	1 (10%)
Modified Total	**8 (40%)**	**3 (15%)**	**4 (20%)**	**0**	**5 (25%)**

5.2.2.5 Preference

While participants were primarily in agreement that the flagger system had more authority, was more visible, and was clearer, when asked whether they preferred the flagger or signal systems they were much more split between the two in the original round of user testing. This split in preference between groups was echoed in the second round of user testing as well where the participants who experienced the flagger first tended to prefer the two signage systems equally, leaning slightly toward the traffic signal/portable top light. Those that experienced the traffic signal first greatly preferred the flagger with four (40%) of the participants selecting the most preference of the flagger and a majority of participants, six (60%), choosing a preference of the flagger over the sign. Similar sentiments were expressed by participants who experienced the traffic signal first in both the first and second round of user testing, in that many felt "caught off guard" and "weren't used to looking for" that type of signage near a work zone. It is this sense of surprise, coupled with the fact that those who experienced the signal system second had a chance to experience a work zone already, that likely created more of a negative connotation with the signal system for those that experienced that system first, see Table 5.9.

Table 5.9 Participant survey responses of preference between the flagger and signal systems

	Which signage system would you prefer to come across while driving?				
	Flagger with sign		**Equal**		**Portable stop light**
Original Flagger First	7 (38.8%)	2 (11.1%)	2 (11.1%)	2 (11.1%)	5 (27.8%)
Original Signal First	10 (55.6%)	3 (16.7%)	2 (11.1%)	1 (5.6%)	2 (11.1%)
Original Total	**17 (47.2%)**	**5 (13.9%)**	**4 (11.1%)**	**3 (8.3%)**	**7 (19.4%)**
Modified Flagger First	1 (10%)	4 (40%)	1 (10%)	1 (10%)	3 (30%)
Modified Signal First	4 (40%)	2 (20%)	3 (30%)	0	1 (10%)
Modified Total	**5 (25%)**	**6 (30%)**	**4 (20%)**	**1 (5%)**	**4 (20%)**

5.3 CONCLUSIONS

Of the four signage systems tested across the two rounds of user testing, the research team believes the modified flagger with the alarm system to be the superior signage system based on both driving performance as well as subjective feedback from the participants. Results from the original first round of user testing highlighted clear areas of improvement and concerns regarding the original traffic signal design, those being the overall visibility and clarity of the system. The modification made to the traffic signal, the yellow border, the STOP HERE sign, and the nearby worker, did not appear to significantly affect driver behavior in the simulations nor the overall perception of the system when compared to the flagger. Conversely, the modifications made to the flagger system for the second round of user testing did appear to improve performance based on preliminary results. There was an overall reduction, in this case 100% compliance of the flagger among participants in the second round of user testing when the LED border and alarm system were added. Additionally, there was reduction in the rate of failure to remain stopped violations due to the introduction of the alarm system to the flagger scenario. These reductions may be due to a small sample size, which will be addressed through additional participants; however, it shows promise that the modifications may be effective in reducing the overall number of violations of the flagger.

CHAPTER 6: VEHICLE TRACKING AND INTRUSION DETECTION SYSTEM

6.1 INTRODUCTION

This chapter presents the details of the vehicle tracking and intrusion detection algorithms developed in this project. A low-cost radar chip and antenna, as described in Chapter 2 are utilized on the smart traffic signal. The radar receives reflections from multiple points on multiple objects in its field of view, with the radial distances of these reflections and the azimuth angles being known. The challenge then is to associate the measurements points with specific objects, detect whether or not an object is a moving vehicle and then track trajectories for each moving vehicle object. The major steps in the vehicle trajectory tracking system are shown in Figure 6.1. Data association refers to the task of finding which measurements points belong to which object being tracked. If the object is detected as being a car, a track is initiated for this object. An Unscented Kalman Filter (a nonlinear estimation algorithm) is then used to track variables related to the trajectory of the car, including its lateral and longitudinal positions, its lateral and longitudinal velocities and its orientation and yaw rate.

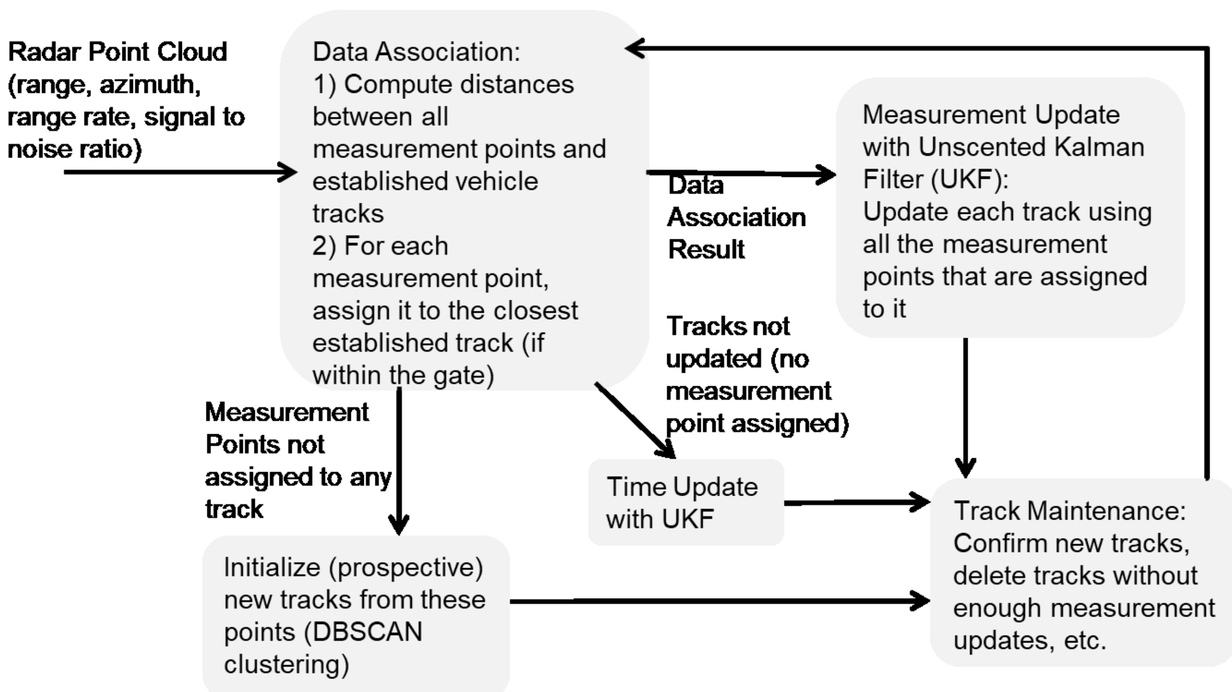


Figure 6.1 An overview of the vehicle tracking framework.

Detailed descriptions of all the steps involved in the vehicle tracking framework of Figure 6.1 are presented in the next few sections of this chapter. The treatment is mathematical in nature but the presentation is rigorous and complete. For the interested reader, further related material can be found in the doctoral dissertation of Zhenming Xie (Xie, 2022).

Once the trajectory of a vehicle is tracked in real-time, an algorithm to decide whether the vehicle is likely to intrude into the work zone is needed. This algorithm is presented in section 6.5 of this chapter. In addition to presenting the details of the algorithms, this chapter also presents simulation and experimental results on the performance of the algorithms.

6.2 MODELS USED FOR VEHICLE TRACKING

In this section, new system dynamic and measurement models are developed for vehicle objects and millimeter wave radar measurements, which together with an Unscented Kalman Filter (UKF) are the main building blocks of the multi-vehicle tracking framework in this work.

6.2.1 System Dynamic Model

A constant steering model incorporating vehicle dimensions is developed for better modelling non-linear vehicle kinematics, as compared to the commonly used constant (coordinated) turn model with polar velocity (CTP) (Li & Jilkov, 2003). The CTP model is good in general for object tracking and is sometimes used together with other models under the interacting-multiple-model (IMM) framework (Bar-Shalom et al., 2001). However, the CTP model can theoretically describe motions that involve only turning with (almost) zero velocity, causing overfitting, since vehicles normally cannot turn under zero velocity. For vehicle tracking, it can be beneficial to consider vehicle kinematics more specifically. Also, with vehicle dimensions, i.e., width and length, being jointly estimated, approximations can be made for intrinsic parameters such as vehicle wheelbase, which is needed for more detailed vehicle kinematic modelling, see Figure 6.2 for demonstration.

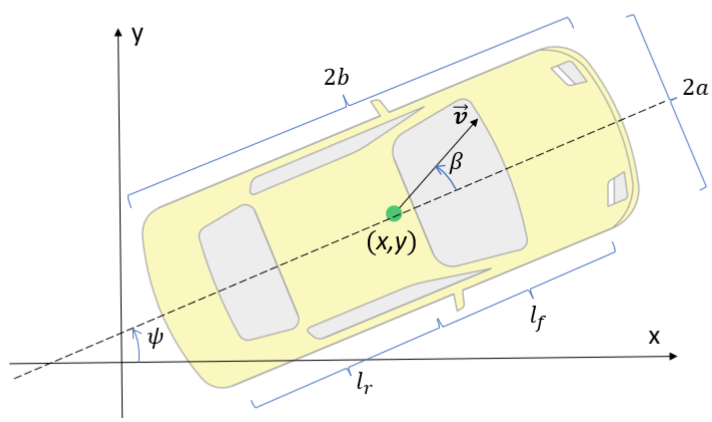


Figure 6.2 Demonstration of variables.

For each vehicle, a state vector of 7 states is used for describing the vehicle's kinematic states and dimensions:

$$x_k = [\mathrm{x}_k, \mathrm{y}_k, v_k, \psi_k, \delta_{s,k}, a_k, b_k]^T \tag{1}$$

where $(\mathrm{x}_k, \mathrm{y}_k)$ is the vehicle center position, v_k is the vehicle's speed, ψ_k is the vehicle's heading angle, $\delta_{s,k}$ is the synthetic steering angle as defined in this chapter. a_k and b_k are the half width and half length of the vehicle. See Figure 6.2 for demonstration. k is the time step for the discrete-time model, which is omitted in some equations later for simplicity.

Consider the bicycle kinematic model for vehicle lateral motion (Rajamani, 2012), and for vehicle with mainly front-wheel steering, the angular velocity or yaw rate of the vehicle can be calculated as:

$$\dot{\psi} = \frac{v \cos\beta \tan\delta_f}{l_f + l_r} \tag{2}$$

where β is the vehicle slip angle, δ_f is the front wheel steering angle. l_f and l_r are the distances from the front and rear axles to the center of gravity (CG) of the vehicle, respectively. Slip angle β can be calculated as:

$$\beta = \tan^{-1}\left(\frac{l_r \tan\delta_f}{l_f + l_r}\right) \tag{3}$$

The synthetic steering angle δ_s is defined as

$$\delta_s \triangleq \frac{\cos\beta \tan\delta_f}{l_f + l_r} \tag{4}$$

such that

$$\dot{\psi} = v\delta_s \tag{5}$$

Here an approximation of l_r is made using the estimated half length of the vehicle:

$$l_r \cong b \tag{6}$$

Then from (3)(4):

$$\beta = \arcsin(l_r\delta_s) \cong \arcsin(b\delta_s) \cong b\delta_s \tag{7}$$

Although (7) is an approximation with inevitable errors, it provides overall better approximation than assuming $\beta \cong 0$.

With the CTP model, the system states are propagated as the following:

$$\begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ v \\ \phi \\ \omega \end{bmatrix}_{k+1} = \begin{bmatrix} \mathrm{x} + \frac{2v}{\omega}\sin\left(\frac{\omega\Delta t}{2}\right)\cos\left(\phi + \frac{\omega\Delta t}{2}\right) \\ \mathrm{y} + \frac{2v}{\omega}\sin\left(\frac{\omega\Delta t}{2}\right)\sin\left(\phi + \frac{\omega\Delta t}{2}\right) \\ v \\ \phi + \omega\Delta t \\ \omega \end{bmatrix}_{k} + w_k \tag{8}$$

where ϕ is the course angle of the vehicle, ω is the yaw rate, Δt is the sensor sampling time, w_k is the propagation noise. The proposed model is built upon the CTP model with the following:

$$\phi = \psi + \beta \cong \psi + b\delta_s \tag{9}$$

$$\omega = \dot{\psi} = v\delta_s \tag{10}$$

Then from (8)(9)(10), the proposed system dynamic model is formulated as:

$$\begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ v \\ \psi \\ \delta_s \\ a \\ b \end{bmatrix}_{k+1} = \begin{bmatrix} \mathrm{x} + \frac{2}{\delta_s}\sin\left(\frac{v\delta_s\Delta t}{2}\right)\cos\left(\psi + b\delta_s + \frac{v\delta_s\Delta t}{2}\right) \\ \mathrm{y} + \frac{2}{\delta_s}\sin\left(\frac{v\delta_s\Delta t}{2}\right)\sin\left(\psi + b\delta_s + \frac{v\delta_s\Delta t}{2}\right) \\ v \\ \psi + v\delta_s\Delta t \\ \delta_s \\ a \\ b \end{bmatrix}_{k} + w_k \tag{11}$$

$$w_k \sim N(0, Q_k)$$

Note that (11) follows from (8)(9)(10) because β being a constant is equivalent to δ_s being a constant, which is a result of $\dot{\psi}$ and v being constants. $\dot{\psi}$ and v being constants is exactly the assumption of the CTP model. One can also derive (11) without using (8) but following a similar procedure as deriving the CTP model. Besides the synthetic steering angle being assumed to be a constant over a sampling period, vehicle dimensions a and b are also assumed to be constants. w_k is the modelled propagation noise and is assumed to be Gaussian and white. Also note that when $\dot{\psi} = v\delta_s \cong 0$, i.e., vehicle travelling in a straight line, (11) returns to a constant velocity model. In this case, care needs to be taken during implementation.

6.2.2 Measurement Model

In each sampling, the radar sensor returns a point cloud from an unknown number of objects. Each measurement point contains information of position, range rate, signal to noise ratio (SNR), etc. Pre-processing, i.e., data association and "measurement synthesis", is performed to obtain synthetic measurements that can be applied to the filtering step. After the pre-processing, the synthetic measurement includes three parts: 1) center position measurement; 2) velocity measurement; 3) vehicle boundary measurement. The computation of each part is described below.

The center position measurement $(\mathrm{x}_c, \mathrm{y}_c)$ is computed as the mean of all the measurement points that are assigned to a specific vehicle (see Figure 6.3 for demonstration) after data association:

$$\begin{bmatrix} \mathrm{x}_c \\ \mathrm{y}_c \end{bmatrix} = \frac{1}{N}\sum\nolimits_{i=1}^{N} \begin{bmatrix} \mathrm{x}_i \\ \mathrm{y}_i \end{bmatrix} = \begin{bmatrix} \mathrm{x} \\ \mathrm{y} \end{bmatrix} + n_p \tag{12}$$

where N is the number of measurement points assigned to the vehicle, n_p represents measurement noise.

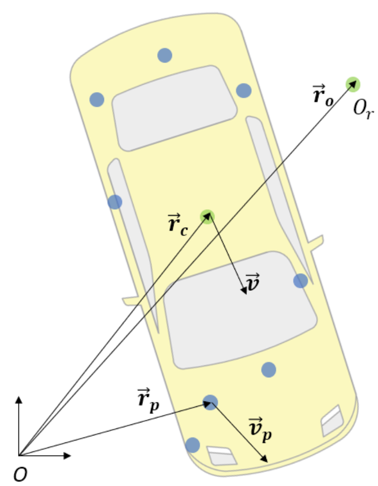


Figure 6.3 Multiple radar measurement points from a vehicle (Radar sensor is located at the origin *O*).

The velocity measurement can be computed as the following. Consider a measurement point *p* (see Figure 6.3 for illustration) on a vehicle at $\vec{\boldsymbol{r}}_p = (r_x, r_y)$, with velocity vector $\vec{\boldsymbol{v}}_{\boldsymbol{p}}$, then the range rate of the point is

$$\frac{d|\vec{\boldsymbol{r}}_p|}{dt} = |\dot{\vec{\boldsymbol{r}}}_p| = \frac{\vec{\boldsymbol{r}}_p \bullet \vec{\boldsymbol{v}}_{\boldsymbol{p}}}{|\vec{\boldsymbol{r}}_p|} \tag{13}$$

Consider the vehicle as a rigid body, with instant rotation center O_r at $\vec{\boldsymbol{r}}_{\boldsymbol{o}}$, vehicle center position at $\vec{\boldsymbol{r}}_{\boldsymbol{c}}$, vehicle center velocity $\vec{\boldsymbol{v}}$, and yaw rate $\vec{\boldsymbol{\omega}}$, then the velocity of the measurement point *p* satisfies

$$\vec{\boldsymbol{v}}_{\boldsymbol{p}} = \vec{\boldsymbol{\omega}} \times \left(\vec{\boldsymbol{r}}_p - \vec{\boldsymbol{r}}_{\boldsymbol{o}}\right) = \vec{\boldsymbol{\omega}} \times \left[\left(\vec{\boldsymbol{r}}_{\boldsymbol{c}} - \vec{\boldsymbol{r}}_{\boldsymbol{o}}\right) + \left(\vec{\boldsymbol{r}}_p - \vec{\boldsymbol{r}}_{\boldsymbol{c}}\right)\right] \tag{14}$$

$$= \vec{\boldsymbol{v}} + \vec{\boldsymbol{\omega}} \times \left(\vec{\boldsymbol{r}}_p - \vec{\boldsymbol{r}}_{\boldsymbol{c}}\right)$$

Note that $\vec{\boldsymbol{v}}_{\boldsymbol{p}} = \vec{\boldsymbol{v}} + \vec{\boldsymbol{\omega}} \times \left(\vec{\boldsymbol{r}}_p - \vec{\boldsymbol{r}}_{\boldsymbol{c}}\right)$ is true even when O_r is infinitely far away (vehicle not rotating). With (13)(14), we have

$$\left|\dot{\vec{\boldsymbol{r}}}_{\boldsymbol{p}}\right|\left|\vec{\boldsymbol{r}}_{\boldsymbol{p}}\right| = \vec{\boldsymbol{r}}_{\boldsymbol{p}} \bullet \left[\vec{\boldsymbol{v}} + \vec{\boldsymbol{\omega}} \times \left(\vec{\boldsymbol{r}}_{\boldsymbol{p}} - \vec{\boldsymbol{r}}_{\boldsymbol{c}}\right)\right] \tag{15}$$

$$= \vec{\boldsymbol{r}}_{\boldsymbol{p}} \bullet \left(\vec{\boldsymbol{v}} - \vec{\boldsymbol{\omega}} \times \vec{\boldsymbol{r}}_{\boldsymbol{c}}\right)$$

Considering that, for two-dimension vehicle motion:

$$|\vec{\boldsymbol{\omega}}| = |\omega_z| \tag{16}$$

$$\boldsymbol{\omega}_{\boldsymbol{z}} = \dot{\boldsymbol{\psi}} = \boldsymbol{v}\boldsymbol{\delta}_{\boldsymbol{s}} \tag{17}$$

Equation (15) can be written in scalar form:

$$\left|\dot{\vec{\boldsymbol{r}}}_p\right|\left|\vec{\boldsymbol{r}}_p\right| = \left[r_x,\ r_y\right]\begin{bmatrix} v\cos(\psi + b\delta_s) + v\delta_s \mathrm{y} \\ v\sin(\psi + b\delta_s)\ - v\delta_s \mathrm{x} \end{bmatrix}, \tag{18}$$

$$\vec{\boldsymbol{r}}_p = \left[r_x,\ r_y\right]^T$$

Equation (18) describes the relationship between the system states and one measurement point. Now consider all the N measurement points:

$$R_r \triangleq \begin{bmatrix} \left|\dot{\vec{\boldsymbol{r}}}_1\right|\left|\vec{\boldsymbol{r}}_1\right| \\ \vdots \\ \left|\dot{\vec{\boldsymbol{r}}}_N\right|\left|\vec{\boldsymbol{r}}_N\right| \end{bmatrix} = R_{xy}v^* \triangleq \begin{bmatrix} r_{1x},\ r_{1y} \\ \vdots \\ r_{Nx},\ r_{Ny} \end{bmatrix}\begin{bmatrix} v\cos(\psi + b\delta_s) + v\delta_s \mathrm{y} \\ v\sin(\psi + b\delta_s) - v\delta_s \mathrm{x} \end{bmatrix} \tag{19}$$

where v^* is the synthetic velocity measurement. Under noise-free conditions, if $rank\left(R_{xy}\right) = 2$, (19) will have a unique solution for v^*. With measurements containing noise, v^* can be solved by using least square:

$$v^* = \left(R_{xy}^T R_{xy}\right)^{-1} R_{xy}^T R_r \tag{20}$$

However, (20) could cause large errors when the measurement points are scattered such that R_{xy} is ill-conditioned. One example of such situations is when there are only a small number of measurement points and they come from a small range of azimuth angles. In this case, R_{xy} is close to being singular, which can result in large error in v^* even when R_r only contains small measurement errors. Therefore, (20) should only be used if R_{xy} is not ill-conditioned. One way to examine this is to check the condition number of R_{xy} (based on induced L^2 norm):

$$\kappa\left(R_{xy}\right) = \frac{\sigma_{max}\left(R_{xy}\right)}{\sigma_{min}\left(R_{xy}\right)} \tag{21}$$

An upper threshold κ_m (50 in this work) can be set for $\kappa\left(R_{xy}\right)$, to determine whether (20) should be used. If $\kappa\left(R_{xy}\right) < \kappa_m$, the velocity measurement can be formulated as

$$v^* = \left(R_{xy}^T R_{xy}\right)^{-1} R_{xy}^T R_r = \begin{bmatrix} v_x^* \\ v_y^* \end{bmatrix} = \begin{bmatrix} v\cos(\psi + b\delta_s) + v\delta_s \mathrm{y} \\ v\sin(\psi + b\delta_s) - v\delta_s \mathrm{x} \end{bmatrix} + n_v \tag{22}$$

where n_v represents measurement noise. Otherwise, if $\kappa\left(R_{xy}\right) \geq \kappa_m$, instead of computing v^*, we formulate an alternative velocity measurement, which is obtained by taking the average of all the rows in (19):

$$v^{**} \triangleq \frac{1}{N}\sum_{i=1}^{N} \left|\dot{\vec{\boldsymbol{r}}}_i\right| \left|\vec{\boldsymbol{r}}_i\right| = \frac{1}{N}\left[\sum_{i=1}^{N} r_{ix}\,,\ \sum_{i=1}^{N} r_{iy}\right] \begin{bmatrix} v\cos(\psi + b\delta_s) + v\delta_s \mathrm{y} \\ v\sin(\psi + b\delta_s) - v\delta_s \mathrm{x} \end{bmatrix} + n_v \tag{23}$$

Equation (23) holds true for as few as a single measurement point.

The last part of the synthetic measurement is the vehicle boundary measurement, which is mainly used for estimating vehicle dimensions. To compute the vehicle boundary measurement, all the measurement points assigned to the vehicle are projected onto the vehicle's body-fixed coordinate, which has an origin at the measured vehicle center ($\mathrm{x}_c, \mathrm{y}_c$), and two axes pointing in the direction of (estimated) ψ and $\psi + \pi/2$. For each measurement point i, the projections are computed as

$$p_i = (\mathrm{x}_i - \mathrm{x}_c)\cos\psi + \left(\mathrm{y}_i - \mathrm{y}_c\right)\sin\psi \tag{24}$$

$$p_i' = -(\mathrm{x}_i - \mathrm{x}_c)\sin\psi + \left(\mathrm{y}_i - \mathrm{y}_c\right)\cos\psi \tag{25}$$

where p_i and p_i' are the projections onto the ψ axis and the $\psi + \pi/2$ axis, respectively. The extent of the vehicle can be approximately captured by the maximum and minimum values of p_i and p_i'. Specifically, the vehicle boundary measurement is computed as:

$$\begin{bmatrix} x_{front} \\ y_{front} \\ x_{rear} \\ y_{rear} \\ x_{left} \\ y_{left} \\ x_{right} \\ y_{right} \end{bmatrix} = \begin{bmatrix} x_c + p_{max}\cos\psi \\ y_c + p_{max}\sin\psi \\ x_c + p_{min}\cos\psi \\ y_c + p_{min}\sin\psi \\ x_c - p'_{max}\sin\psi \\ y_c + p'_{max}\cos\psi \\ x_c - p'_{min}\sin\psi \\ y_c + p'_{min}\cos\psi \end{bmatrix} = \begin{bmatrix} x + b\cos\psi \\ y + b\sin\psi \\ x - b\cos\psi \\ y - b\sin\psi \\ x - a\sin\psi \\ y + a\cos\psi \\ x + a\sin\psi \\ y - a\cos\psi \end{bmatrix} + n_d \tag{26}$$

where n_d represents measurement noise, and

$$p_{max} = \max\{p_i, i = 1, \dots, N\} \tag{27}$$

$$p_{min} = \min\{p_i, i = 1, \dots, N\} \tag{28}$$

$$p'_{max} = \max\{p'_i, i = 1, \dots, N\} \tag{29}$$

$$p'_{min} = \min\{p'_i, i = 1, \dots, N\} \tag{30}$$

The idea is illustrated in Figure 6.4, where the red stars represent the four boundary measurement points (front, rear, left and right) from the projections. The blue dots represent measurement points that are assigned to the vehicle. Similar to the vehicle center position measurement, the boundary measurement contains errors due to the randomness of the radar reflection locations. Proper data association and filtering can mitigate the measurement errors. Also, constraints are imposed on the vehicle dimension states a and b, so that the dimension estimation performance is improved for most vehicle types. Specifically, after each measurement update, a and b are constrained by their upper bounds and fastest decreasing rates:

$$\alpha_a \hat{a}_k^- \leq \hat{a}_k^+ \leq a_{max} \tag{31}$$

$$\alpha_b \hat{b}_k^- \leq \hat{b}_k^+ \leq b_{max} \tag{32}$$

where $\hat{a}_k^+$ and $\hat{b}_k^+$ are the posterior estimates after a measurement update, while $\hat{a}_k^-$ and $\hat{b}_k^-$ are the prior estimates. In this work, $\alpha_a = \alpha_b = 0.99$, $a_{max} = 1.5\ (meters)$, $b_{max} = 6.0\ (meters)$. The constraints are implemented by checking (31)(32) after a measurement update. If (31) or (32) is not satisfied, depending on which of the four bounds are broken, $\hat{a}_k^+$ and $\hat{b}_k^+$ are projected to the bounds using the projection approach with maximum probability in chapter 7 of (Simon, 2006). The projection could also affect other states based on the estimated covariance matrix, resulting in a constrained state estimate under maximum probability. The upper bounds in (31)(32) ensure that erroneously large vehicle dimension estimates are not possible. While the lower bounds in (31)(32) ensure that vehicle dimensions will not be underestimated by too much when measurement points don't cover the whole extent of the vehicle, which can happen quite often in real-world practice, see Figure 6.4.

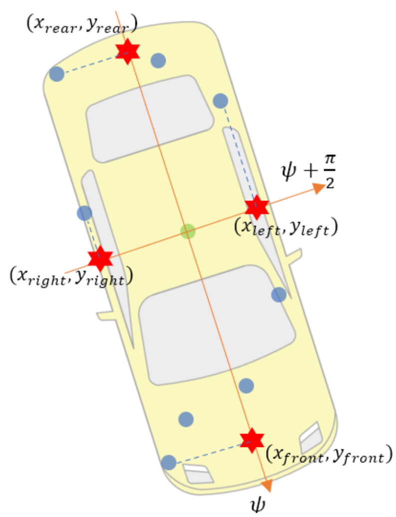


Figure 6.4 Vehicle boundary measurement by projection.

In summary, two measurement models are proposed based on the condition number of R_{xy} (21). If $\kappa(R_{xy}) < \kappa_m$, the measurement model is:

$$\begin{bmatrix} \mathrm{x}_c \\ \mathrm{y}_c \\ v_x^* \\ v_y^* \\ \mathrm{x}_{front} \\ \mathrm{y}_{front} \\ \mathrm{x}_{rear} \\ \mathrm{y}_{rear} \\ \mathrm{x}_{left} \\ \mathrm{y}_{left} \\ \mathrm{x}_{right} \\ \mathrm{y}_{right} \end{bmatrix}_k = \begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ v\cos(\psi + b\delta_s) + v\delta_s \mathrm{y} \\ v\sin(\psi + b\delta_s) - v\delta_s \mathrm{x} \\ \mathrm{x} + b\cos\psi \\ \mathrm{y} + b\sin\psi \\ \mathrm{x} - b\cos\psi \\ \mathrm{y} - b\sin\psi \\ \mathrm{x} - a\sin\psi \\ \mathrm{y} + a\cos\psi \\ \mathrm{x} + a\sin\psi \\ \mathrm{y} - a\cos\psi \end{bmatrix}_k + n_k, \qquad n_k = \left[n_p^T, n_v^T, n_d^T\right]_k^T \sim N(0, R_k) \tag{33}$$

Otherwise, if $\kappa(R_{xy}) \geq \kappa_m$, the measurement model is

$$\begin{bmatrix} x_c \\ y_c \\ v^{**} \\ x_{front} \\ y_{front} \\ x_{rear} \\ y_{rear} \\ x_{left} \\ y_{left} \\ x_{right} \\ y_{right} \end{bmatrix}_k = \begin{bmatrix} x \\ y \\ \hat{v}^{**} \\ x + b\cos\psi \\ y + b\sin\psi \\ x - b\cos\psi \\ y - b\sin\psi \\ x - a\sin\psi \\ y + a\cos\psi \\ x + a\sin\psi \\ y - a\cos\psi \end{bmatrix}_k + n_k, \qquad n_k = \left[n_p^T, n_v^T, n_d^T\right]_k^T \sim N(0, R_k) \tag{34}$$

$$\hat{v}^{**} = \frac{1}{N}\left[\sum_{i=1}^{N} r_{ix}, \sum_{i=1}^{N} r_{iy}\right]\begin{bmatrix} v\cos(\psi + b\delta_s) + v\delta_s y \\ v\sin(\psi + b\delta_s) - v\delta_s x \end{bmatrix} \tag{35}$$

In (33) and (34), n_k is the modelled measurement noise and is assumed to be Gaussian and white with zero mean and covariance R_k (R_k can have different sizes depending on the specific measurement model used). The synthetic measurement vector is computed by (12)(22)(23)(26) accordingly.

While the vehicle dynamic models and the measurement models have been presented in this section, the design of the Unscented Kalman filters for this application is not presented here. The interested reader is referred to the textbook (Simon, 2006) and the doctoral dissertation (Xie, 2022) for this material.

6.3 MULTI-VEHICLE TRACKING FRAMEWORK

This section describes the approaches to data association, initialization, and track maintenance. These together with the filtering methods described in the previous sections form the multi-vehicle tracking framework.

6.3.1 Data Association

In this work, data association is handled efficiently by assigning individual measurement points to established tracks based on their statistical distances. In this way we avoid performing clustering or segmentation in each frame, which can greatly reduce the computational cost of the algorithm.

For each measurement point i, it is either being assigned to an established track, or being treated as a measurement point from a potential new track. To decide, we calculate the statistical distance between each point i and each established track j:

$$d_{ij} = \left(p_p^i - p_t^j\right)^T {S^j}^{-1}\left(p_p^i - p_t^j\right) + \ln\left(1 + \left|P_{xy}^j\right|\right) + \Delta\dot{r}_{ij} \tag{36}$$

where p_p^i and p_t^j are the position measurement of point i and the position estimate of track j:

$$p_p^i = \begin{bmatrix} \mathrm{x}_p^i \\ \mathrm{y}_p^i \end{bmatrix}, \quad p_t^j = \begin{bmatrix} \mathrm{x}_t^j \\ \mathrm{y}_t^j \end{bmatrix} \tag{37}$$

Matrix P_{xy}^j in (36) is the estimated position covariance of p_t^j. Matrix S^j is a covariance matrix that describes track j's position and dimension uncertainty:

$$S^j = P_{xy}^j + C_\psi^j diag\left\{ {b^j}^2, {a^j}^2 \right\} {C_\psi^j}^T \tag{38}$$

$$C_\psi^j = \begin{bmatrix} \cos\psi^j & -\sin\psi^j \\ \sin\psi^j & \cos\psi^j \end{bmatrix} \tag{39}$$

where C_ψ^j is a rotation matrix with an angle of track j's heading ψ^j, a^j and b^j are track j's dimension estimates. In (36), $\ln(1 + |P_{xy}^j|)$ is used for penalizing tracks with high position uncertainty. $\Delta\dot{r}_{ij}$ in (36) is the range rate difference between the range rate measurement of point i and the prediction based on track j:

$$\Delta\dot{r}_{ij} = \alpha_{rr} \left\{ \frac{1}{|\vec{\boldsymbol{r}}_{\boldsymbol{i}}|} [r_{ix}, \, r_{iy}] v^{*j} - |\dot{\vec{\boldsymbol{r}}}_{\boldsymbol{i}}| \right\}^2 \tag{40}$$

$$v^{*j} = \begin{bmatrix} v\cos(\psi + b\delta_s) + v\delta_s \mathrm{y} \\ v\sin(\psi + b\delta_s) - v\delta_s \mathrm{x} \end{bmatrix}^j \tag{41}$$

where $|\vec{\boldsymbol{r}}_i|$ and $|\dot{\vec{\boldsymbol{r}}}_i|$ are the range and range rate measurement of point i, $\vec{\boldsymbol{r}}_{\boldsymbol{i}} = [r_{ix}, \, r_{iy}]^T$, v^{*j} is calculated based on the estimated states of track j. Readers can also refer to (19) for the physical meaning of (40). α_{rr} is a weighting coefficient (set to 0.01 in this chapter).

From (36), a distance matrix $\{d_{ij}\}$ is calculated. For each measurement point i, find the minimum distance to a track and compare it to a gating threshold γ_g, if

$$\min\{d_{ij}, j = 1, \dots, M\} < \gamma_g \tag{42}$$

then measurement point i is assigned to track j_i, where

$$j_i = \underset{j}{\operatorname{argmin}}\{d_{ij}, j = 1, \dots, M\} \tag{43}$$

Otherwise, point i is treated as a measurement point of a potential new track. M is the number of established tracks.

6.3.2 Initialization and Track Maintenance

While the developed system dynamic model has good performance in predicting state propagation, like all other models with polar velocity, the initial value of vehicle heading is important. An initial estimated heading angle with large error could result in incorrect data association and therefore low tracking performance or track drops. Instead of differentiating the first two (synthetic) position measurements or using the range rate measurements to calculate the initial heading, a coordinate-uncoupled model is used after a track is first initialized. This track is called a potential track, as opposed to a confirmed track. The confirmed tracks are updated by the Maximum Correntropy Criterion- Unscented Kalman Filter (MCC-UKF) described in section III with the models described in section II, while the potential tracks are updated by a linear Kalman filter.

A potential track has the following state vector:

$$x'_k = \left[\mathrm{x}'_k, \mathrm{y}'_k, v'_{xk}, v'_{yk}, a'_{xk}, b'_{yk}\right]^T \tag{44}$$

where $(\mathrm{x}'_k, \mathrm{y}'_k)$ is the vehicle center position, (v'_{xk}, v'_{yk}) is the vehicle's velocity in Cartesian coordinates, (a'_{xk}, b'_{yk}) is the (half) dimension estimate of the vehicle in global x and y directions. This results in the following linear dynamic model which assumes constant velocity propagation:

$$\begin{bmatrix} \mathrm{x}' \\ \mathrm{y}' \\ v'_x \\ v'_y \\ a'_x \\ b'_y \end{bmatrix}_{k+1} = \begin{bmatrix} \mathrm{x}' + v'_x\Delta t \\ \mathrm{y}' + v'_y\Delta t \\ v'_x \\ v'_y \\ a'_x \\ b'_y \end{bmatrix}_k + w_k \tag{45}$$

The following linear measurement model is used:

$$\begin{bmatrix} \mathrm{x}_c \\ \mathrm{y}_c \\ \mathrm{x}_\Delta \\ \mathrm{y}_\Delta \end{bmatrix}_k = \begin{bmatrix} \mathrm{x}' \\ \mathrm{y}' \\ 2a'_x \\ 2b'_y \end{bmatrix}_k + n_k \tag{46}$$

$$\mathrm{x}_\Delta = \max\{\mathrm{x}_i, i = 1, \dots, N\} - \min\{\mathrm{x}_i, i = 1, \dots, N\} \tag{47}$$

$$\mathrm{y}_\Delta = \max\{\mathrm{y}_i, i = 1, \dots, N\} - \min\{\mathrm{y}_i, i = 1, \dots, N\} \tag{48}$$

where N is the number of measurement points assigned to the vehicle of interest, $(\mathrm{x}_c, \mathrm{y}_c)$ is the center position measurement as in (12). $(\mathrm{x}_\Delta, \mathrm{y}_\Delta)$ is the extent measurement in global x and y directions. When a potential track is confirmed, its estimated state vector is transformed from the form of (44) into the form of (1) with some heuristics (subscript k omitted):

$$\begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ v \\ \psi \\ \delta_s \\ a \\ b \end{bmatrix} = \begin{bmatrix} \mathrm{x'} \\ \mathrm{y'} \\ \left({v'_x}^2 + {v'_y}^2\right)^{1/2} \\ \mathrm{atan2}(v'_y, v'_x) \\ 0 \\ \min\{a_{max}, \left({a'_x}^2 + {b'_y}^2\right)^{1/2}/2\} \\ \min\{b_{max}, \left({a'_x}^2 + {b'_y}^2\right)^{1/2}\} \end{bmatrix} \tag{49}$$

The corresponding estimated covariance matrix is re-initialized when a track is confirmed.

During data association, measurement points are assigned to all potential tracks and confirmed tracks based on (42)(43). For measurement points that are outside of the gating threshold of any track, density-based spatial clustering of applications with noise (DBSCAN) is run to form potential tracks from these points.

Track maintenance is handled by a simple track score system based on the number of measurement updates a track is getting and missing over time. The track score T^j for track j at time step k is

$$T_k^j = \max\{U_k^{mea} - U_k^{miss}, T_{max}\} \tag{50}$$

where U_k^{mea} is the number of measurement updates the track had since initialized, U_k^{miss} is the number of measurement updates the track missed since initialized due to data association results and T_{max} is the maximum track score a track can have. A track transitions from “potential” to “confirmed” when the track score increases above a threshold T_{con}, which is set based on the noise level of the measurements. While a track is deleted when the track score falls below a threshold T_{del}.

An overview of the multi-vehicle tracking framework is shown in Figure 6.5.

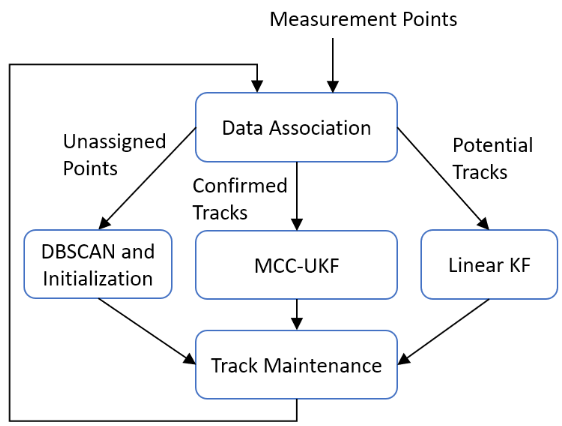


Figure 6.5 Overview of the multi-vehicle tracking framework.

6.4 SIMULATIONS AND EXPERIMENTAL EVALUATION

This section describes the approaches to data association, initialization, and track maintenance. These together with the filtering methods described in the previous sections form the multi-vehicle tracking framework.

6.4.1 Simulations

Simulations are run under both clutter-free and cluttered situations with different vehicle maneuvers to evaluate the tracking performance of the proposed method.

Two vehicle maneuvers are simulated. The first one is a turning maneuver, in which the vehicle first goes straight toward the sensor and then decelerates and makes a left turn. The second one is a straight driving maneuver, in which the vehicle goes in a straight line across the sensor's field of view, decelerates and then accelerates. These two maneuvers cover both the "non-maneuvering" type of dynamics (straight driving without much velocity change) and the "maneuvering" type of dynamics (acceleration, deceleration and turning).

Under clutter-free situations, a varying number of measurement points are generated from a simulated vehicle. For each frame, the number of measurement points follows a binomial distribution, assuming each potential measurement point has the same probability of being detected. The maximum number of measurement point for a vehicle is set to be 30, with a detection probability of 0.5 for each measurement point. After determining the number of measurement points for the current frame, each measurement point is sampled from a two-dimensional uniform distribution over the vehicle's extent, which is assumed to be a rectangle. The range rate of each measurement point is corrupted by a uniformly distributed noise in the interval of [-0.75, 0.75] m/s. Example vehicle trajectories with several frames over time are shown in Figure 6.6 (a) (for turning maneuver) and in Figure 6.7 (a) (for straight driving maneuver).

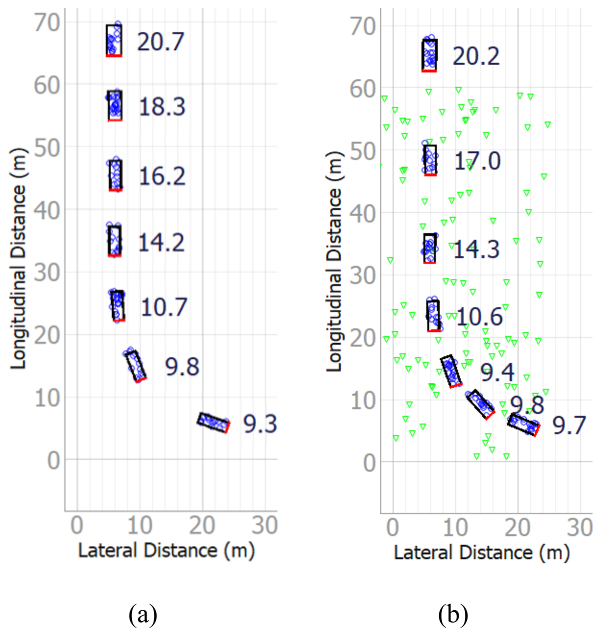


Figure 6.6 Simulated vehicle trajectory (left turn in several frames).
Small circles/triangles are the measurement points (blue circles are assigned to the vehicle while green triangles are out of the gating threshold). Rectangles represent the estimated vehicle positions, headings, and extent/dimensions. The digit near each rectangle is the estimated vehicle speed in m/s. (a): clutter-free; (b): cluttered

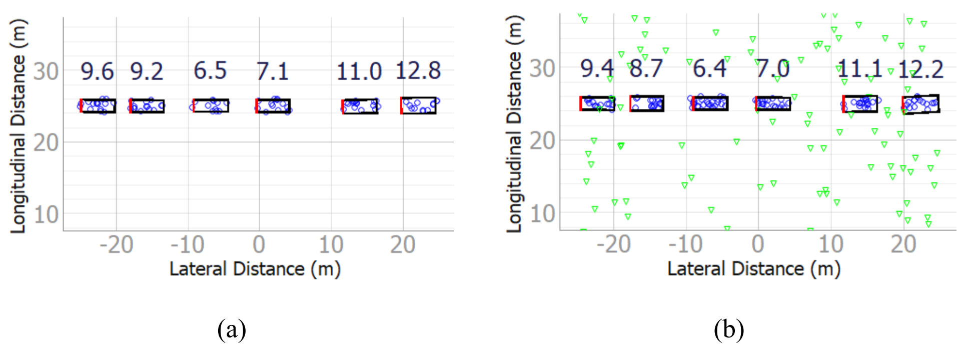


Figure 6.7 Simulated vehicle trajectory (straight driving in several frames). (a): clutter-free; (b): cluttered

Three methods are compared in the simulations. Specifically, "MCC-UKF" is the method proposed in this work, which includes both the MCC-UKF with the dynamic and measurement models and the multi-vehicle tracking framework developed in previous sections. "Baseline" differs from the "MCC-UKF" method in the sense that it uses original UKF with a constant-turn dynamic model and a measurement model with just the average position and range rate, and without using the doppler distribution, see Figure 6.8. "Baseline 2" is identical to "MCC-UKF" except it uses the original UKF format for filtering. All these methods are configured to use the same initialization and track maintenance method (developed in IV) with the same parameters for a fair comparison, i.e., all the methods receive the same initial condition in each run.

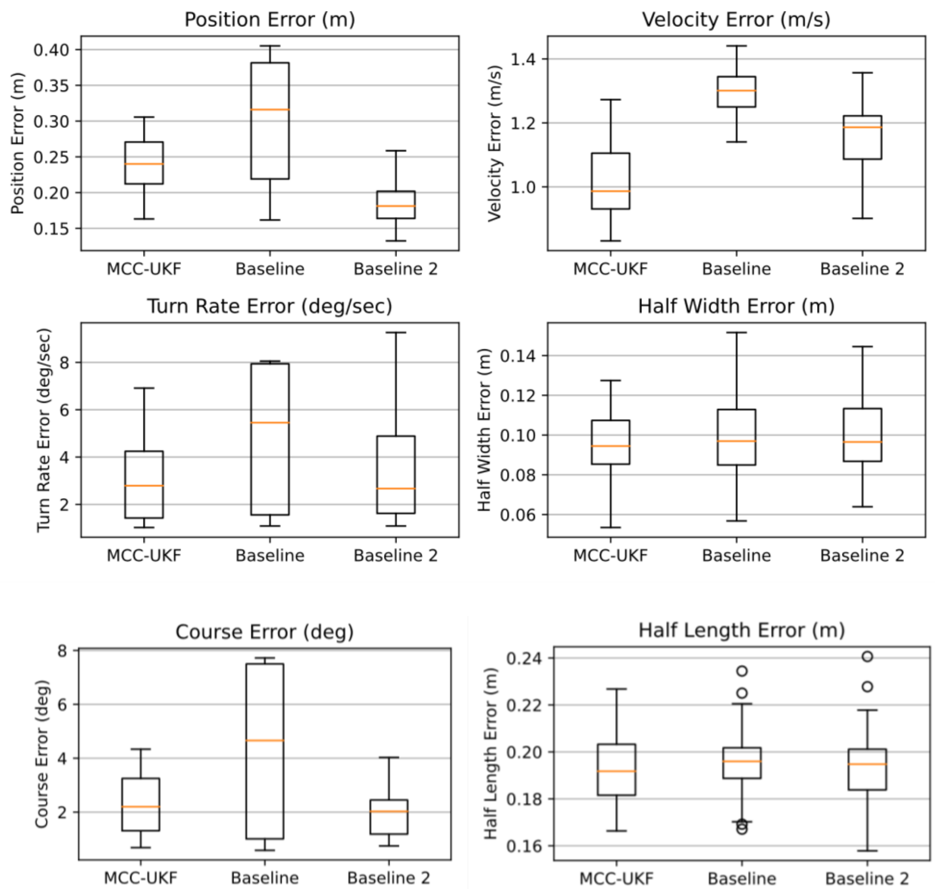


Figure 6.8 RMSE comparison between the MCC-UKF-based method and baseline methods under clutter-free situations

Under clutter-free situations, simulations with random measurements are run 50 times, including 25 runs with the left-turn maneuver and 25 runs with the straight-driving maneuver. Box plots of the root-mean-square errors (RMSE) of different estimation methods are shown in Figure 6.8. As shown in Figure 6.8, “MCC-UKF” shows similar estimation performance as “Baseline 2”, with “Baseline 2” actually performs slightly better in some states, which shows that the original UKF performs well with the uniformly distributed measurement points from the vehicle extent. Compared to “Baseline UKF”, both “MCC-UKF” and “Baseline 2” show improved performance, which shows the advantages of the dynamic and measurement models developed in this work. Overall, under clutter-free situations, the three methods have similar performance without very significant differences. However, in real-world applications one needs to consider false alarms/detections, micro-doppler effects, among other factors that result in cluttered measurements. Therefore, cluttered situations are simulated as a comparison.

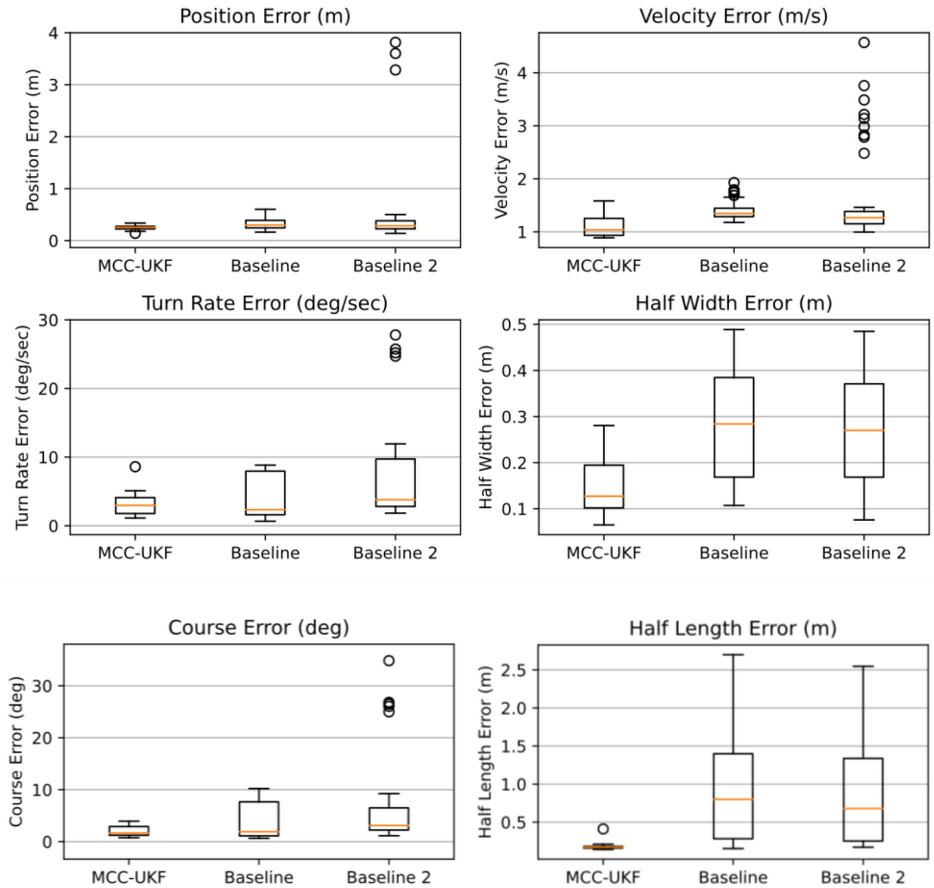


Figure 6.9 RMSE comparison between the MCC-UKF-based method and baseline methods under cluttered situations

Under cluttered situations, besides the measurement points generated from the vehicle, there are also measurement points from random locations, which have random range rate values between -10 to 10 m/s. The number of cluttered measurement points also follows a binomial distribution, with a maximum of 10 points and an occurrence probability of 0.15 for each point. Example vehicle trajectories are shown in Figure 6.6 (b) (for turning maneuver) and in Figure 6.7 (b) (for straight-driving maneuver).

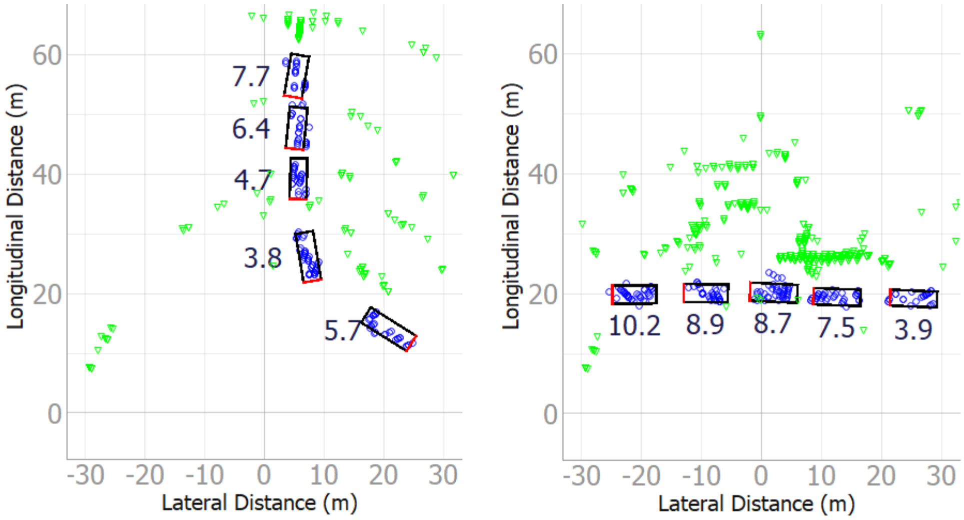
Under cluttered situations, simulations are again run 50 times, with 25 runs on each maneuver. Box plots of RMSE of different methods are shown in Figure 6.9. The same methods as in the clutter-free situations are compared. As shown in Figure 6.9, “MCC-UKF” shows overall better performance in all estimated states, with lower average RMSE over the runs in all the states and lower dispersions for most states except velocity. Comparing the results of cluttered situations to the clutter-free situations, “MCC-UKF” shows relatively small performance decrease, while the baseline methods show more significant performance decrease, especially “Baseline 2”. Comparing “Baseline 2” with “Baseline”, one can see that the more sophisticated models in “Baseline 2” cause the method to be more sensitive to clutters/non-Gaussian noise.

In conclusion, the MCC-UKF based method proposed in this work shows superior performance compared to baseline methods and performs significantly better under situations with clutters/non-Gaussian noise.

6.4.2 Experimental Evaluation

Experiments are performed with a Texas Instrument IWR 6843 ISK millimeter-wave radar, which operates at 60-64 GHz. It has 4 receive (RX) 3 transmit (TX) antennas with 120° azimuth field of view (FoV) and 30° elevation FoV. An Ouster OS1-64 lidar is used as a reference sensor. Lidar reference states (vehicle position, velocity, and course angle) are estimated from lidar measurements with an optimal smoother (the Rauch-Tung-Striebel Smoother). Lidar-estimated vehicle dimensions are averaged from measurements in multiple frames. Experimental data are collected on public roads with random vehicles.

The same maneuvers as in the simulations are considered. The turning maneuver and the straight driving maneuver are shown in Figure 6.10 (a) and Figure 6.10 (b), respectively. It's shown that the proposed method performs well in both vehicle tracking and vehicle dimension estimation under real-world cluttered measurements. Same as in the simulation study, with experimental data, the proposed method (i.e., "MCC-UKF") are again compared with the same baseline methods (i.e., "Baseline" and "Baseline 2"), and with the lidar estimation. The results of these comparisons for a left-turn vehicle and a straight-driving vehicle are shown in Figure 6.11 and Figure 6.12 respectively. It can be seen in Figure 6.11 and Figure 6.12 that the proposed method overall performs better than the two baseline methods with less deviation from the lidar reference estimates. In these cases, the half width estimates ($\hat{a}$) are constrained by the upper bound of $a_{max} = 1.5\ meters$ (31), so the estimation difference between methods is not large. But for the half length ($\hat{b}$) estimation, which is barely constrained by the $b_{max} = 6\ meters$ upper bound (32), the proposed method shows clearly better performance compared to the baseline methods. For more quantitative comparisons, the root-mean-square errors (RMSE) of different methods are shown in Table 6.1, with the lidar estimation as ground truth. As shown in Table 6.1, "MCC-UKF" shows better performance compared to both baseline methods, with the most significant improvements in course angle and vehicle dimension (length) estimation. "MCC-UKF" shows overall better performance than "Baseline 2", which means the MCC-UKF does better at rejecting noise from cluttered measurements. "Baseline 2" shows overall better performance than "Baseline", which means the developed dynamic model and measurement model have advantages over the less sophisticated models used in "Baseline". Overall, the experimental results agree with the simulation results, both of which validate the advantage of the proposed method.



(a) (b)

(a): Left-turn maneuver; (b) Straight-driving maneuver

Figure 6.10 Vehicle trajectories from experimental data (in several frames).
Small circles/triangles are the measurement points (blue circles are assigned to the vehicle while green triangles are out of the gating threshold). Rectangles represent the estimated vehicle positions, headings, and extent/dimensions. The digit near each rectangle is the estimated vehicle speed in m/s.

Table 6.1 RMSE Comparison of Different Estimation Methods

		x (m)	y (m)	v (m/s)	$\psi+\beta$ (deg)	a (m)	b (m)
Left Turn	MCC-UKF	0.254	0.689	0.580	4.560	0.161	0.481
	Baseline	0.372	0.714	0.715	13.728	0.160	0.698
	Baseline 2	0.271	0.661	0.517	5.791	0.162	0.714
Straight Driving	MCC-UKF	0.675	0.219	0.832	1.823	0.264	0.543
	Baseline	0.710	0.413	1.150	8.226	0.276	1.085
	Baseline 2	0.700	0.248	1.035	3.017	0.265	0.618
Average	MCC-UKF	0.465	0.454	0.706	3.193	0.212	0.512
	Baseline	0.541	0.564	0.933	10.977	0.218	0.892
	Baseline 2	0.486	0.455	0.776	4.404	0.214	0.666

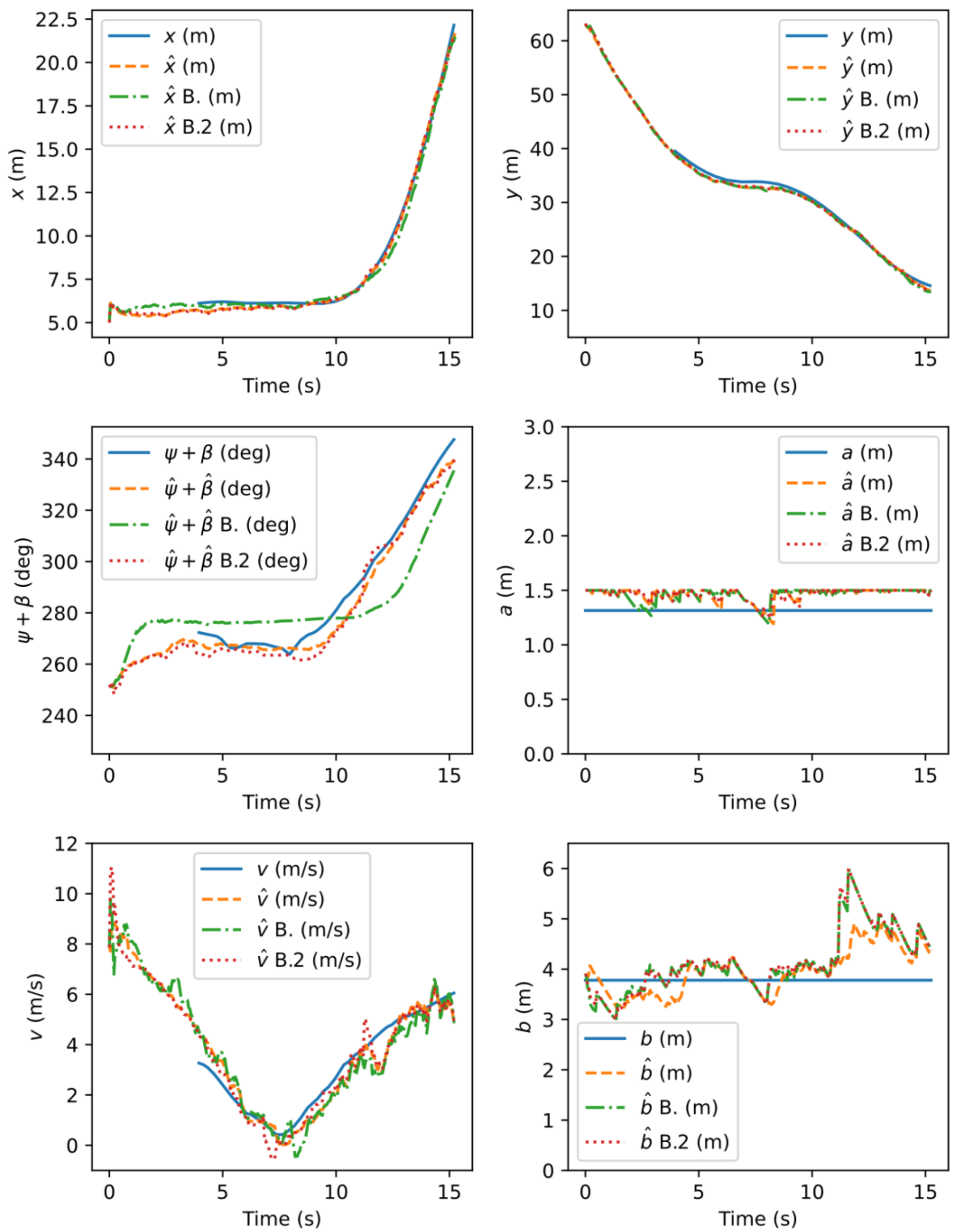


Figure 6.11 Comparison between the MCC-UKF-based method and baseline methods for left-turn vehicle. (x,y) is vehicle center position, v is vehicle speed, $(\psi + \beta)$ is the vehicle course angle (i.e., direction of vehicle center velocity), (a, b) is the half width and half length of the vehicle. Variables with hat are estimates from radar, while variables without hat are estimates from lidar. "B." means the "Baseline" method while "B. 2" means the "Baseline 2" method.

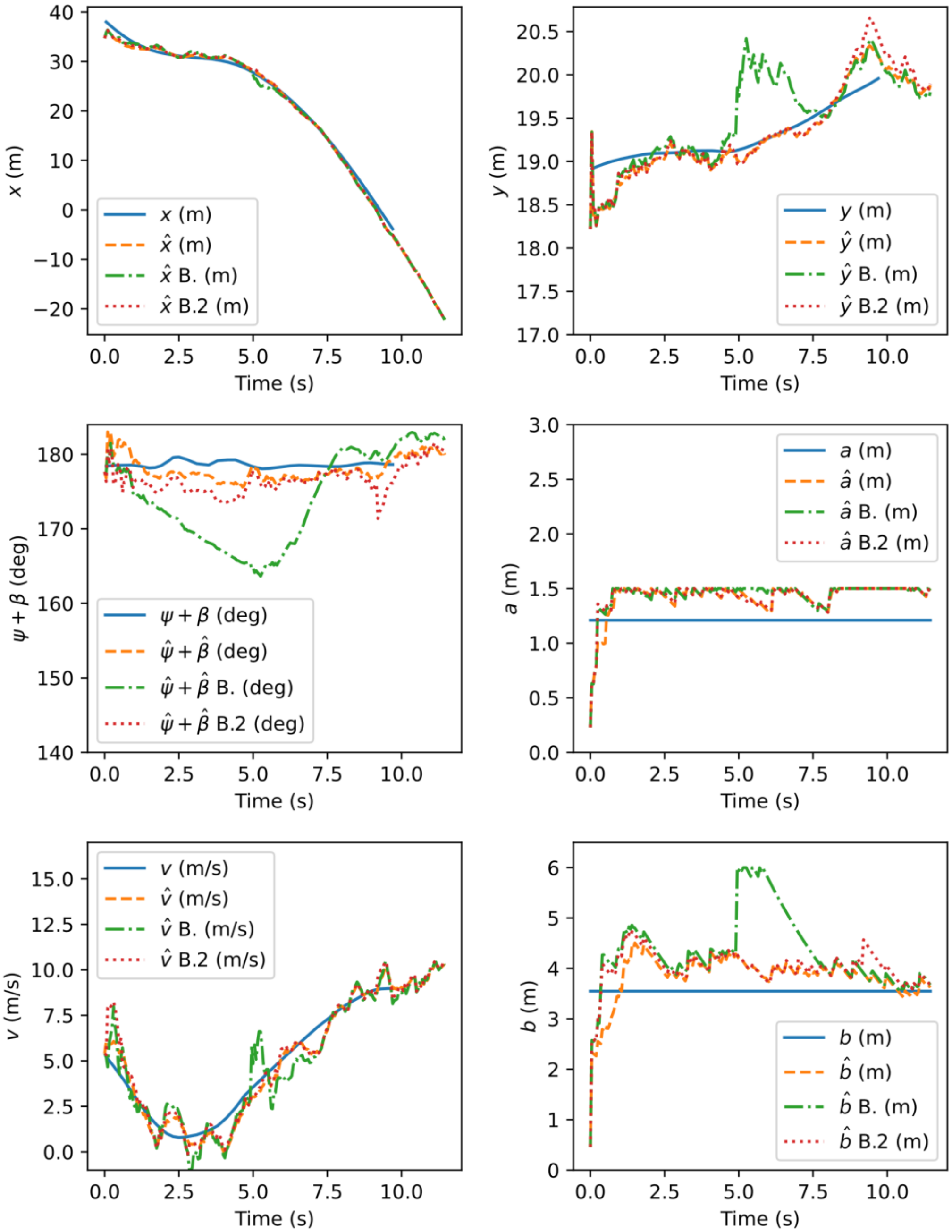


Figure 6.12 Comparison between the MCC-UKF-based method and baseline methods for straight-driving vehicle. (x,y) is vehicle center position, v is vehicle speed, ($\psi + \beta$) is the vehicle course angle (i.e., direction of vehicle center velocity), (a, b) is the half width and half length of the vehicle. Variables with hat are estimates from radar, while variables without hat are estimates from lidar. "B." means the "Baseline" method while "B. 2" means the "Baseline 2" method.

6.5 INTRUSION DETECTION

Once vehicle trajectories are being tracked in real-time, it is then necessary to predict whether a particular vehicle is in danger of intruding into a work zone. This section describes the algorithm developed for intrusion detection (prediction).

An intrusion is defined as a vehicle approaching the traffic sign at a speed higher than a threshold. The value of this threshold depends on the vehicle's distance to the traffic sign. As the vehicle gets closer to the traffic sign, the value of this speed threshold decreases. This methodology is based on assumptions regarding how quickly a vehicle can decelerate. The details of the speed versus distance threshold determination are as follows.

- A "speed limit vs distance curve" is designed with an assumption on maximum vehicle deceleration, and a predefined speed limit in a predefined area. In other words, vehicles should slow down adequately and be below the speed limit when they are close to the traffic sign.
- Specifically, if we assume a vehicle should brake at no more than a_m (m/s^2), and it should at least slow down to v_l (m/s) when it's d_0 (m) from the traffic sign, the vehicle's speed v at distance d should satisfy

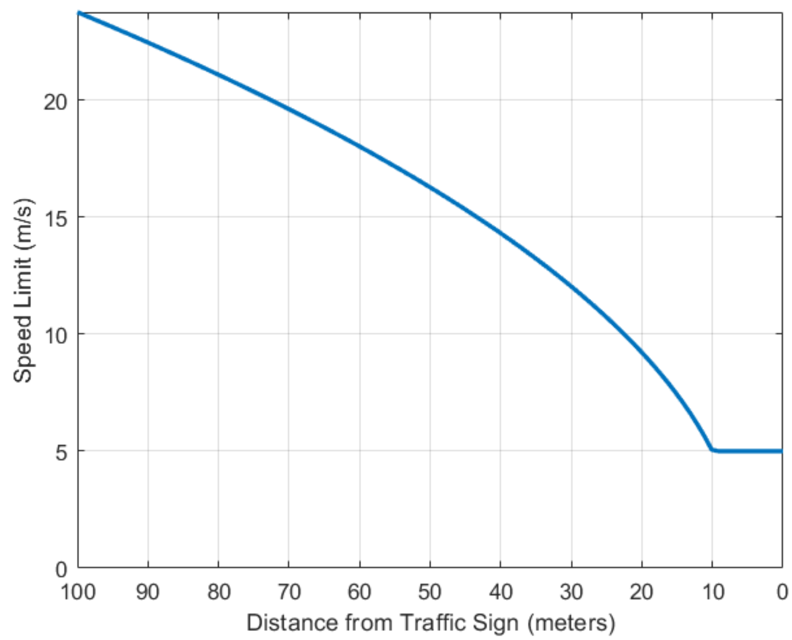
$$v^2 \leq v_l^2 + 2a_m(d - d_0), \; d > d_0$$

$$v^2 \leq v_l^2, \; d \leq d_0$$

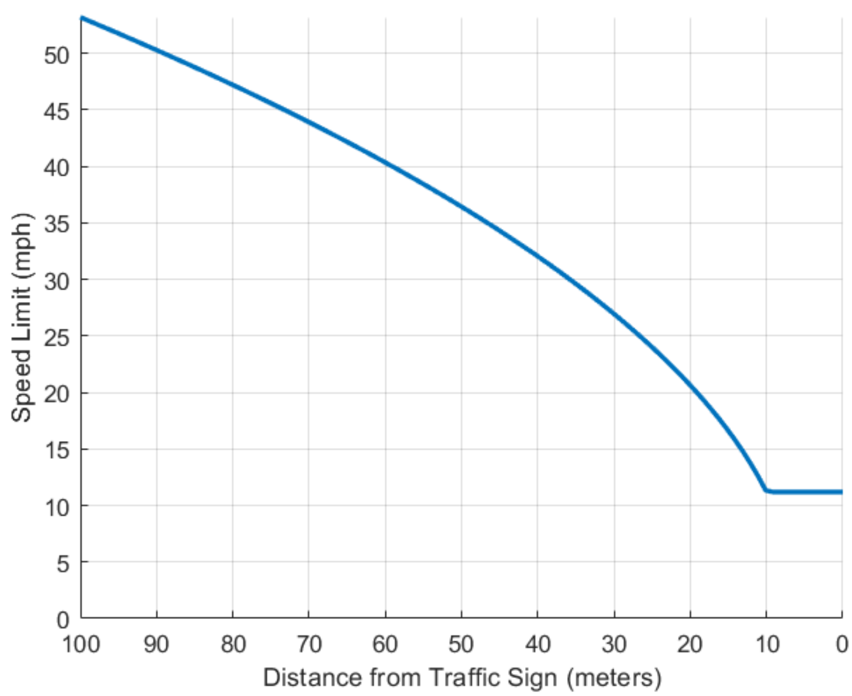
- Different parameters of a_m, v_l, and d_0 can be used under different signal conditions. E.g., with a solid red light, v_l should be very small or zero since vehicles should come to a full stop before the red light. If not, the above condition would not be satisfied and a loud audio warning to the vehicle would be provided (intrusion detected).
- If we use the parameters below as an example

$$d_0 = 10\,m, \; v_l = 5\,m/s, \; a_m = 3\,m/s^2$$

The "speed limit vs distance curve" will look like the following curve shown in Figure 6.13 (in m/s and mph):



(a)



(b)

Figure 6.13 Maximum allowed speed versus distance curve for a vehicle approaching the smart traffic light (a) Speed in mph and (b) Speed in m/s

An intrusion is detected if at any point a vehicle's speed is above the speed limit curve. In this case, an audio warning is triggered to warn the driver and the flag workers, see Figure 6.14.

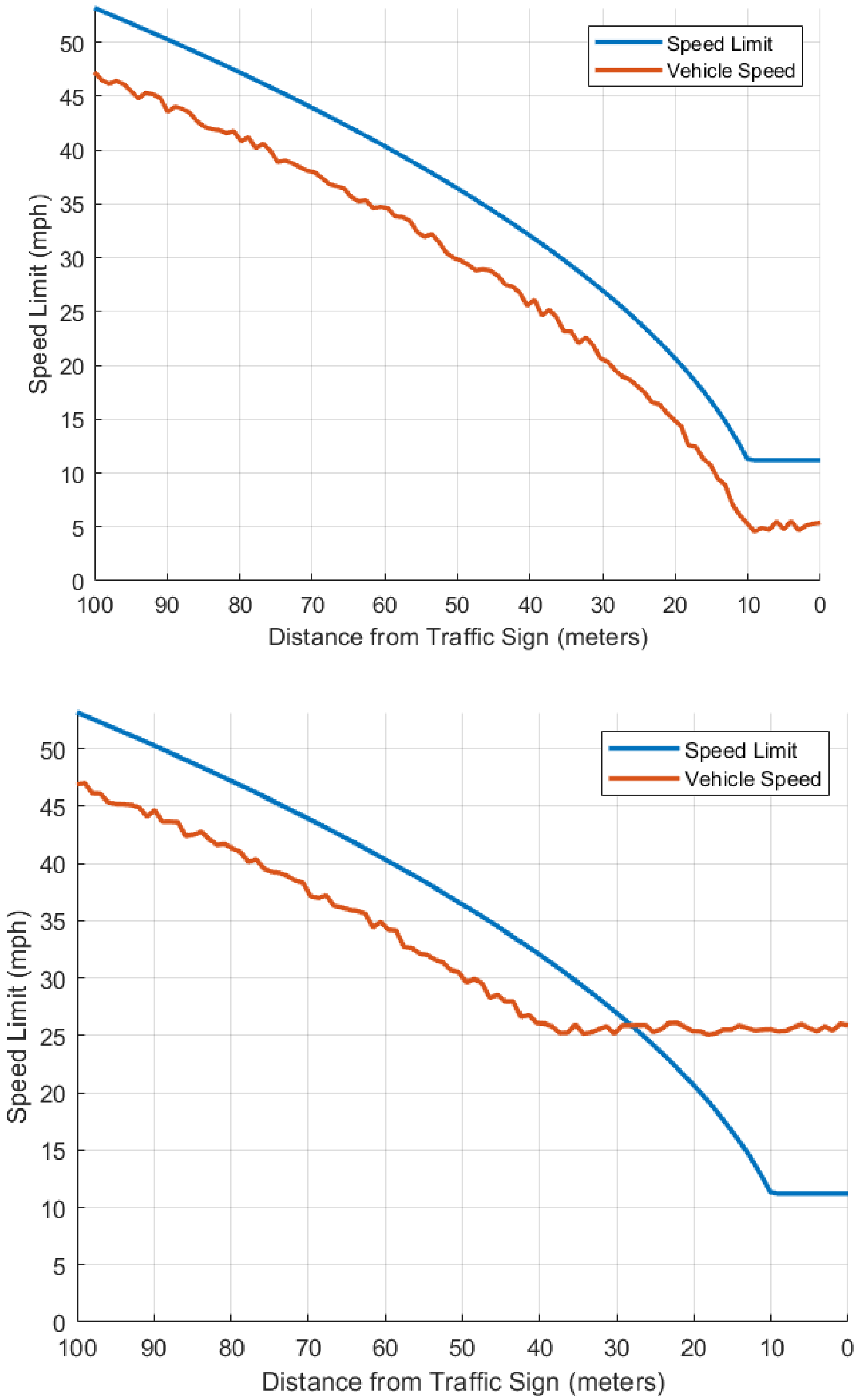


Figure 6.14 Examples of (top) non-intrusion and (bottom) intrusion

Figure 6.14 shows examples of non-intrusion (top figure) and intrusion (bottom figure). In the bottom figure, the vehicle speed is over the speed limit when the vehicle is at around 29 meters from the traffic sign. It is therefore considered an intrusion since the vehicle didn't slow down enough to be below the speed limit.

To estimate vehicle intrusion detection accuracy, 24 vehicle runs were conducted during two hours of testing over an afternoon in September 2022. Of these, 11 runs were made during red light mode and 13 runs were made during flashing yellow. All intrusions during the red mode were correctly detected. Warnings were provided during both modes if the vehicle was too fast and no warnings occurred if vehicle was sufficiently slow. The actual speeds and distances of the vehicles were not being measured with reference sensors during these tests – hence this is not a rigorous evaluation of accuracy. However, the system appeared to work correctly with all intrusions being correctly predicted.

CHAPTER 7: DISCUSSION

7.1 INITIAL AIMS

This project aimed to develop an automated intrusion detection system to alert drivers who are unsafely approaching or entering a flagger-controlled work zone. The successful future implementation of such a system must address several technical and human factors considerations to ensure that the system meets technical specifications and results in intended human-systems interactions.

The technical aims of the project included both functional and cost considerations. First, the developed sensing system must be accurate in its detection of threat vehicles as they approach a work zone, both in terms of sensitivity (i.e., correctly identifying threat vehicles) and specificity (i.e., correctly identifying non-threat vehicles). This would help reduce the risks of missed detections of threat vehicles and prevent false alarms. Further, an important implementation consideration of the technical development is that the systems are low cost to afford greater opportunity to scale the system across multiple work zones to support a greater number of maintenance workers.

The originally proposed design of this system was to incorporate low-cost sensors and processors on a modified STOP/SLOW sign supported by a rolling platform, see Figure 7.1. The sensors would include a pair of laser scanners capable of monitoring lateral and longitudinal intrusions, a microprocessor capable of processing the events in real-time, an audio-visual warning system to capture the attention of errant drivers, a camera to capture the events via video stream, and batteries to power the unit. Given the modification of the standard STOP/SLOW sign with the additional hardware and the added weight, the system would need to be designed with wheels to support workers in the manual rotation of the STOP/SLOW sign.

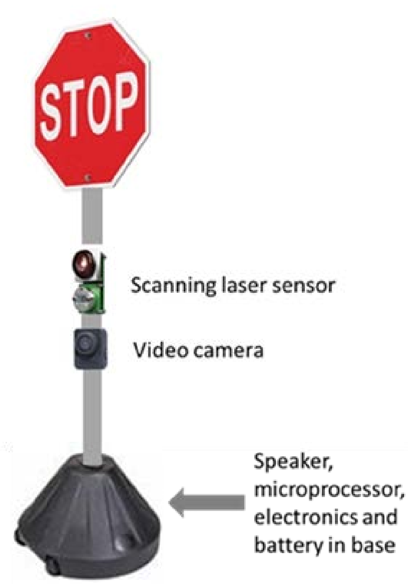


Figure 7.1 Initial STOP/SLOW prototype design proposed by engineering team

The planned human factors activities of this project were designed to support the engineering work through a worker-centered design process. The intent of these activities was to determine workers needs and expectations of using the proposed system early in the design process. This feedback and insight would help guide early design decisions before proposed substantial changes would be too difficult or costly to make following final usability testing. Additionally, these activities aimed to safely measure the expected driver responses when presented with the system in a simulated distracted driving scenario. This activity would help to validate that the system achieved the intended driver response of correcting unsafe approaches or intrusions into the work zone.

7.2 PRELIMINARY OUTCOMES

The worker-centered design process that was central to this project guided the human factors team to engage in user requirements gathering activities with maintenance workers. The purpose of this activity was to identify workers needs and expectations of a safety system, such as the one being proposed in this project. The team conducted interviews with eight maintenance staff members with supervisory roles at both state and county truck stations and extensive experience in maintenance work zones. The researchers engaged in a semi-structured discussion with supervisors about the proposed sign's efficacy expectations, communication abilities, physical structure, and other usage and durability considerations.

The key findings of these discussions were that maintenance workers expressed a strong desire for the new safety system to be designed so that it would not include a STOP/SLOW sign which would require a worker to physically stand near and operate it. This reluctance was due to a perception that drivers occasionally do not understand that the STOP sign required them to "stop and stay stopped" and not simply treat the STOP sign like a standard STOP controlled intersection in which a brief stop is required. Further, workers communicated the risks of placing a worker in the roadway with the sign and instead wished to remove the worker from the roadway/sign. A solution suggested by workers to separate the proposed safety system from a STOP/SLOW sign concept was to instead integrate it within a modified traffic light. The alternative traffic light system was preferred because it was expected to better communicate with drivers that they should stop and remain stopped. Further, this system was also preferred because it would allow the flagger to be placed further away from incoming/outgoing traffic.

7.3 MODIFIED AIMS

In response to worker feedback, the engineering team modified the original design of the sign to a new portable traffic signal which can convey a red ball, yellow ball (flashing and steady), and optionally include a green ball, see Figure 7.2, and could be controlled remotely by a nearby worker on the side of the road. Notably, this sign change did not influence the approach of the engineering team's sensing system development in terms of detecting and identifying threat vehicles and establishing algorithms to activate an alarm system to warn both drivers and workers when threats are detected.

Figure 7.2 Revised traffic signal prototype design

Moreover, the human factors team modified their simulation study to integrate the simulated safety system into a modified traffic signal and compare its performance to a traditional flagger at a rural work zone. The expected outcomes of this modified approach were that the modified traffic signal with the alarm system should perform the same or better than the traditional flagger at capturing drivers' attention as they approached the simulated work zone and better correct errors after they occur than the traditional flagger. Further, this system was expected to better support flagger worker safety by removing them from the roadway.

The combined initial and modified aims were carried forward by the joint research teams. The modified approach allowed the engineering team to test the experimental sensing system within the modified signal configuration while the human factors team determined the efficacy of the modified signal and alarm system to capture the attention of distracted drivers and correct errors before they entered the work zone. The human factors findings could then inform and recommend final design changes to enhance the signal.

7.4 INTERIM AIMS AND OUTCOMES

The human factors team conducted a driving simulation study to measure driver responsiveness and compliance to the experimental traffic signal with the alarm system compared to a traditional flagger. The results found that drivers were more likely to fail to stop or stop late with the experimental signal than with the flagger and were less likely to remain stopped. The alarm of the experimental signal did show some indication that it helped to stop some drivers who initially failed to notice the signal. Follow up discussions with participants found that drivers reported higher expectancies and perceived authority for the flagger than the signal, but they preferred the signal concept due to its safety benefits.

In response, the human factors team proposed two design changes to the two experimental sign conditions in a revised simulation study. The first would increase the conspicuity of the experimental traffic signal with high visibility border, signage to provide clarity about stopping expectations, and a nearby simulated maintenance worker. This enhanced design was also integrated into the engineering team's final prototype to demonstrate its appearance during their testing of the sensing system (see Figure 7.3). The second would be to add the alarm system to the flagger by adding a simulated red LED border to the STOP/SLOW sign which would flash when the audio alarm was activated by a detected intruding driver. The intent of this revised study was to increase the strength of the conclusions about the efficacy of the alarm system on the traffic signal and to determine if it may be better suited on the STOP/SLOW sign.

Figure 7.3 Final traffic signal prototype design

The results of the revised simulation study reveal positive results for the modified STOP/SLOW flagger design with the alarm system. No initial stop failures were observed with the alert flagger system among drivers who were presented with it in the first work zone drive and only one initial stop failure was observed among drivers who experienced the alert flagger system in the second work zone drive. These results suggest that the alert STOP/SLOW flagger system may be more compatible with driver expectations of signage indicating work zone presence and results in better responsiveness upon initial detection. Additionally, whereas 22.8% of drivers with the traditional flagger without the alarm system stopped *but did not remain stopped*, however, only 10% of drivers presented with the alert flagger system committed the same failure. This suggests that the automated alert system may be successful in helping to address some of the observations raised by workers in the initial interviews about driver confusion with the STOP signs used in work zones.

Meanwhile, the engineering team was successful in advancing the sensing system to be capable of simultaneous multi-vehicle tracking (including estimation of vehicle position, velocity, and heading) with a range of up to 60 meters and angular azimuth range of 120 degrees. This intrusion detection algorithm was based on a safe speed versus distance curve, with an assumed value of maximum safe deceleration. Vehicle intrusion detection accuracy was validated with a high-density lidar. Twenty-four vehicle runs were measured during the testing session. These runs included 11 vehicles staged to intrude the test area and 13 staged to safely stop or to quickly approach but to stop before intruding. All intruding vehicles were correctly detected. Warnings were provided during both modes if the vehicle was too fast and no warnings were activated if the vehicle approached sufficiently slowly.

CHAPTER 8: CONCLUSIONS

From 2011 through 2020, 577 U.S. workers were killed by a moving vehicle at a road work site, accounting for 63% of all worker deaths (Bureau of Labor Statistics, 2022). This highlights the immense risks faced when working in maintenance, construction, and other road work sites. Work zones experience higher crash risks and crash severities than other stretches of road due primarily to the change in road geometry and traffic flow (Garber & Zhao, 2001; Khattak et al., 2002). Risks are influenced by a combination of factors with some features providing a protective effect, e.g., flaggers present, and some increasing risk, e.g., two-lane roadways, (Li & Bai, 2008). Designing safer work zones through automated devices for flaggers and work zone intrusion notification systems are identified in *Minnesota's 2020-2024 Strategic Highway Safety Plan's Strategic Focus Areas* (MnDOT, 2020). Developing automated systems to better protect workers from drivers who intrude into the work zone will improve the safety of work zones and reduce worker risks.

Developing a system that can warn workers and drivers of impending intrusions may help to alleviate the stress experienced by flaggers and support them in their frustrations in interacting with aggressive or distracted drivers who threaten their safety (Debnath et al., 2015). However, additional design changes should be explored to determine whether possibilities exist to remotely control the STOP/SLOW sign and allow workers to separate themselves from the sign and traffic. Such future modifications could help decrease worker stressors from managing complex traffic scenarios and their own safety (Marois et al., 2018).

Work zones accounted for an average of 2.86% of all Minnesota roadway deaths from 2016-2020 (FARS, 2023). While this percentage may seem small, the 31 deaths that occurred over this period represented $54,250,000 in economic losses to the state and immense pain and distress for Minnesota families. Advancing this research in an implementation study could help reduce risks and advance safety measures to prevent deaths and serious injuries in Minnesota work zones in the future.

8.1 RECOMMENDATIONS AND FUTURE WORK

The findings and outcomes of this work advanced the development of a worker-centered smart traffic sign device to automatically detect potential intruding vehicles near work zone flaggers and automatically alert the threat driver and surrounding crew. The advancements of the engineering team to use low-cost sensors and processors to detect threat vehicles was deemed successful and is recommended to be advanced to an implementation study to test its efficacy in a pilot study. Future research using the experimental sensor system and algorithms should be further developed to allow it to be extended to other work zone layouts and roadway speeds.

The sign system on which this alarm system should be integrated is recommended to be a STOP/SLOW flagger system rather than the modified traffic signal (see Figure 8.1). This proposed design would incorporate the LED flashing border feature into the original prototype design shown in Figure 7.1. The alert STOP/SLOW flagger system should be advanced in the implementation study to determine its worker acceptance and whether the driver behavior observed in the simulation study extends to real work zone settings.

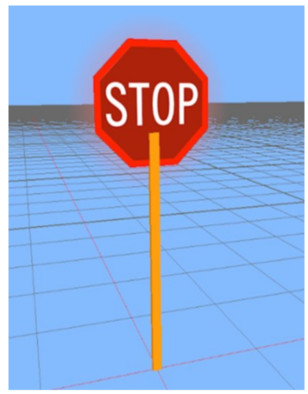


Figure 8.1 Image of alert STOP/SLOW flagger sign presented in the revised simulation

Future implementation studies should examine a variety of occupational safety considerations to ensure the system best supports workers. This work should include examining the signal-to-noise ratio and vehicle penetration of the auditory alarm in the work environment. Importantly, NIOSH sound level safety considerations should be included to ensure that the volume of the alarm does not damage worker hearing. Additionally, the design of the system, its ability to break down, and the weight (i.e., ≤ 30LBS) and coupling of its individual components should be examined to ensure there is no expected risk of back injury from its handling.

Finally, ongoing user-centered design studies should be conducted to continuously measure sign design and function against worker needs, wants, and expectations. These studies should include, among other investigations, worker stress and safety perceptions, sign maneuverability, assembly, battery life and manual interactions, remote-controlled capabilities, and cross-unit communication.

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APPENDIX A

FEATURES OF INSTRUMENTED PORTABLE SIGN

Prepared by: Zhenming Xie, Lee Alexander, and Raj Rajamani

Below is a table of which features raised by the human factors team that can be included in the prototype instrumented sign and some that might not be possible to include.

	Feature	Included in current prototype?	Additional comments
1)	Automated tracking of vehicle trajectories in the neighborhood of the instrumented sign	Yes	Will predict danger of intrusion into work zone and sound an alarm
2)	Red and green signal lights	Yes	a. A full signal containing red, yellow and green is heavier and bigger. b. Either red or green can be flashed, stay on or stay off.
3)	Remote operation of lights by flag worker	Yes	A remote operation radius of up to 20 feet is envisioned.
4)	Battery duration of 2 hours	Yes	Extended duration of up to 10 hours can be obtained by additional inclusion of batteries in the future.
5)	Extra battery swapping	Yes	A parallel battery configuration allowing battery swapping will be implemented.
6)	Clear indication of state of charge of battery	Yes	Unsure of how accurate the SoC will be. It will be a commercial mete based on terminal voltage.
7)	Easy assembly/ disassembly	Yes	The bottom case will be heavier and lend stability. It will be possible to quickly disassemble the pole and sign from the base.
8)	Video camera on traffic sign	Yes	Automatic back up of critical video segments.
9)	Big dolly wheels on base of traffic sign	Yes	
10)	Easy to pick up?	Yes	Total weight less than 50 pounds. Disassembled weight of base less than 30 pounds.
11)	Networking and coordination between two traffic signs	No	A cellular connection using a wireless carrier may be needed for coordination of messages between signal lights separated by a distance that could be as large as 1 mile. Also, an application software (smart phone app) may be needed. This could be done in the future, but not in the current research project.
12)	Automated operation of signal lights	No	Enhanced feature, can be developed in the future. Will need cellular network connectivity between traffic signs.
13)	Automated counting of vehicles (traffic counts)	No	Enhanced feature, can be developed in the future.

APPENDIX B

USABILITY TEST SCREENING QUESTIONNAIRE

1. Are you at least 18 years of age or older?
   - If NO, exclude.
2. Do you have a current Minnesota drivers' license?
   - If NO, exclude.
3. Have you had a U.S. driver's license for at least one year?
   - If NO, exclude.
4. Do you have at least 20/40 visual acuity, either corrected or uncorrected?
   - If NO, exclude.
5. Do you have normal color vision?
   - If NO, exclude.
6. Do you have any history of hearing loss which inhibits everyday conversation?
   - If YES, exclude.
7. Do you have any health problems that affect your driving?
   - If YES, exclude.
8. Do you experience inner ear problems, dizziness, vertigo, or balance problems?
   - If YES, exclude.
9. Do you have a history of motion sickness? (e.g., back seat of car, boats, amusement park rides, etc.)
   - If YES, exclude.
10. Can you read in the car?
    - If NO, exclude.
11. Do you have a history of sea sickness?
    - If YES, exclude.
12. Are you suffering from any lingering effects of stroke, tumor, head trauma, or infection?
    - If YES, exclude.
13. Do you or have you ever suffered from epileptic seizures?
    - If YES, exclude.
14. Do you have a history of migraines?
    - If YES, exclude.

APPENDIX C

WORK ZONE USABILITY TEST SCRIPT

Thank you for agreeing to participate in this study.

In this study, you will drive 3 rural simulated drives. The first will be a practice drive, followed by two test drives.

During the drives, we ask that you attempt to drive exactly 50 mph and follow at a 2 seconds or two car lengths following distance as exactly as you can. You may exceed 50 mph for a short time if you fall behind and need to catch up to the truck. Most importantly, follow all rules of the road over all else.

In the practice drive, you will have the opportunity to practice maintaining 50 mph speed and following distance of two car lengths. You will receive a visual warning if you are too close or too far back.

Be mindful of feelings of simulation sickness. If you start to feel warm, have a sour or watery feeling in your mouth, or in any way feel nauseous or unwell, please bring the car to a gradual stop and put it into park. Your wellbeing is more important than completing the drive, so do not hesitate to stop if you begin noticing any of these symptoms. We will assess your wellness after each drive to be sure you are able to proceed.

Do you have any questions?

APPENDIX D

WORK ZONE USABILITY TEST GENERAL QUESTIONNAIRE

Demographics

1. Please enter your age: _______
2. What is your gender?
    - Male
    - Female
    - Other
3. What is your highest level of education?
    - Some high school
    - High school diploma or GED
    - Associate degree
    - Some college, no degree
    - Bachelor's degree
    - Graduate or professional degree
    - Other
4. What is your ethnicity?
    - Hispanic or Latino
    - Not Hispanic or Latino
5. What is your racial background?
    - American Indian or Alaska Native
    - Asian
    - Black or African American
    - Hawaiian or Other Pacific Islander
    - White
    - Multiracial
    - Other
6. Please enter your zip code:__________
7. Do you consider yourself to live in an urban, suburban, or rural area?
    - Urban
    - Suburban
    - Rural
8. In which area(s) do you drive the most often?
    - Urban
    - Suburban
    - Rural

Personal Involvement Questions

1. How important is it for you that roadway designs are changed to improve safety?

1 Not important at all	2	3	4	5 Very important

2. How happy are you with the state of Minnesota roadways?

1 Not happy at all	2	3	4	5 Absolutely happy

Driver Behavior Questions

1. Ignore a yield sign and almost collide

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

2. Fail to notice pedestrians crossing

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

3. Underestimate the speed of an oncoming vehicle

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

4. Get into the wrong lane when approaching

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

5. Fail to check your mirrors before pulling

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

6. In a line of cars nearly hit the car in front of you

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

7. Brake too hard on a slippery road

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

8. When turning right nearly hit a cyclist

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

9. Hit something when backing up

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

10. Attempt to pass a vehicle that you hadn't noticed was signaling

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

11. Intending to drive to destination A, realize you are en route to B

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

12. Forget where you parked your car

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

13. Realize you have no clear recollection of the road

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

14. Switch on one thing instead of another

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

15. Attempt to leave a parking space in the wrong gear

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

16. Drive especially close to or flash the car in front of you

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

17. Get involved in unofficial races

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

18. Deliberately disregard the speed limit

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

19. Feel angered by another driver’s behavior

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

20. Drive over the legal blood-alcohol limit

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

APPENDIX E

WORK ZONE USABILITY TEST WELLNESS ASSESSMENT

Participant ___________ Researcher_____________ Date____________

Wellness Assessment Questionnaire

Instructions: Circle how much each symptom below is affecting you right now.

1.	General Discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye strain	None	Slight	Moderate	Severe
5.	Difficulty focusing	None	Slight	Moderate	Severe
6.	Salivation increasing	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty concentrating	None	Slight	Moderate	Severe
10.	Fullness of the Head	None	Slight	Moderate	Severe
11.	Blurred vision	None	Slight	Moderate	Severe
12.	Dizziness with eyes open	None	Slight	Moderate	Severe
13.	Dizziness with eyes closed	None	Slight	Moderate	Severe
14.	*Vertigo	None	Slight	Moderate	Severe
15.	**Stomach awareness	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe

*Vertigo is experienced as loss of orientation with respect to vertical upright.

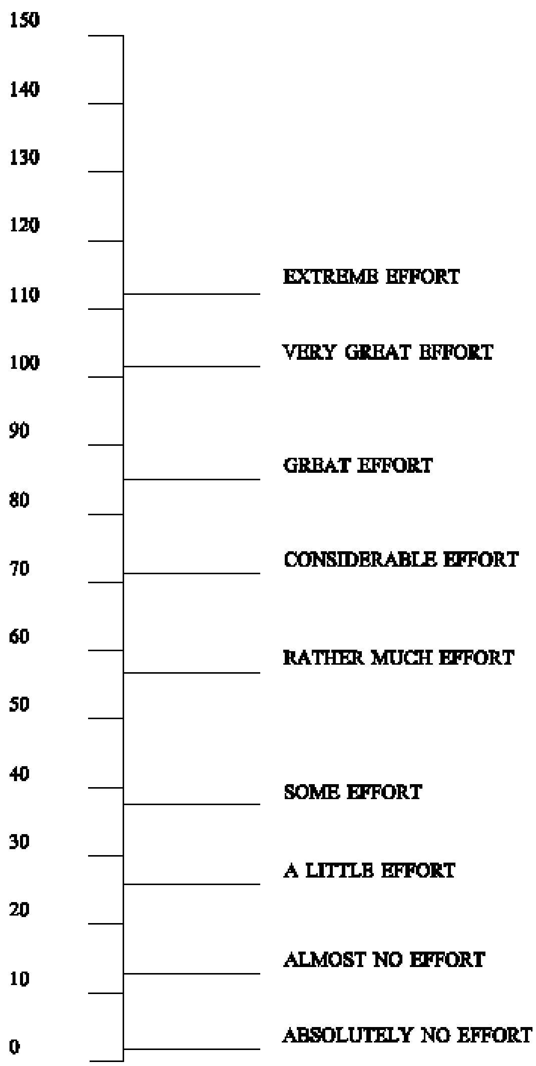
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

APPENDIX F

WORK ZONE USABILITY TEST SELF REPORT SCALES

Rating Scale Mental Effort

Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task you've just finished



	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

1. How confusing was the work zone you just drove through?

1 Not confusing at all	2	3	4	5 Extremely confusing

2. How stressful was the work zone you just drove through?

1 Not stressful at all	2	3	4	5 Extremely stressful

3. How irritating was the work zone you just drove through?

1 Not irritating at all	2	3	4	5 Extremely irritating

4. How overwhelming was the work zone you just drove through?

1 Not overwhelming at all	2	3	4	5 Extremely overwhelming

5. How well did the signage help you to be prepared to stop?

1 Not well at all	2	3	4	5 Extremely well

6. How safe did it feel as you approached the work zone?

1 Not safe at all	2	3	4	5 Extremely safe

APPENDIX G

WORK ZONE USABILITY TEST POST STUDY SELF-REPORT QUESTIONNAIRES

Post Study Self-Report Questionnaire:

1. Which signage system was clearer to understand and follow?

Flagger with sign		Equal		Portable stop light

2. Which signage system was more visible?

Flagger with sign		Equal		Portable stop light

3. Which signage system would you prefer to come across while driving?

Flagger with sign		Equal		Portable stop light

4. Which signage system do you think has more authority to direct your driving?

Flagger with sign		Equal		Portable stop light

Final questions:

Do you recall hearing an alarm sound?

Did you know where the sound came from?

Do you have any other thoughts about that sound?

Any other thoughts about the signage you experienced?

APPENDIX H

SIMULATED WORK ZONE IMAGES

North Work Zone with Traditional Flagger (control)


SLOW

SLOW

South Work Zone with Traditional Flagger (control)


STOP


STOP

South Work Zone with Experimental Traffic Control (Treatment)